

U.S. Steam Turbine Valve Metallurgy Guide

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REPORT SUMMARY

This report provides nuclear and fossil plant personnel with current information on the metallurgical aspects of the steam turbine valve components used in U.S. power plants.

Background

The Electric Power Research Institute (EPRI) published the *Guidelines and Procedures for Turbine Valve Condition Assessments* (1010211) in December 2005. Two topics that would complement the work in the EPRI guide are alternative materials that are used in valve components and the metallurgy associated with the valve materials. This report contains these two topics.

Objectives

- To provide technical information for the use of alternative materials in steam turbine valve stems and bushings
- To provide plant maintenance personnel with the metallurgical aspects of the materials used for steam turbine valve components

Approach

A Technical Advisory Group was formed that consisted of steam turbine owners from members of the EPRI Steam Turbines, Generators, and Balance-of-Plant Program and the Nuclear Steam Turbine Initiative Program. Extensive research was performed regarding the turbine valve materials used in the industry.

Results

The guide includes metallurgical information for the steam turbine valve (stop/governor, control/throttle, reheat stop, and intercept) bushings, discs, pressure seal heads, seats, and stems. The metallurgical topics include alloy standards, chemical composition, physical properties, mechanical properties, heat treatment, damage mechanisms, and repairs.

EPRI Perspective

The reliable operation of the steam turbine valves is crucial for the continued operation of nuclear and fossil generating plants. The metallurgy for the valve components is an important aspect of the reliability of the valve components.

Keywords

Turbine valve

Metallurgy

Life assessment

Damage mechanism

Physical properties

Chemical composition

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INTRODUCTION

1.1 Background

Steam turbine valves are one of the critical components required for safe, reliable, and efficient operation of both fossil fuel and nuclear power plants. To properly assess the current condition of these components and ensure continued serviceability, the Electric Power Research Institute (EPRI) has provided guidelines and procedures for the condition assessment of turbine valves [1]. In addition to condition assessment for steam turbine valves, on-line monitoring techniques have been developed [2, 3]. The driving forces for the current metallurgical study as well as the condition assessment and on-line monitoring efforts are the same: increase turbine/valve reliability and decrease costs through an increase in the time between turbine valve outages. One important and proven approach to increasing reliability is the use of improved materials/coatings and upgrades in valve component materials. The choices involved in these materials issues require technical and metallurgical information on current and alternative turbine valve materials.

The need for the attention given to steam turbine valves is highlighted by the results of an analysis of steam turbine reliability data in the Generating Availability Data System (GADS) [2] from the Northern American Electric Reliability Council (NERC). The analysis used a cause-code approach that allowed the unit availability to be tracked by specific components or subsystems. Six cause-code groups were used:

- High-pressure/intermediate-pressure turbine
- Low-pressure turbine
- Turbine valves
- Turbine lube oil system
- Hydraulics, control, overspeed
- Miscellaneous

The availability lost due to turbine valves was the fourth highest cause for fossil units from 1983 to 2002.

Recently, research efforts have been expanded to develop metallurgical data for steam turbine valves, shells/casings, blades, and stationary components. Based on the use of alternative materials by the Tennessee Valley Authority (TVA), it was decided to develop one comprehensive metallurgical guide that covered the metallurgical aspects for both traditional and alternative materials used in steam turbine valves.

1.2 Objectives

The objectives of the *U.S. Steam Turbine Valve Metallurgy Guide* are the following:

- To provide technical information for the use of alternative materials for steam turbine valve stems and bushings
- To provide plant maintenance personnel with the metallurgical aspects of the materials used for steam turbine valve components

The steam turbine valve components of interest are the following:

- Stems
- Bushings
- Seats
- Main and bypass valve discs
- Pressure seal heads

The technical information for the alternative materials includes the background and basis for their selection and the same metallurgical aspects that are given for the traditional turbine valve materials. The metallurgical aspects for each material include the following:

- Alloy standards and materials used by the different manufacturers
- Chemical composition
- Physical and mechanical properties
- Metallurgy: microstructure, heat treatments, coatings
- Damage mechanisms
- Repairs: welding, coatings, heat treatment

1.3 Guide Content

The *U. S. Steam Turbine Valve Metallurgy Guide* has seven sections and two appendices:

- Section 1 is the project introduction. This section contains the background information, project objectives, guide content, a brief discussion of metallurgical standards, and generic drawings of typical steam turbine valves.
- The metallurgical information for the existing valve materials are given in Sections 2–6 for the stems, bushings, seats, discs, and pressure seal heads, respectively.
- Section 7 provides the technical and metallurgical information for the alternative valve materials that are used for stems and bushings.
- The glossary of terms specific to the study of metallurgy, wear, heat treating, and steam turbine valve components is provided in Appendix A.
- Appendix B has a tabular summary of the tensile properties, the mean coefficient of thermal expansion, and a qualitative ranking of the wear and oxidation resistance for the steam turbine valve materials.

1.4 Metallurgical Standards

Metallurgical standards originate primarily from two sources in the United States: the American Society for Metals (ASM) International and the American Society for Testing and Materials (ASTM). Both of these societies publish handbooks, reference volumes, and conference proceedings. From their web sites (<http://www.asminternational.org> and <http://www.astm.org>), it is possible to order or download published literature without being a member of the organizations (albeit at a cost higher than for members).

For steam turbine valve applications, the metallurgical standards and reference books published by ASM International, along with a brief statement of content, are listed here:

- *ASM Metals Handbook, Volume 1: Properties and Selections: Irons, Steels, and High Performance Alloys*, 1990. Contents include compositions, properties, and selection for low-alloy steels, stainless steels, and superalloys.
- *ASM Metals Handbook, Volume 4: Heat Treating*, 1991. Contents include heat treating of steels, surface hardening of steel, and heat treating of stainless steels and superalloys.
- *ASM Metals Handbook, Volume 6: Welding, Brazing, and Soldering*, 1993. Contents include welding fundamentals, consumable selection, and procedure development.
- *ASM Metals Handbook, Volume 9: Metallography and Microstructures*, 2004. Contents include metallographic specimen preparation, etching, and photomicrographs of typical microstructures of metallic materials.
- *ASM Metals Handbook, Volume 18: Friction, Lubrication and Wear Technology*, 1992. Contents include a guide to basic concepts, definitions, and materials selection for wear resistance.

- *Superalloys: A Technical Guide*, 2002. Contents include superalloys' properties, heat treatment, microstructures, and selection.
- *Practical Nitriding and Ferritic Nitrocarburizing*, 2003. Contents include basic introduction to surface-hardened materials' process, materials, microstructures, and properties.
- *Handbook of Thermal Spray Technology*, 2004. Contents include principles, processes, types of coatings, applications, performance, and testing/analysis.
- *Damage Mechanisms and Life Assessment of High-Temperature Components*, 1989. Contents include materials and damage mechanisms for steam turbine rotors, casings, valves and steam chests.

The metallurgical standards and reference books published by ASTM, as well as a brief statement of content for the standards, are listed below. The documents are the current standards and include the following:

- *ASTM E7 - 03 Standard Terminology Relating to Metallography*. Contents include definition of terms and standard terminology used in metallography.
- *ASTM E340 - 00(2006) Standard Test Method for Macroetching Metals and Alloys*. Contains methods used to macro etch metals and alloys to reveal the macrostructure of the alloy.
- *ASTM E3 - 01(2007) Standard Guide for Preparation of Metallographic Specimens*. Contents include guidelines on selection of specimen location, orientation, and type based on the objective of the study and a description of useful and standard metallographic specimen preparation techniques.
- *ASTM E407 - 07 Standard Practice for Microetching Metals and Alloys*. Standard gives methods and solutions for etching to reveal the microstructure of most major alloys.
- *Metallographic and Materialographic Specimen Preparation, Light Microscopy, Image Analysis, and Hardness Testing*, 2007.

In addition to the sources of metallurgical standards cited above, several EPRI publications have provided metallurgical information of value for steam turbine valve materials as follows:

- *Steam Turbine Bolting Maintenance Guide, Revision 1*. EPRI, Palo Alto, CA: 2008. 1016958.
- *The Grade 22 Low Alloy Steel Handbook*. EPRI, Palo Alto, CA: 2005. 1012840.

1.5 Generic Valve Drawings

The two basic types of valves are stop valves and control valves. The valves are installed in the main steam line that supplies steam to the high-pressure (HP) turbine and in the hot reheat steam line that supplies steam to the intermediate-pressure (IP) (for fossil turbines) and low-pressure (LP) turbines. The purpose of steam turbine valves is twofold: (1) to control unit load and frequency and (2) to prevent turbine overspeed and failure in emergencies, such as the loss of generator load and other operational failures.

The majority of the steam turbine valves in service at U.S. plants were manufactured by General Electric and Siemens-Westinghouse. Generic drawings of the turbine valves that are included in this guide are shown in Figures 1-1 to 1-4 for General Electric fossil turbine valves and in Figures 1-5 to 1-8 for Siemens-Westinghouse fossil turbine valves. The generic drawings were taken from the EPRI *Guidelines and Procedures for Turbine Valve Condition Assessment* [1] and were supplied by Turbine Technology International, Inc. The drawings illustrate the basic geometry of the various valves for each original equipment manufacturer (OEM) and the valve components of interest for this guide.

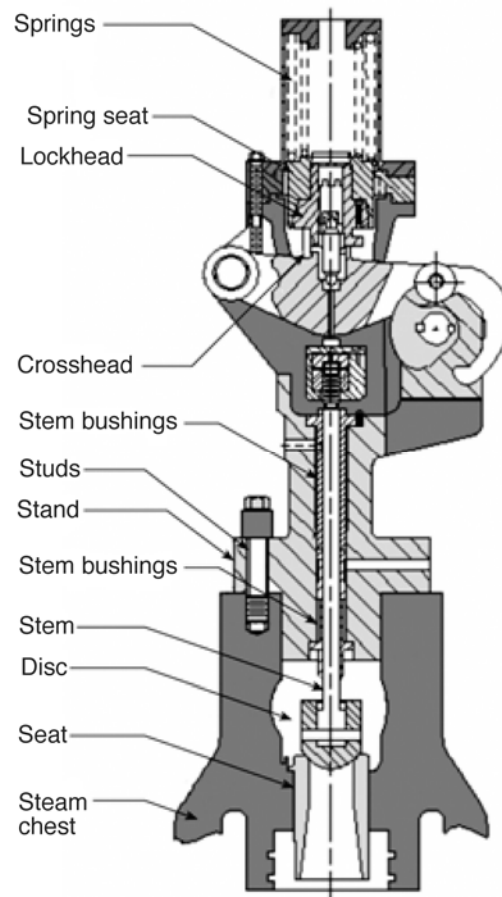


Figure 1-1
General Electric fossil turbine camshaft-operated control valve
(Courtesy of Turbine Technology International, Inc.)

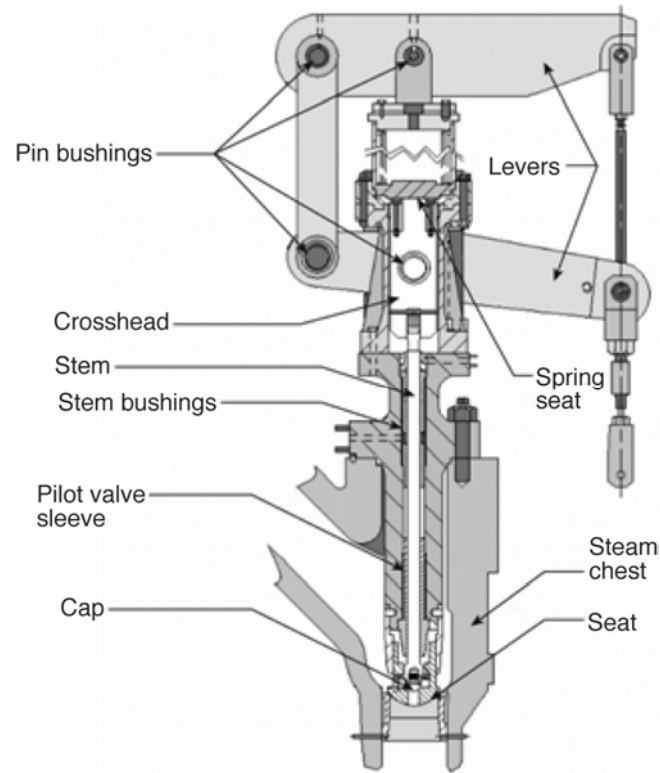


Figure 1-2
General Electric fossil turbine separately mounted control valve
(Courtesy of Turbine Technology International, Inc.)

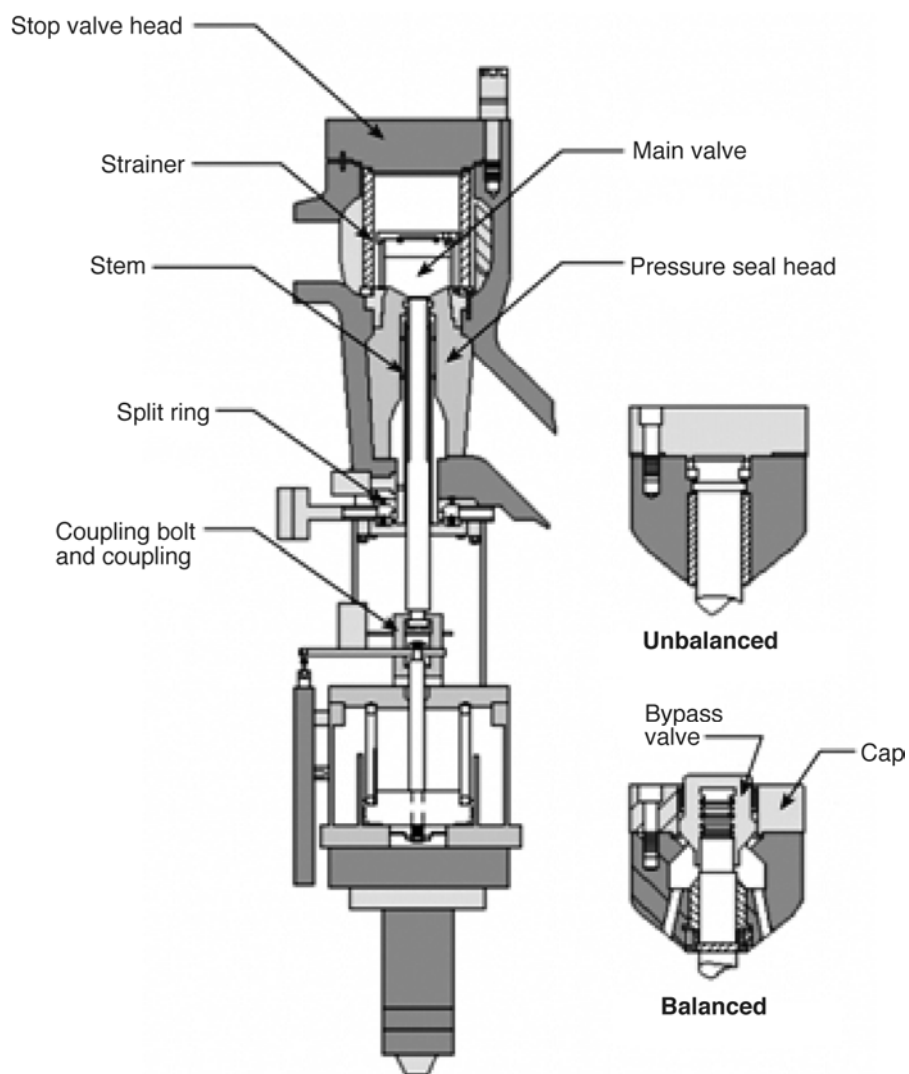


Figure 1-3
General Electric fossil turbine main stop valve
 (Courtesy of Turbine Technology International, Inc.)

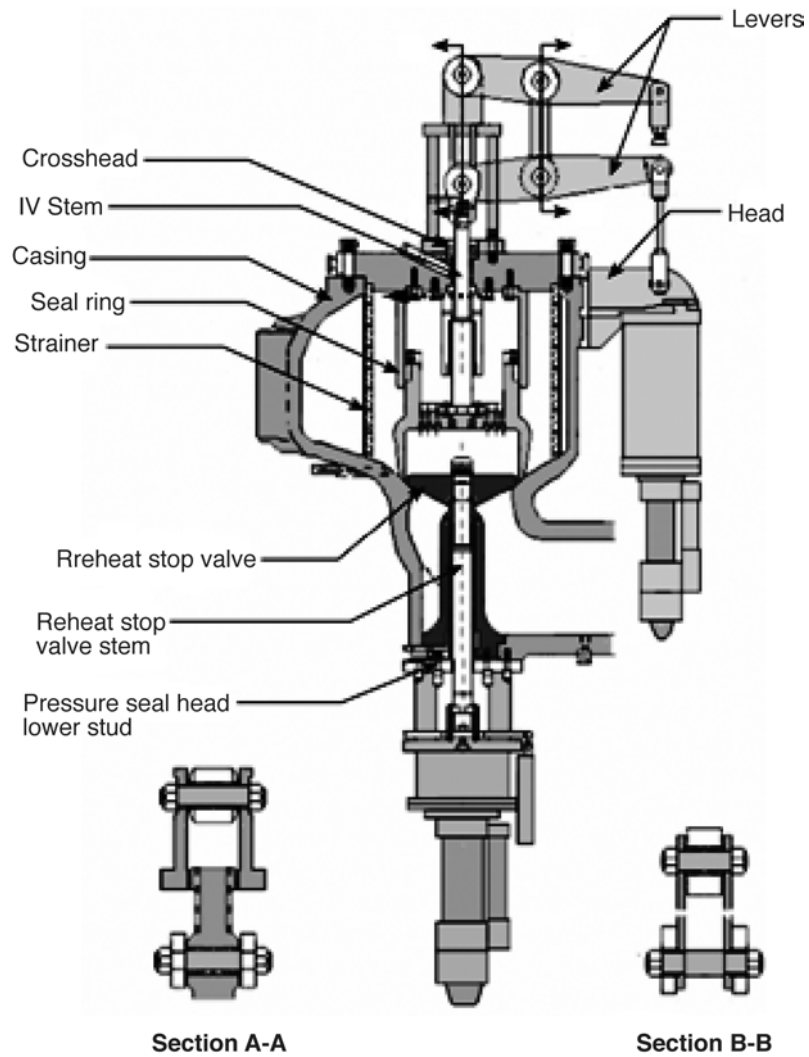


Figure 1-4
General Electric fossil turbine reheat and intercept valve
(Courtesy of Turbine Technology International, Inc.)

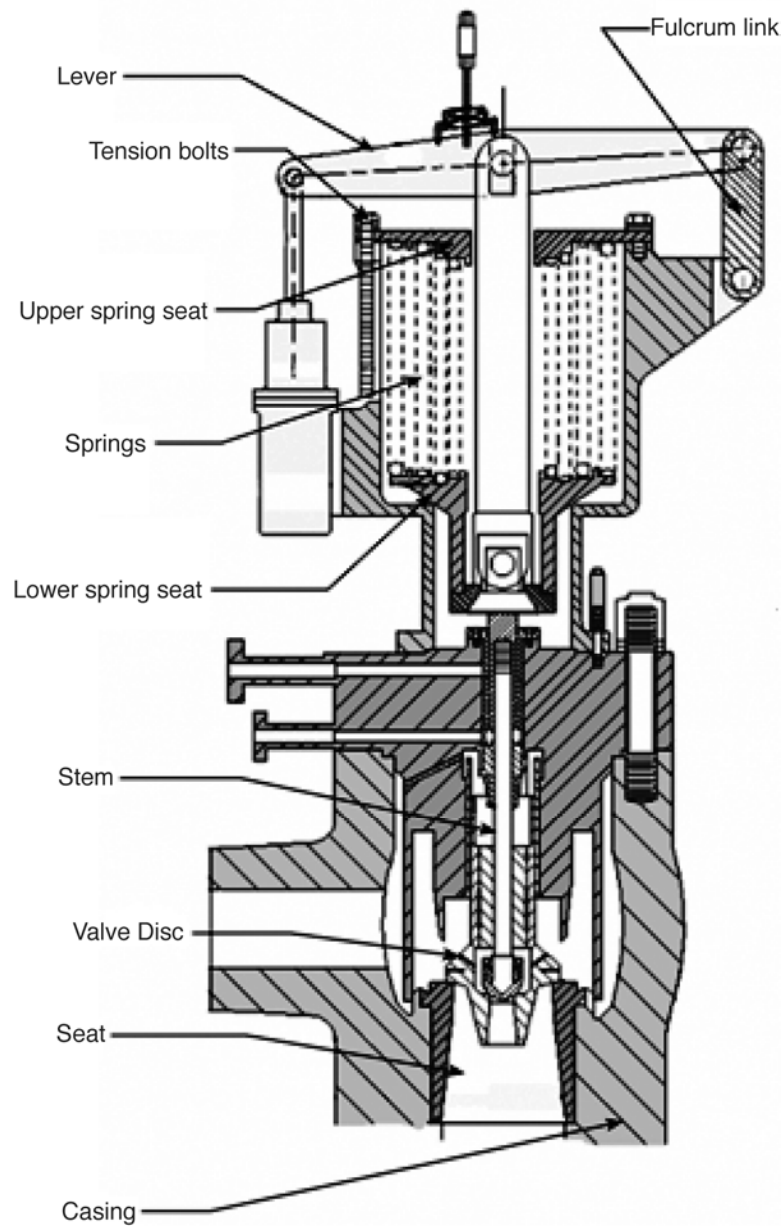


Figure 1-5
Siemens-Westinghouse fossil turbine throttle valve
(Courtesy of Turbine Technology International, Inc.)

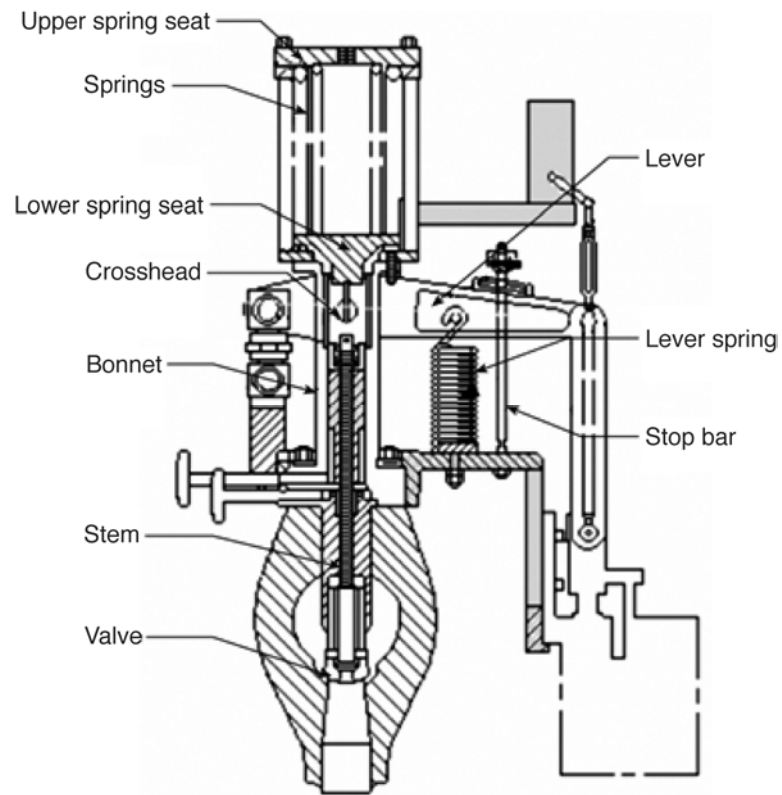


Figure 1-6
Siemens-Westinghouse fossil turbine chest-mounted governor valve
(Courtesy of Turbine Technology International, Inc.)

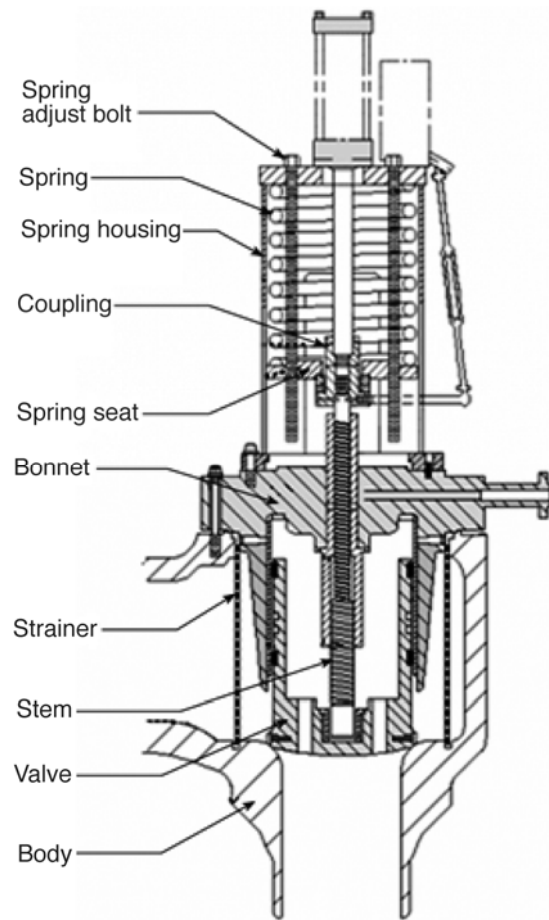


Figure 1-7
Siemens-Westinghouse fossil turbine intercept valve
(Courtesy of Turbine Technology International, Inc.)

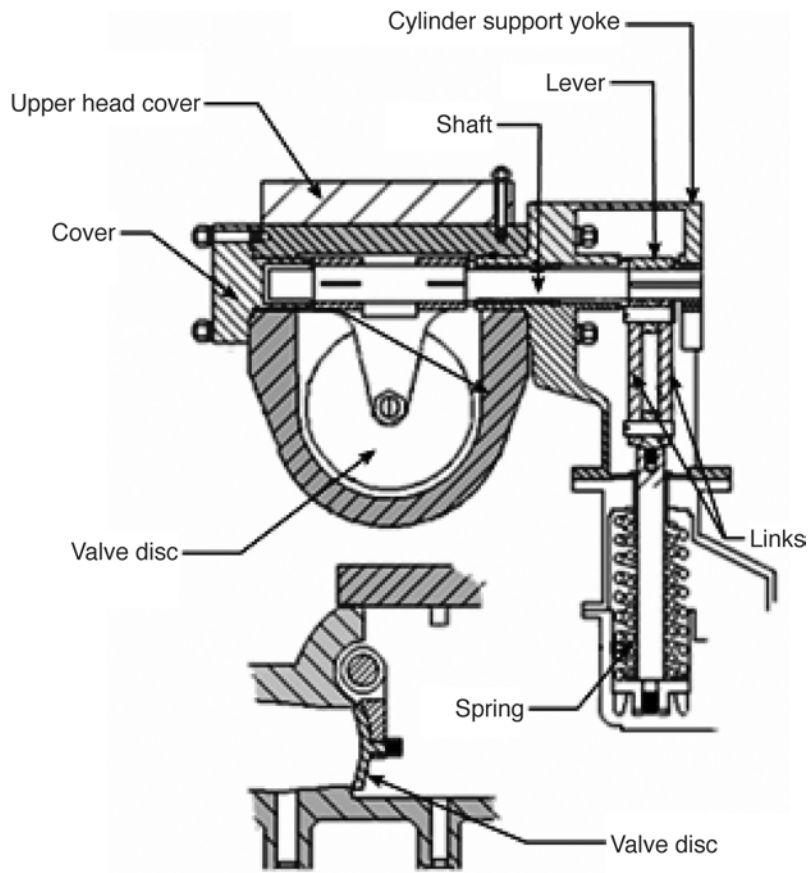


Figure 1-8
Siemens-Westinghouse fossil turbine reheat stop valve
(Courtesy of Turbine Technology International, Inc.)

The steam turbine valve components of interest are shown in the figures and include the following:

- Stems
- Bushings
- Seats
- Main and bypass valve discs
- Pressure seal heads

Definitions of turbine and metallurgical terms are given in Appendix A. Based on the figures, it is possible to discern the typical geometry and anticipate the function of the various steam turbine valve components covered in this report:

- The stem is a rod- or similar-shaped piece that spans the inside and outside of the valve and translates motion to control the internal disc from outside the valve.
- The bushing is a cylinder-shaped piece used to guide and align the stem to ensure accurate positioning of the disc and seat. Valves frequently have an upper and lower bushing.
- The mating surfaces of the valve are the seat and disc or plug.
 - The valve seat is in the interior surface of the valve body and contacts or could contact the disc to form a seal. The seal should be steam-leakage-tight when the valve is closed.
 - The disc is located inside the valve body, and flow through the valve can be partly or completely blocked by the disc. The disc is attached to the stem and is moveable so that it can control flow. The main stop valve has two discs in some designs. The bypass disc is used for finer control on turbine startup.
- The pressure seal heads hold the bushings in place and are typically welded to the valve body. The geometry of the pressure seal heads for steam turbine valves is a hollow cylinder.
- The valve body is the vessel or casing that holds the fluid (steam) going through the inside of the valve.

1.6 References

1. *Guidelines and Procedures for Turbine Valve Condition Assessments*. EPRI, Palo Alto, CA: 2005. 1010211.
2. *Turbine Condition Assessments and Monitoring Methodology*. EPRI, Palo Alto, CA: 2004. 1004963.
3. *Turbine Steam Valve Diagnostic Testing*. EPRI, Palo Alto, CA: 2004. 1004960.

2

VALVE STEM MATERIALS

2.1 General Discussion

The stems of steam turbine valves are the moving part of the valve. They are connected to the actuator at one end and to the valve disc at the other end. The actuator causes the stem to move based on the desired control action. The stroke or the range of travel for the stem that is required for valve operation varies and depends on the size and type of valve.

The disc contains one of the mating surfaces (the seat is the other one) that are pushed together to make the sealing surface and stop steam flow through the valve. Generally, there are threads at the actuator end of the stem and a pin connection at the disc end of the stem.

Steam turbine valve stems have a solid bar geometry, and the outside diameter is not usually constant but varies along the length as required by the function at that position. For proper valve operation, it is critical for the valve stem to be straight and to have minimal run-out. The stems are relatively long, slightly less than 3 feet (~1 m), and slender (in order of magnitude 2 in. (50 mm)). Figure 2-1 shows a photograph of a typical control valve stem that has solid particle erosion (SPE) damage at the pin connection end.



1 inch = 25.4 mm

Figure 2-1

A typical control valve stem with solid particle erosion damage at the pin connection end

The major considerations in material selection for valve stems are galling, wear, oxidation, and tensile strength. In those locations where metal-to-metal contact occurs, galling or sticking of the components (stems and bushings) is a concern. To address this potential problem, nitriding of the affected surfaces is effective and commonly used.

Excessive wear of either the stem or bushing can result in misalignment and improper opening and closing of the valve. Oxidation is important because excessive scale growth on either the stem or bushing decreases the clearance, which can result in binding and failure of the valve to control the flow and/or close. A material with high yield strength at operating temperatures and a good fatigue life is needed to ensure that the stem is not permanently deformed, bent, or broken. Rapid closing or excessive travel can result in higher-than-expected design stresses, and contingency in material strength is useful in these off-nominal loading situations.

To meet the wear requirements, a nitriding process is frequently used to develop a thin, hard, wear-resistant case. Nitriding is a surface-hardening method that produces a composite material consisting of the case at the surface of the part and the core, that is, the bulk of the material beneath the case. The wear and oxidation properties of the nitrided valve parts such as the stems are determined by the chemistry and microstructure of the nitrided case. The tensile strength properties of interest for the composite, nitrided material are those developed in the core of the part. Other surface treatments or coatings have been used on stems for wear properties. These treatments include weld overlays with Stellite and a chrome carbide coating, one of the alternative stem materials.

The materials used for steam turbine valve stems in General Electric and Siemens -Westinghouse at U.S. fossil power plants are listed in Table 2-1.

Table 2-1
Valve stem materials

General Electric
Nitralloy 135M – (135M Nitrided)
AISI Type 410 Stainless Steel – Nitrided
AISI Type 422 Stainless Steel – Nitrided
EME – Nitrided
ASTM A 453 Gr 651 (19-9 DL) – Nitrided
Incoloy 901 – Nitrided
Siemens-Westinghouse
Nitralloy 135M – (135M Nitrided)
AISI Type 422 Stainless Steel – Nitrided
AMS 5700 – Nitrided
Incoloy 901 – Nitrided
Refractalloy 26 – Nitrided
W-545 – Nitrided

The alloys used in steam turbine valve stems are diverse, and many of the alloys used are the same ones that are used for the valve bushings. The alloys can be categorized as follows, based on alloy type and expected similar properties:

- Low alloy, for example, Nitralloy 135M (135M nitrided)
- Stainless steels
- Superalloys

The costs for the stem materials vary as the prices for the alloying elements vary and are known to increase as the alloying element concentrations increase from the lowest to highest category. For example, austenitic stainless steels are about an order of magnitude more expensive than low-alloy steels. The material chosen for the stems is based primarily on the operating temperature of the valve, with the higher alloy steels used at the higher operating temperatures.

This section provides a brief discussion of the nitriding process, physical metallurgy for each valve stem material, and damage mechanisms. Discussion of the physical metallurgy is given for each of the three types of material: Nitralloy 135M, stainless steels, and superalloys. The topics covered in the metallurgy discussion include the alloy standards for each material (if applicable), heat treatment, hardness, microstructure, physical properties, and mechanical properties. For hardness values, the actual measured values are given in parentheses. The measured values are converted to Rockwell C values for discussion purposes and are shown first in this report.

2.2 The Nitriding Process

Nitriding is a surface-hardening heat-treatment process that diffuses atomic or nascent nitrogen into steels [1]. The nitriding process was initially developed for ferritic steels in the 1920s. Prior to nitriding, the part is heat treated and machined. The heat treatment develops the desired strength and ductility properties in the core of the ferrous alloy.

The typical nitriding temperatures are in the range of 923°F–1049°F (495°C–565°C), that is, below the lower critical temperature, A_{C1} , for the transformation of ferrite to austenite. The nitriding temperatures should not exceed the material's lower critical temperature because higher temperatures will change the properties of the core. Because the nitriding process does not involve austenitizing and quenching, no significant distortion or dimensional changes for the part take place. Also, there are no significant core property changes because typical tempering temperatures are above the nitriding temperature.

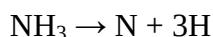
The advantages and reasons for nitriding steam valve parts are to do the following [2]:

- Obtain high surface hardness, wear strength, and good antigalling properties
- Provide resistance to overtempering and good high-temperature hardness
- Improve fatigue life and decrease fatigue notch sensitivity

- Maintain dimension stability
- Improve corrosion resistance for non-stainless steels

The nitriding process is applicable to a variety of alloys including the specifically designed Nitralloys, austenitic stainless steels, martensitic stainless steels, and superalloys such as Incoloy 901. Typical nitriding methods are gas, liquid (salt bath), and plasma or ion nitriding. Gas and plasma nitriding have been commonly used for valve parts. Plasma or ion nitriding allows for improved control of the compound layer of the nitride case [3].

The gas nitriding process uses ammonia gas that dissociates at the steel surface by the following reaction:



For gas nitriding, single-stage and double-stage processes have been used. The single-stage process uses an atmosphere with a 15%–30% dissociation of ammonia. For Nitralloy 135M, the single-stage nitrided steel has a relatively thick, brittle white layer that is observed in the metallurgical microscope for a steel etched with nital (2%–5% nitric acid in alcohol). The white layer or compound layer consists of two iron nitrides, γ' - nitride (Fe_4N) and ϵ - nitride (Fe_{2-3}N). The two-stage process was developed to decrease the thickness of the white layer. The first stage in the two-stage process is similar to that used in the single stage. However, the dissociation in the second stage is increased to 65%–85%, resulting in a reduction of the ammonia that supplies nitrogen to the surface of the steel. Thus, the iron nitride layer does not grow as fast and, in fact, dissolves to supply nitrogen to the interior. The nitriding times in the second stage are long, from ~10 to 100 hours. The case depths (or thickness) depend on the alloy and application. The growth rate of the case depth has the parabolic or $\sqrt{}$ (square root) time relation. Parabolic growth rates are expected for a diffusion controlled process.

The microstructure of a nitrided steel has four regions starting at the outside surface as follows [1]: (1) compound, dual-phase zone or white layer, (2) diffusion zone, (3) transition zone from diffusion to core, and (4) core. The microstructure of the diffusion zone has fine alloy nitrides and interstitial nitrogen. The precipitates are below the limit of detection for optical metallography. Figure 2-2 shows the microstructure of a service exposed valve stem made of Nitralloy 135M. There is no white layer in this case. The outside layer is the oxide scale, about 0.0025 in. (60 microns) thick, formed due to oxidation in service. The oxide scale has the expected duplex structure for low-alloy ferritic steels, consisting of a dense inner layer and a porous outer layer [4]. The dark etching region below the scale is the diffusion zone portion of the case that has fine alloy nitrides, primarily iron and aluminum nitrides. The case thickness is about 0.0175 in. (440 microns). The core microstructure is tempered martensite.

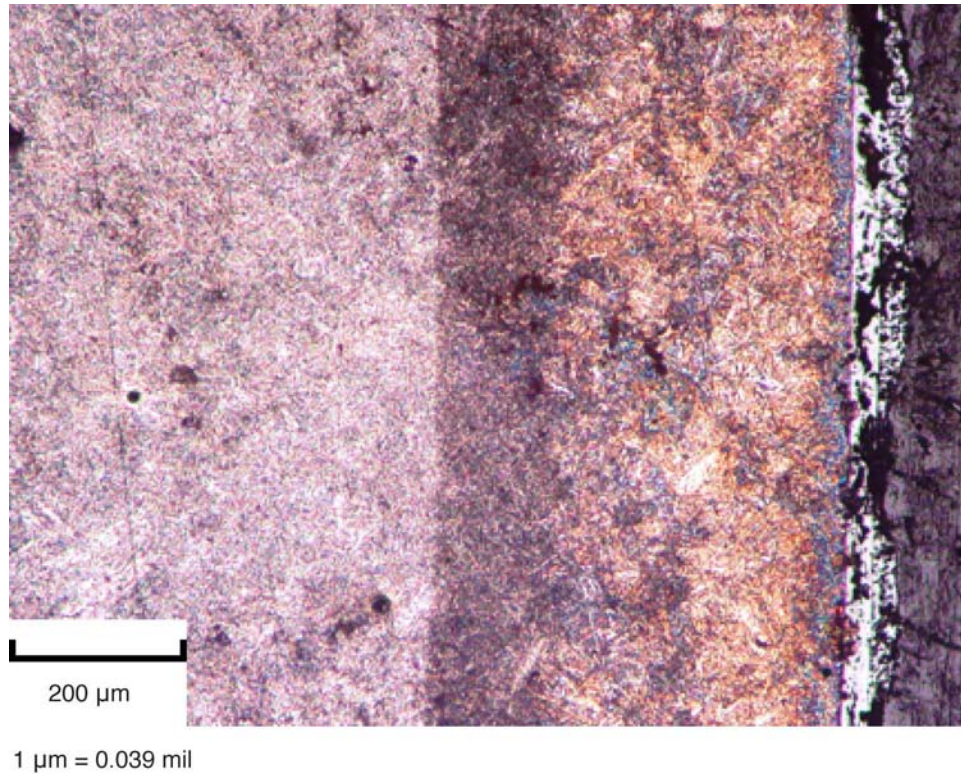


Figure 2-2
Microstructure of a service-exposed valve stem made of Nitralloy 135M

Figure 2-3 is a plot of the microhardness versus depth for a nitrided Nitralloy 135M stem (measured for a sample different from the one shown in Figure 2-2). The hardness values were measured on the Knoop scale and converted to the Rockwell C scale. Values are shown at different positions along the stem, near the larger diameter head and the smaller diameter shaft remote from the ends of the stem.

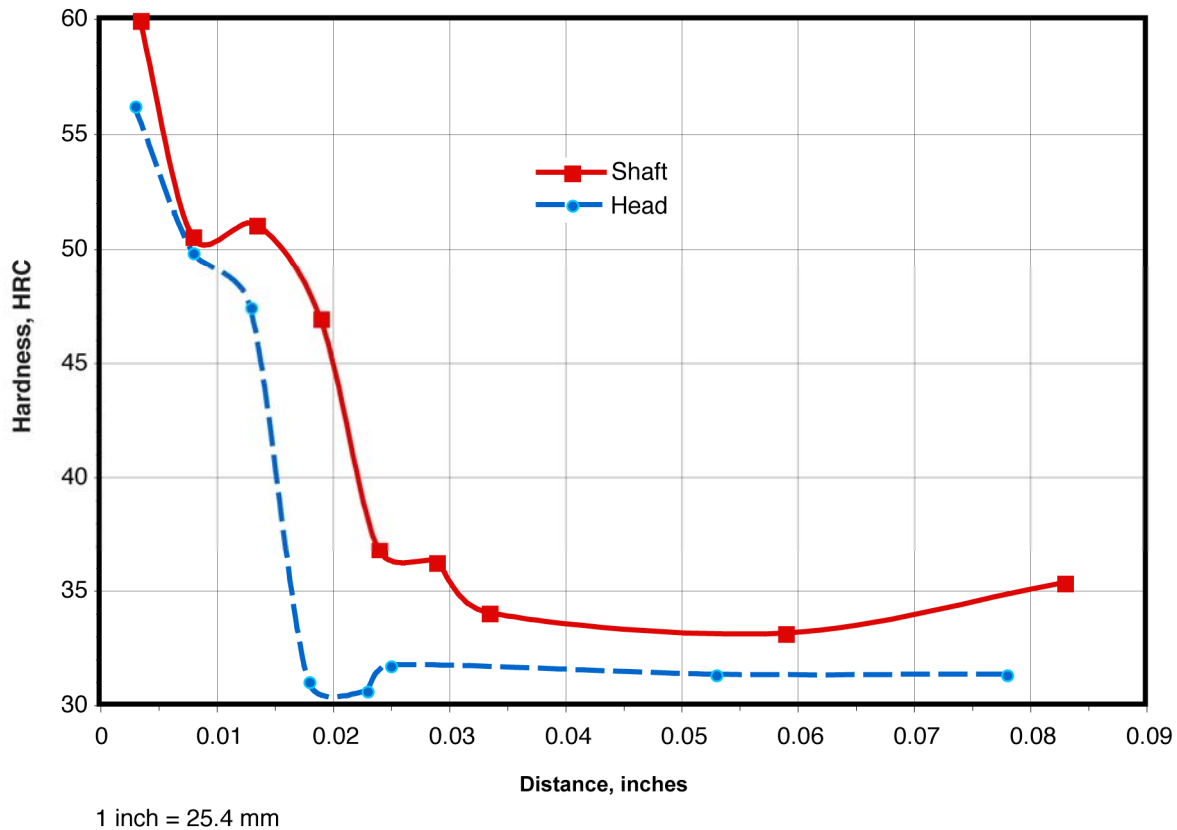
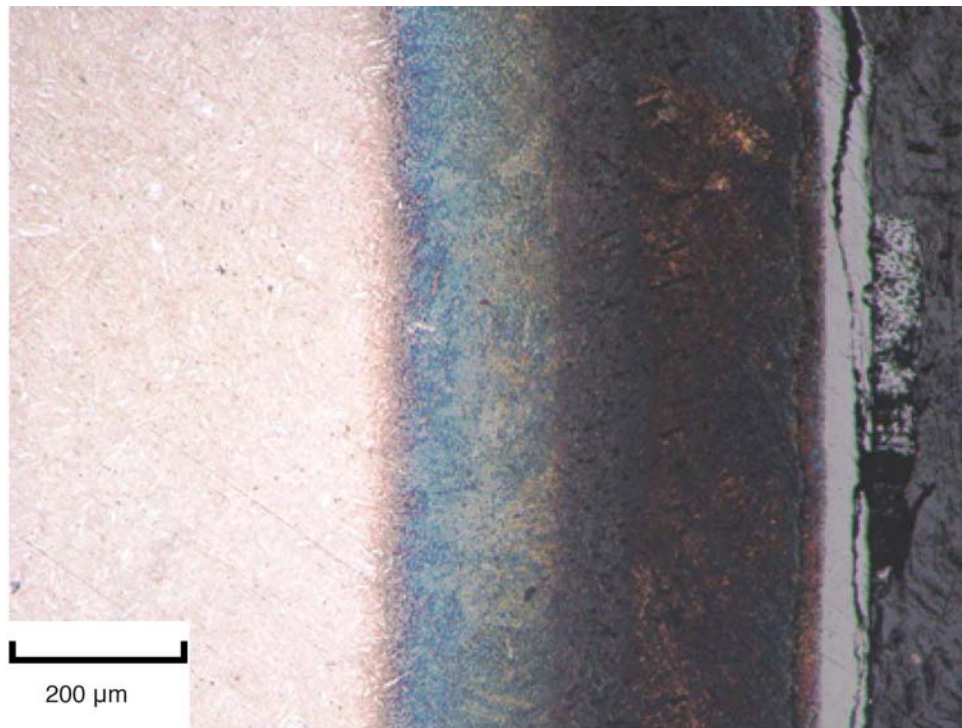


Figure 2-3
Microhardness versus depth for a Nitralloy 135M stem
(Courtesy of TVA)

Stainless steels and superalloys can also be nitrided, but the passive chromium oxide scale must be removed prior to the nitriding process. There are a variety of techniques that can be used to remove the chromium oxide scale including honing, pickling, reducing atmospheres, or proprietary processes such as Malcomizing [2]. Malcomizing was developed by Crane and is commonly used on stainless steels and superalloys. It is claimed that superior properties are obtained for Malcomized parts compared to conventional gas-nitrided parts.

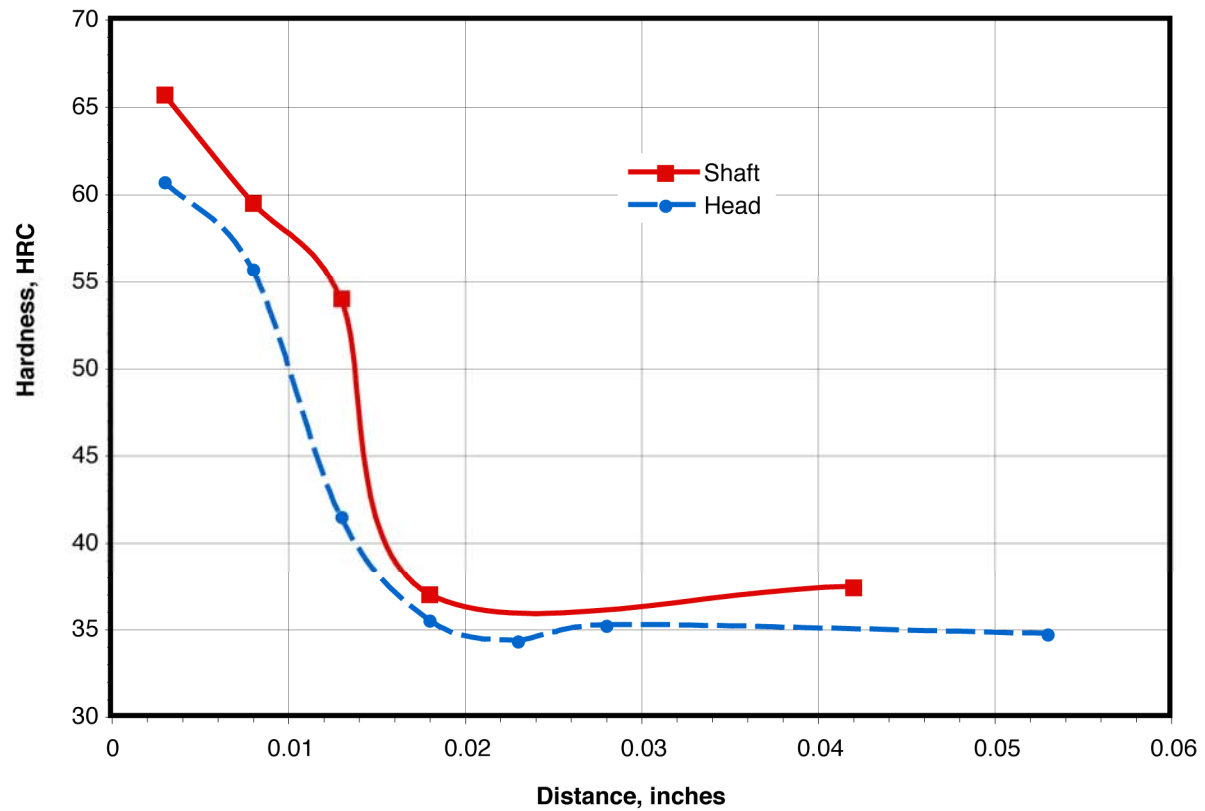
The thickness and hardness of the nitride case depends on the type of steel and the process parameters. Austenitic stainless steels are more difficult to nitride than the martensitic stainless steels, and the case thickness and hardness values are generally lower for the austenitic steels compared to the martensitic steels. The temperature range for nitriding of stainless steels is from 925°F to 1100°F (495°C to 595°C), and time durations of 20–48 hours are typical for the single-cycle nitriding process.

Figure 2-4 shows the microstructure for a 422 martensitic stainless steel stem that has been nitrided. The case depth is approximately 0.015 in. (380 microns). There is a thin, duplex steamside oxide scale on the outside surface of this surface-exposed stem. The hardness traverse shown in Figure 2-5 is for a nitrided 422 stainless steel stem. Figure 2-6 shows the microstructure and hardness traverse for an austenitic stainless steel, EME alloy stem. The EME stem also has an oxide scale, and the case depth is approximately 0.008 in. (200 microns).



1 μm = 0.039 mil

Figure 2-4
Microstructure of a nitrided 422 martensitic stainless steel valve stem



1 inch = 25.4 mm

Figure 2-5
Hardness traverse for a nitrided 422 stainless steel valve stem
(Courtesy of TVA)

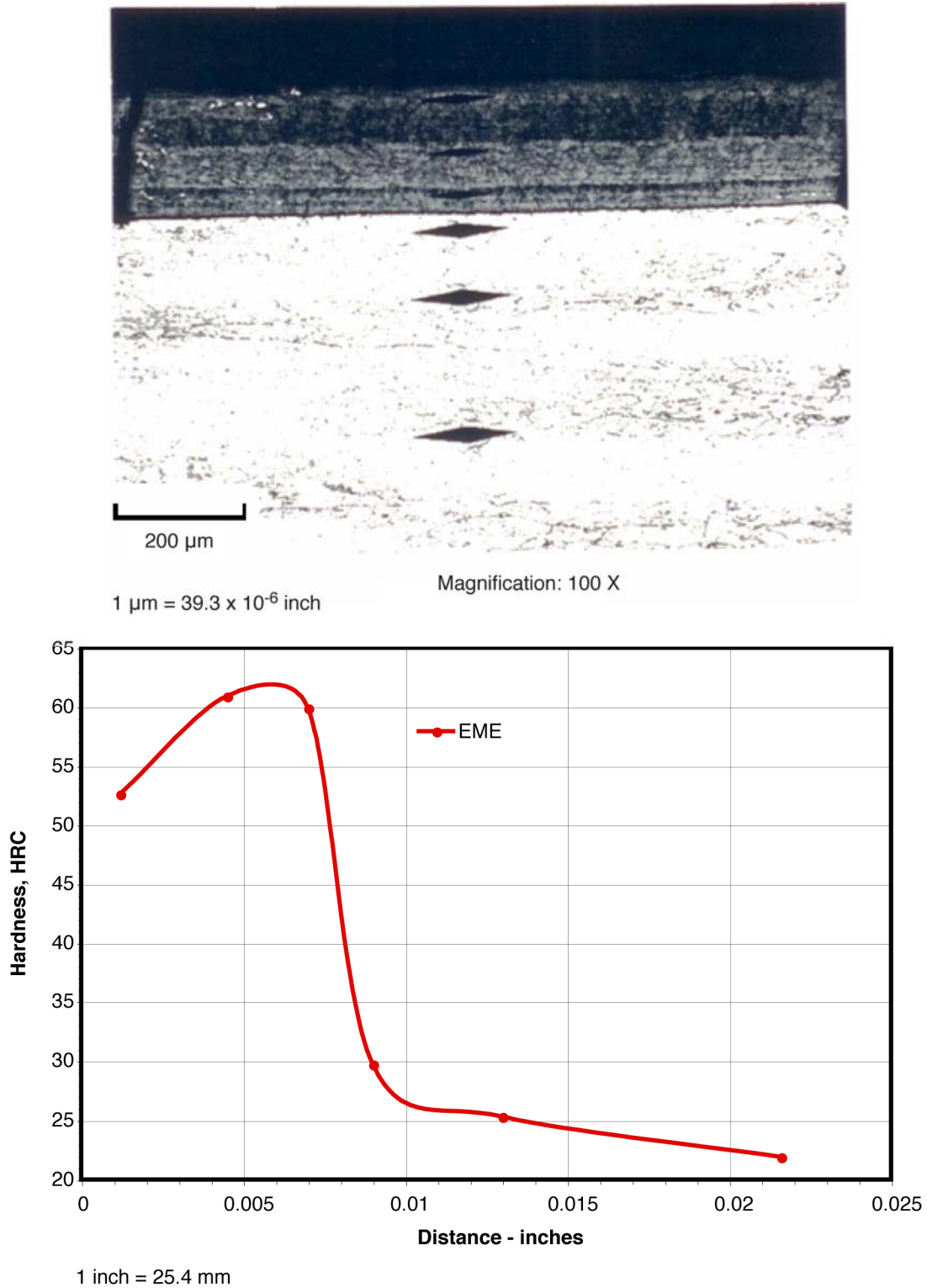


Figure 2-6
Microstructure (a) and hardness traverse (b) for an austenitic stainless steel, alloy EME stem
 (Courtesy of TVA)

The hardening mechanism for the nitrided case on stainless steels and superalloys with significant chromium content involves the formation of chromium nitrides, which decrease the chromium content of the alloy. The chromium depletion results in a lower corrosion resistance for the case. Although the corrosion resistance of nitrided stainless steels is not as good as those for un-nitrided steels, they are considerably better than those for low-alloy steels, such as Nitralloy 135M.

2.3 Nitralloy 135M Material

Nitralloy 135M is an aluminum alloy containing low-alloy steel that has been specifically formulated for nitriding applications. The two-stage nitriding process discussed in Section 2.2 is commonly used to develop the antigalling and wear-resistant case for turbine valve stems. Aluminum is one of the strongest nitride-forming elements, and additions of aluminum in the range of 0.85%–1.50% are typically used for nitriding steels. The specified compositions of 135M (AMS 6470) and American Iron and Steel Institute (AISI) 4140 alloy steel are compared in Table 2-2. Based on the similar chemical compositions for the two steels, the physical and mechanical properties of the core material for both materials are expected to be nominally the same (provided the heat treatment and part dimensions are nominally the same).

Table 2-2
Chemical compositions of 135M and AISI 4140 materials

Element	135M (AMS 6470)	4140
C	0.38–0.43	0.38–0.43
Mn	0.50–0.70	0.75–1.00
P	0.040	0.035
S	0.040	0.040
Si	0.20–0.40	0.20–0.35
Cr	1.40–1.80	0.80–1.10
Al	0.90–1.35	--
Mo	0.30–0.40	0.15–0.25

To develop the strength and ductility requirements for the core, the typical heat treatment for 135M prior to nitriding is the following:

1. Austenitized at 1750°F (955°C)
2. Air-cooled or quenched
3. Tempered at 1230°F–1300°F (665°C–705°C) [2]

Table 2-3 compares the tensile properties for Nitralloy 135M material and AISI 4140 carbon steel. The tensile properties for Nitralloy 135M were taken from the ISO standards. The specified hardness of the nitrided surface is 68 on the Rockwell C (HRC) scale (950 HV, Vickers hardness number), and the ISO-specified U-notch impact energy is 18 ft-lb (25 J). The tensile properties for AISI 4140 are taken from the *Aerospace Structural Materials Handbook* [5] and are for bar that has been given the following heat treatment:

1. Normalized at 1550°F (843°C)
2. Oil quenched
3. Tempered at 1265°F (685°C)

Table 2-3
Tensile properties of Nitralloy 135M and AISI 4140 materials

Material	Temperature in °F (°C)	Ultimate Tensile Strength in ksi (MPa)	Yield Strength in ksi (MPa)	Elongation %	Reduction in Area - %
Nitralloy 135M	Room temperature	120–142 (830–980)	93 (640)	14	--
AISI 4140	Room temperature	125 (862)	109 (752)	19	58
AISI 4140	1000 (538)	82 (565)	60 (413)	29	75

Photomicrographs of the microstructure of nitrided Nitralloy 135M at the near surface region are shown in the *ASM Handbook, Volume 9* [6], and in Figure 2-2 for a service-exposed stem. The expected microstructure of the core is tempered martensite for steam turbine stems.

2.4 Stainless Steel Materials

The compositions of the stainless steel alloys used for steam turbine valve stems are given in Table 2-4 and the nominal tensile properties are given in Table 2-5. Depending on the microstructure and strengthening mechanism, stainless steels are classified as the following:

- Austenitic
- Ferritic
- Duplex
- Martensitic
- Precipitation-hardened

Alloy EME and AMS 5700 are austenitic stainless steels and have face-centered, cubic crystal structure. The austenitic stainless steels are solid solution-strengthened alloys and cannot be strengthened by heat treatment. AISI Type 410 and 422 stainless steel materials are martensitic (body-centered, tetragonal crystal structure) and are typically given a quenched and tempered heat treatment to develop optimal strength and ductility properties.

An overview of the physical properties and metallurgy is provided in this section for each of the stainless steels.

Table 2-4
Chemical compositions for stainless steel valve materials

Element	AISI 410	AISI 422	EME	AMS 5700	ASTM A 453 Gr 651 (19-9 DL)
C	0.15	0.20–0.25	0.12–0.17	0.40–0.50	0.28–0.35
Mn	1.00	1.00	0.40–0.60	0.70	0.75–1.50
Si	1.00	0.75	0.40–0.60	0.30–0.80	0.30–0.80
Cr	11.5–13.0	11.0–13.0	18.75–19.75	13.00–15.00	18.00–21.00
Ni	--	0.5–1.0	11.5–12.5	13.00–15.00	8.0–11.0
P	0.04	0.025	--	0.03	0.040 max.
S	0.003	0.025	--	0.03	0.030 max.
Mo		0.75–1.25	--	0.20–0.50	1.00–1.75
W		0.75–1.25	3.00–3.50	1.75–3.00	1.00–1.75
Nb		--	0.85–1.25		0.25–0.60
V		0.15–0.3	--		--
Ti					0.10–0.35
N			0.10–0.20		--

Table 2-5
Tensile properties of stainless steel valve materials

Material	Temp in F (C)	Ultimate Tensile Strength in ksi (MPa)	Yield Strength in ksi (MPa)	Elongation %	Reduction in Area - %
AISI 410	RT	100–120 (690–825)	80–90 (550–620)	12	40
AISI 410	800 (427)	95 (655)	82 (565)	17	70
AISI 410	900 (482)	85 (586)	77 (531)	19	72
AISI 410	1000 (593)	71 (490)	65 (448)	22	80
AISI 422	RT	150 (1027)	125 (862)	18.5	52
AISI 422	1000 (538)	96 (662)	82 (565)	24.8	67
AISI 422	1100 (593)	76 (524)	72 (496)	29.6	69
AISI 422	1200 (649)	52 (358)	45 (310)	30	83
EME	RT	125–145 (862–1000)	85–103 (586– 710)	21-28	--
EME	1200 (649)	78–86 (538–590)	75–79 (517– 545)	14-21	--
ASTM A 453 Gr 651 (19-9 DL)	RT	109 (750)	68 (470)	39	48
ASTM A 453 Gr 651 (19-9 DL)	1000 (593)	89 (615)	42 (290)	43	52
AMS 5700	RT	110 (758)	48 (331)	40	45
AMS 5700	1202 (650)	75 (517)	34 (234)	35	45

2.4.1 AISI Type 410 Material

AISI Type 410 material is a martensitic stainless steel, and the Unified Numbering System (UNS) designation is S41000. The bar specification for Type 410 material is ASTM A 276. The alloy is effectively a binary iron-chromium steel. The nominal chromium content of about 12% is sufficient for good corrosion and oxidation resistance for Type 410 material that is un-nitrided. Type 410 stainless steel has also been used extensively for steam turbine valve parts at nuclear plants.

The expected heat treatment for high-temperature applications of Type 410 stainless steel is the following:

1. Austenitize at 1665°F–1850°F (925°C–1010°C)
2. Air or oil quench
3. Temper at 1125°F (607°C)

Following this heat treatment, the hardness values of AISI 410 stainless steel are from 25 to 31 on the Rockwell C scale (HRC). Tempering at 1200°F (649°C) has also been used for Type 410, and lower hardness and tensile strengths are found for the higher tempering temperature material compared to the lower tempering temperature. The microstructure of quenched and tempered AISI 410 stainless steel is expected to be 100% martensite, lath-type microstructure.

The range of typical tensile strength properties of quenched and tempered Type 410 stainless steel at room temperature is given in Table 2-3 [7]. The range of strengths is due to the variations in material chemistry, solution temperature, quenching rates, and tempering temperatures. The single value for tensile strengths obtained using the 1125°F (607°C) tempering treatment is given in the table at higher temperatures.

The Charpy energy versus temperature curves for martensitic stainless steels have a brittle-to-ductile transition. The upper- and lower-shelf energies are not greatly affected by heat treatment, but the transition temperature range is. For a steel tempered at 1229°F (665°C) to a hardness of 24 HRC, the transition temperature range is from about –148°F to 212°F (–100°C to 100°C), and the Charpy impact energy is about 37 ft-lb (50 J) at 32°F (0°C) [7].

The typical physical properties of the coefficient of thermal expansion, thermal conductivity, specific heat, resistivity, magnetic permeability, and melting temperature range are given in the *ASM Handbook, Volume 1* [7]. The mean coefficient of thermal expansion of Type 410 stainless steel is 6.4×10^{-6} per °F (11.6×10^{-6} per °C) for temperatures from 32°F to 1000°F (0°C to 538°C).

One of the damage mechanisms for turbine valve stems is oxidation. The service experience for steam turbine valve stems and bushings made from nitrided Type 410 and 422 stainless steel was discussed by Kneer et al. [2]. From this reference, it was reported that nitriding was successful in increasing wear resistance, and many valve stems and bushings have operated for 20 or more years without problems. However, an oxide scale (light blue in color) was found to grow on the nitrided stems during elevated temperature service. The oxide scale growth resulted in an increase in the outside diameter and reduction in the stem-bushing clearance.

2.4.2 AISI Type 422 Material

AISI Type 422 (UNS S42200) material is a martensitic stainless steel and is also used for steam turbine and valve bolting applications. The typical specification for steam turbine valve stem material is ASTM A 565, Grade 616, condition H. The actual chemical specification requirements used by turbine valve manufacturers are slightly different than those shown in

Table 2-4; they are usually tighter on the range allowed for certain elements. The chemical specifications used by the OEMs for steam turbine valve parts are typically based on their experience with the alloys and internally developed data relating chemistry and properties. The heat treatment and fabrication sequence for turbine valve stems consists of the following:

1. Quenched and tempered
2. Machined to final shape
3. Nitrided
4. Vertical stress relief

The physical metallurgy of 12% chromium steel was reviewed in a recent EPRI report on bolting materials [8]. The microstructure of AISI Type 422 stainless steel is a tempered martensite, and the case and core of a nitrided turbine valve stem were shown in Figure 2-4. The tempering reduces the hardness of the as-normalized material, stabilizes the carbides, and improves the fracture toughness. The carbides are a chromium-rich $M_{23}C_6$ and M_2C alloy. The M_2C carbide is relatively small, and the fine dispersion of this carbide contributes to an increase in the creep strength.

The *Aerospace Structural Materials Handbook* [9] has compiled a relatively comprehensive review of the physical and mechanical properties of Type 422 stainless steel. The physical properties include the usual properties of thermal expansion, thermal conductivity, specific heat, etc. The mean coefficient of thermal expansion of Type 422 stainless steel is given as a function of temperature and is 6.6×10^{-6} per $^{\circ}F$ (11.9×10^{-6} per $^{\circ}C$) for temperatures from 32 to 1000 $^{\circ}F$ (0 to 538 $^{\circ}C$). The mechanical data include tensile, fatigue, creep, creep-rupture, and impact properties. The Charpy impact energy was shown as a function of test temperature for bar stock tempered at 1200 $^{\circ}F$ (649 $^{\circ}C$) and 1400 $^{\circ}F$ (760 $^{\circ}C$). At room temperature, the Charpy impact energy values were 15 ft-lb (20 J) for the 1200 $^{\circ}F$ (649 $^{\circ}C$) tempered material and 38 ft-lb (51 J) for the 1400 $^{\circ}F$ (760 $^{\circ}C$) tempered bar material. The Charpy impact energy of service exposed and damaged Type 422 stainless steel bolts have been found to be significantly lower than unexposed bolts and temper embrittlement has been found after long-term aging of Type 422 stainless steel at temperatures of 572 $^{\circ}F$ and 842 $^{\circ}F$ (300 $^{\circ}C$ and 450 $^{\circ}C$) [8].

An extensive creep-rupture testing program was conducted on 12Cr-1Mo-1W-0.3V stainless steel bars (SUS¹ 616B) for turbine blades [10]. The tests were long-term (about 20,000–60,000 hours), and testing included heat-to-heat effects, that is, multiple heats of material. Regression analysis of the rupture data was performed using four common time-temperature parameters to estimate the average rupture strength as a function of time and temperature. In addition, results of tensile tests at temperatures from room temperature to 1202 $^{\circ}F$ (650 $^{\circ}C$) and metallographic examination of as-received material were given in the data sheet. Figure 2-7 shows the yield and tensile strengths of Type 422 stainless steel as a function of temperature.

¹ SUS is a grade in the Japanese Industrial Standards and stands for Steel Use Stainless.

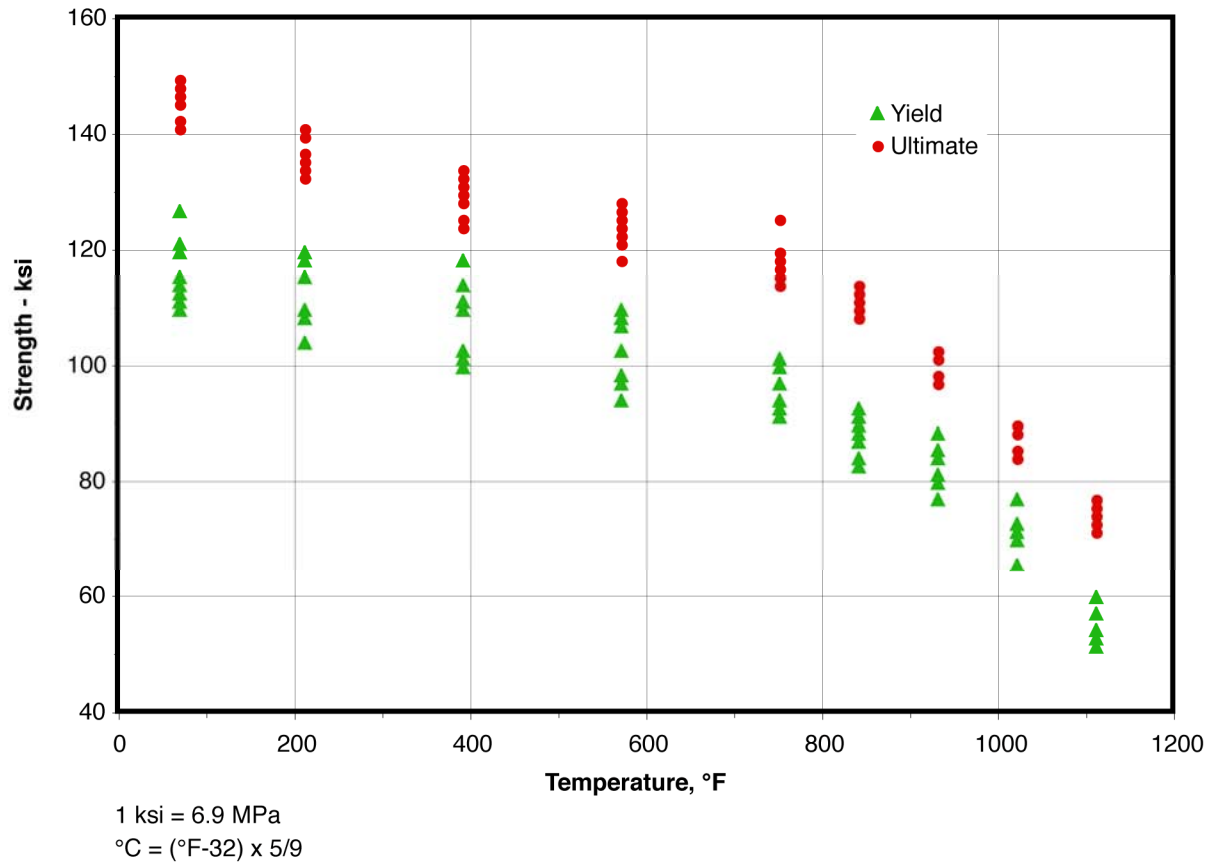


Figure 2-7
Tensile properties for Type 422 stainless steel [10]

Creep and stress relaxation tests were performed on Type 422 bolting material [11]. As part of an EPRI project on life assessment of high-temperature turbine bolting [12], creep equations were developed using the National Institute for Materials Science (NIMS) creep data. The creep equation was used to calculate the stress relaxation behavior. Good agreement was found between the predicted and observed relaxation data.

2.4.3 EME Material

The EME alloy is an austenitic stainless steel with a nominal composition (weight percent) of 19 chromium, 12 nickel, 3 tungsten, and 1 niobium. The Midvale Company developed the EME alloy for potential use in jet engines and gas turbines. Results of mechanical testing and metallurgical examinations were reported by Reynolds et al. for a contour forged disc of EME alloy [13]. They also discussed the General Electric test results for a disc forging and tests on bar stock performed by Midvale.

The strength properties of the forged disc were below those of the bar stock [13]. The lower strengths were believed to be the result of the forging/working process. Supporting this hypothesis is the increased tensile property data for an EME disc forged by Midvale using an improved forging process. Because the stems are usually made from bar stock material, the tensile strength ranges given in Table 2-5 are those for the bar stock.

Austenitic steels like EME cannot be strengthened by heat treatment, but they do respond to hot-cold working. The typical hot-cold working fabrication method starts the forging at a temperature of 2000°F–2100°F (1093°C–1149°C) and has the final working in the temperature range from approximately 1650°F to 1200°F (899°C to 649°C). Stress relieving is done at 1200°F–1400°F (649°C–760°C) with a minimum hold time of 1 hour.

The microstructure of EME is shown in Figure 2-8 and consists of an austenitic matrix with niobium-rich precipitates, probable nitrides, carbides, or carbonitrides. The microstructure has alternating bands of equiaxed and elongated grains. The banded microstructure is related to the bar manufacturing process and is possibly due to segregation or recrystallization. The Brinell hardness values for the bar stock materials were from 22 to 29 HRC (237 to 277 HB).

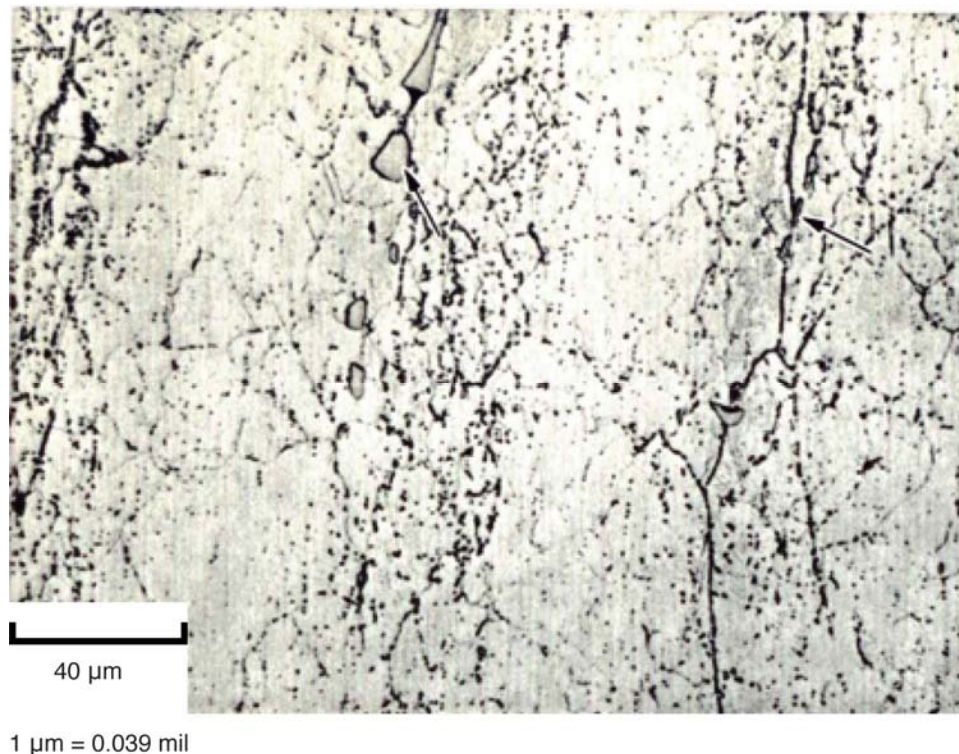


Figure 2-8
Microstructure of EME, which consists of an austenitic matrix with niobium-rich precipitates, probable nitrides, carbides, or carbonitrides
(Courtesy of TVA)

Short-term creep-rupture tests were performed on the forged discs. The rupture strength of the General Electric disc was similar to that cited in the ASTM data compilation and was significantly stronger than that for the disc tested by Reynolds et al. [13]. At 1200°F (649°C), the rupture strengths were 44 ksi (303 MPa) for 100 hours and 35 ksi (241 MPa) for 1000 hours.

It has been reported that the austenitic alloy 19-9DX has been substituted for EME. The composition and tensile properties of 19-9 DL are given in Tables 2-4, 2-5, B-2, and B-5. Based on similar alloy elements, composition, and austenitic microstructure, the Charpy properties and coefficient of thermal expansion of EME are expected to be similar to that of 19-9DX. At 76°F (24.4°C), the Charpy impact energy for 19-9 DL is greater than 22 ft-lb (30 J). The mean coefficient of thermal expansion of 19-9 DL from 70 to 1000°F (21 to 538°C) is $9.78 \times 10^{-6}/^{\circ}\text{F}$ ($17.6 \times 10^{-6}/^{\circ}\text{C}$).

2.4.4 AMS 5700 Material

AMS 5700 (UNS K66009) is a solid-solution-strengthened austenitic steel with chromium, nickel, tungsten, and molybdenum alloying additions. In addition to being used as a steam turbine valve material, it has also been used as a bolting material [14]. The common heat treatments for AMS 5700 are the following:

1. Full anneal at 1650°F (899°C) for 1 hour, followed by rapid cooling
2. Stress relieve anneal at temperatures of 1200°F–1400°F (649°C–760°C) for 2–4 hours
3. Air cooled

The tensile strengths shown in Table 2-5 are for the full anneal heat treatment, and the Brinell hardness values for this treatment are from 95 to 99 HRB (207 to 235 HB).

The mean thermal coefficient of thermal expansion from 77°F to 1000°F (25°C to 538°C) is 10.2×10^{-6} per °F (18.4×10^{-6} per °C) for AMS 5700. The nominal Charpy V-notch impact energy is 38 ft-lb (52 J) at room temperature.

2.5 Superalloy Materials

The chemical compositions of the superalloy stem materials are given in Table 2-6. Only the nominal composition is given for W-545; the single values in the table for Incoloy 901 and Refractalloy 26 are maximum values. The chemical requirements for ASTM A 453 Grade 665 bolting material are also given in the table for comparison with the W-545 stem material. Table 2-7 lists the tensile properties for the superalloy materials.

Table 2-6
Chemical compositions for superalloy valve stem materials

Element	Incoloy 901	Refractalloy 26	W-545	ASTM A 453 Grade 665
C	0.10 max.	0.08 max.	0.08	0.08 max
Mn	1.00 max.	0.40–1.00	1.6	1.25–2.00
Si	0.60 max.	0.50–1.50	0.45	0.10–0.80
Cr	11.00–14.00	16.00–20.00	13.5	12.0–15.0
Ni	40.00–45.00	35.00–39.00	25.0	24.0–28.0
P	0.030 max.	--	--	0.040 max
S	0.030 max	--	--	0.030 max
Mo	5.00–7.00	2.50–3.50	1.75	1.25–2.25
Ti	2.35–3.10	2.30–2.90	3.0	2.7–3.3
Al	0.35 max.	0.25 max.	0.15	0.25 max
Co	1.00 max.	18.00–22.00	1.0	--
B	0.010–0.020	0.001–0.01	0.09	0.01–0.07
Cu	0.50 max.	--	.25	0.25 max
Fe	Balance	Balance	Balance	Balance

Table 2-7
Tensile properties of superalloy valve stem materials

Material	Temp – °F (°C)	Ultimate Tensile Strength in ksi (MPa)	Yield Strength in ksi (MPa)	Elongation in %	Reduction in Area -%
Incoloy 901	RT	175 (1205)	130 (895)	14	
Incoloy 901	1000 (538)	149 (1030)	113 (780)	14	
Incoloy 901	1200 (649)	139 (960)	110 (760)	13	
Refractalloy 26	RT	154 (1060)	91 (627)	19	20
Refractalloy 26	1000 (538)	143 (986)	85 (586)	18	
Refractalloy 26	1200 (649)	136 (938)	89 (614)	15	
W-545	RT	150–181 (1030–1248)	105–132 (725–910)	10	12
W-545	1000 (593)	127–154 (877–1062)	96–120 (660–827)	12–15	31–37
W-545	1200 (649)	110–133 (760–917)	91–114 (625–786)	15–21	33–46

2.5.1 Incoloy 901 Material

Incoloy 901 (UNS N09901) is a nickel-based, precipitation-hardening superalloy material. The strengthening is due to the precipitation of fine particles of the γ' (gamma) phase within the austenite matrix. The volume fraction γ' particle is about 5% and remains constant up to temperatures of about 1400°F (800°C) [15]. The γ' particles have a composition of $\text{Ni}_3(\text{Ti}, \text{Al})$, and the γ' is ordered. The lattice of $\text{Ni}_3(\text{Ti}, \text{Al})$ is face-centered cubic (FCC). For the case of perfect order, the ordered FCC structure has all of the nickel atoms at the faces and all of the aluminum and titanium atoms at the corners of the unit cell. The precipitation-strengthening results from several sources including the small interparticle spacing and the difficulty associated with fracture and/or dislocation bypass of the particle. In addition to the γ' particles, carbides are precipitated at the grain boundaries and within the grain matrix.

There are two heat treatments that are commonly applied to Incoloy 901 material [16]. The first is a three-step process and develops optimal creep-rupture properties. The three-step heat treatment process is the following:

1. Solution heat treatment for 2 hours at 1975°F–2025°F (1080°C–1110°C); air cool or faster cooling.
2. Stabilize or age at 1425°F–1475°F (775°C–800°C) for 2–4 hours; air cool or faster cooling.
3. Precipitate or age at 1300°F–1375°F (704°C–750°C) for 24 hours, and then air cool.

The second heat treatment is used to improve the tensile and fatigue properties. For the current application of steam turbine valve stems, the tensile and fatigue properties are considered of greater importance than creep-rupture strength. The second heat treatment consists of the following steps:

1. Solution heat treatment at 1800°F–1900°F (980°C–1040°C) for 2 hours; air cool or faster cooling.
2. Age at 1300°F–1350°F (704°C–732°C) for 6–20 hours, air cool or faster cooling.
3. Age at 1175°F–1225°F (635°C–660°C) for 12–20 hours, and then air cool.

The mechanical properties listed in Table 2-7 are those for Incoloy 901 material that has been given a double age hardening heat treatment. The tensile strengths and ductility are a function of titanium content, with increasing strength and decreasing ductility for increasing titanium content (the cited range was from 2.6 to 2.85% titanium). The hardness values for the double aged material are from 32 to 42 HRC (302 to 388 Brinell hardness). The hardness and tensile properties of a service-exposed 901 stem failure are discussed in Section 2.6.7 and are in good agreement with the values given here. The typical Charpy impact energy is 30 ft-lb (41 J) at room temperature. The mean coefficient of thermal expansion between room temperature and 1000°F (21°C and 538°C) is 8.5×10^{-6} per °F (15.3×10^{-6} per °C) [18].

Frank and Mahidhara [17] have studied the effects of the two types of heat treatment on the microstructure and mechanical properties of Incoloy 901 material. The heat treatments were performed over the range of conditions allowed by the specifications using a statistical approach. The evaluation tests were room temperature tensile tests and stress rupture tests performed at

1200°F (649°C) and 90 ksi (620 MPa). Their results showed a significant advantage of the Type 1 heat treatment in rupture time compared to that for Type 2 heat-treated material. The Type 1 material had slightly better tensile strength and significantly better ductility than the Type 2 material.

2.5.2 Refractalloy 26 Material

Refractalloy 26 material is a precipitation-hardening nickel-based superalloy. A summary of the physical and mechanical properties is given in an alloy digest data sheet published by ASM International [18]. The alloy was developed by Westinghouse, and it has been used for bolting, turbine blades, and turbine valve parts. The maximum intended service temperature for turbine bolting and valve applications is about 1050°F–1100°F (566°C–593°C). The chemical composition of Refractalloy 26 material is given in Table 2-6. The composition of AISI 690 [8] is within the range specified for Refractalloy 26 material except for the slightly lower nickel content of 33% for AISI 690. The primary alloy additions are cobalt, chromium, iron, molybdenum, and titanium.

The microstructure of Refractalloy 26 material is nominally 100% austenite with some second phase particles at the grain boundaries and inclusion stringers in the grain matrix. X-ray diffraction was performed on Refractalloy 26 material, and TiC was present in the minor phase of the extracted residues [19].

The tensile and creep properties of Refractalloy 26 depend on the heat treatment. There are two primary heat treatments, termed A and B, that have been used [18]. Heat treatment A provides for better long-term creep-rupture strength and is an age-hardening-type heat treatment. The age-hardening heat treatment consists of the following steps:

1. 2100°F (1149 °C) for 1 hour
2. Oil quench
3. 1500°F (816°C) for 20 hours and air cool
4. 1350°F (732°C) for 20 hours and air cool

The hardness range for age-hardened samples was from 23 to 33 HRC (241 to 311 Brinell) and the expected hardness is 31 HRC (295 Brinell).

Heat treatment B is used to develop high tensile and fatigue strength properties. Heat treatment B consists of the following steps:

1. 1800°F (982 °C) for 1 hour
2. Oil quench
3. 1350°F (732°C) for 44 hours and air cool

The expected hardness for heat treatment B is 344 Brinell. The tensile strength values in Table 2-7 are for the age-hardened heat treatment.

The 1000-hour rupture strength values were the same: 65 ksi (448 MPa) for both heat treatments at 1200°F (649°C). But the age-hardened material was stronger at 1350°F (732°C) and 40 ksi (275.8 MPa) rupture strength for heat treatment A, versus 28 ksi (193 MPa) for heat treatment B. The fatigue endurance limit, strength at 10^8 cycles, was higher for heat treatment B than for heat treatment A. For example, at 1200°F (649°C), the fatigue endurance strengths were 84 ksi (579 MPa) for heat treatment B and 54 ksi (372 MPa) for heat treatment A.

Refractalloy 26 material has been used as a bolting material for steam turbine casings and valves. For the Refractalloy 26 bolt material, the service experience was reviewed and mechanical testing was performed [20]. The percentage of failed bolts in service was about 3%, and the failure mechanisms were stress corrosion and excessive preload. The stress corrosion failures are associated with steam impurities, and the failures are typically intergranular stress corrosion cracking (IGSCC) [21, 22].

The mechanical properties were measured for the steel given a double age-hardening heat treatment. The measured Charpy impact energies were from 60 to 67 ft-lb (83 to 92 J) at room temperature. The mean coefficient of thermal expansion between 70 and 1000°F (21 and 538°C) is 8.2×10^{-6} per °F (14.8×10^{-6} per °C) [18].

Relatively long-term, creep-rupture tests were performed at 1022°F (550°C) and 1112°F (600°C) [20]. Both smooth bar and notched bar tests were performed. The EPRI test results showed notch strengthening. The smooth bar rupture data for Refractalloy 26 material are shown in Figure 2-9.

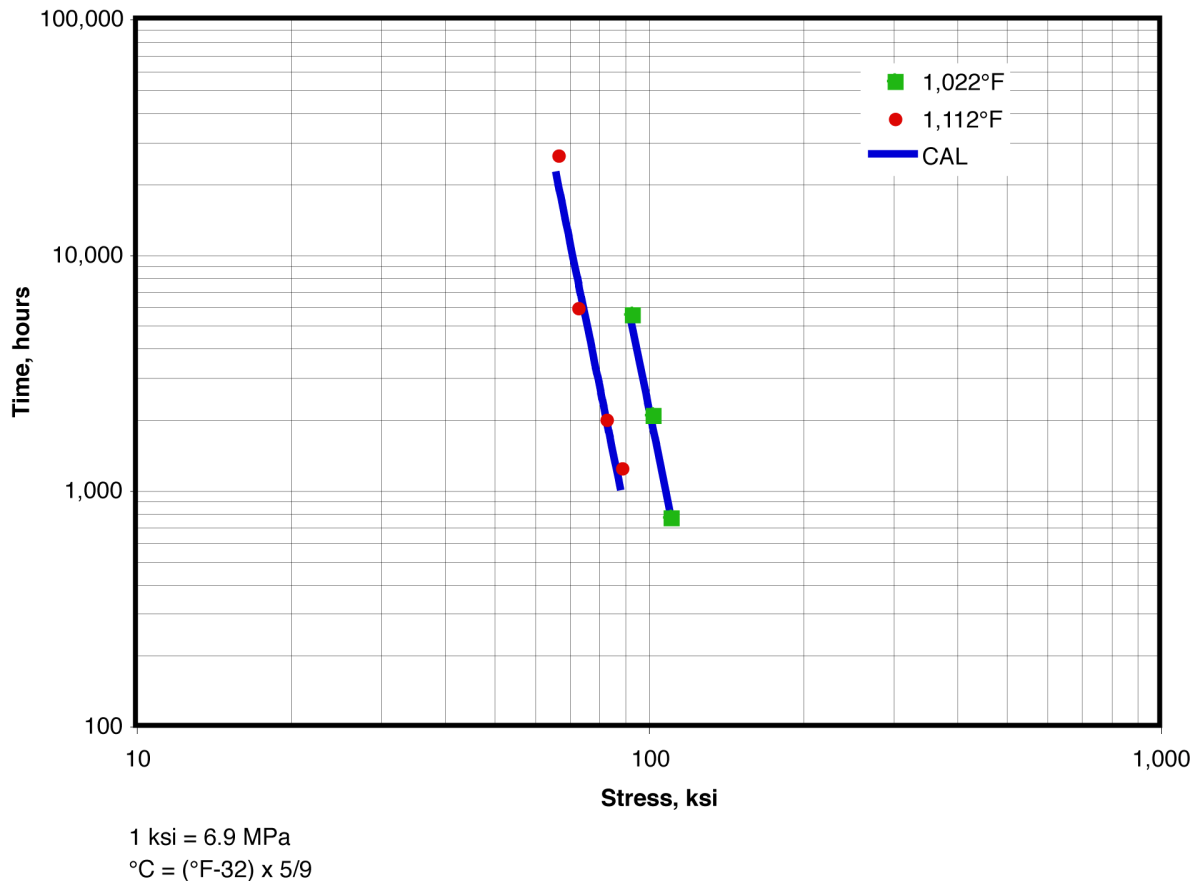


Figure 2-9
Rupture properties of Refractalloy 26 material

Davis and Manjoine [23] performed a comprehensive series of notched rupture tests on Refractalloy 26. The testing included the effects of notch geometry, heat treatment, and ductility. Their tests showed notch strengthening except for the sharpest notch geometry ($r/d=0.0012$) with notch weakening for the brittle heat-treated materials. For the notch weakening cases at 1200°F (649°C) and 1000 hours, the rupture strength of the sharp notched bar was approximately 5%–35% below that of the smooth bar.

2.5.3 W-545 Material

W-545 is an iron-based, precipitation-hardening superalloy. The chemical composition given in Table 2-6 is the nominal chemical composition given by Siemens-Westinghouse. The nominal chemical composition of W-545 [24] matches the Siemens-Westinghouse W-545 chemistry within limits for all elements except the nickel and cobalt levels. Siemens-Westinghouse has the specific inclusion of cobalt with a limit of 1% maximum and a specification on nickel plus cobalt of 26%. The difference in compositions reflects the experience of Siemens-Westinghouse and implies possible differences in properties, probably high-temperature strength and ductility.

Also shown in a table in the Donachie paper is the composition of ASTM A 453/A 453M Grade 665 (UNS S66545) [25]. With regard to expected physical and mechanical properties (except for long-time creep-rupture properties), the Siemens-Westinghouse W-545 material and the A 453 Grade 665 material are expected to be nominally the same—provided similar heat treatments are used.

The A 453 Grade 665 specification is for a high-temperature bolting material with a thermal expansion coefficient comparable to austenitic materials. Siemens-Westinghouse uses W-545 as a bolting material for austenitic pressure vessels such as valves and turbine cylinders at a maximum service temperature of 1100°F (593°C).

The minimum values of the room temperature tensile properties given in Table 2-7 are for the Siemens-Westinghouse W-545 material. Based on these strength levels, the probable heat treatment was a solution, quench, and age hardening heat treatment. The ASTM A 453 Grade 665 specification for the B heat treatment gives a solution temperature of 2000°F (1095°C) for 3 hours, liquid quench, and a double ageing/hardening treatment with the following steps:

1. Allow material to cool to 1350°F–1400°F (730°C–760°C), and hold for 20 hours.
2. Furnace cool to 1200°F (650°C), and hold for 20 hours.
3. Air cool.

The specified minimum tensile properties for the B heat-treated Grade 665 material are 155 ksi (1070 MPa) for ultimate tensile strength and 120 ksi (830 MPa) for yield strength. The minimum values given in Table 2-7 are OEM specifications for the W-545 stem material. The hardness requirements for the Grade 665 material are 311–388 Brinell hardness number or 32–41 HRC.

Figure 2-10 shows the yield and tensile properties for W-545 as a function of titanium content and temperature [26]. Higher strength levels are found for the higher titanium content material. The higher values for the tensile properties given in Table 2-7 are for the average value of the W-545 properties at the two titanium content levels.

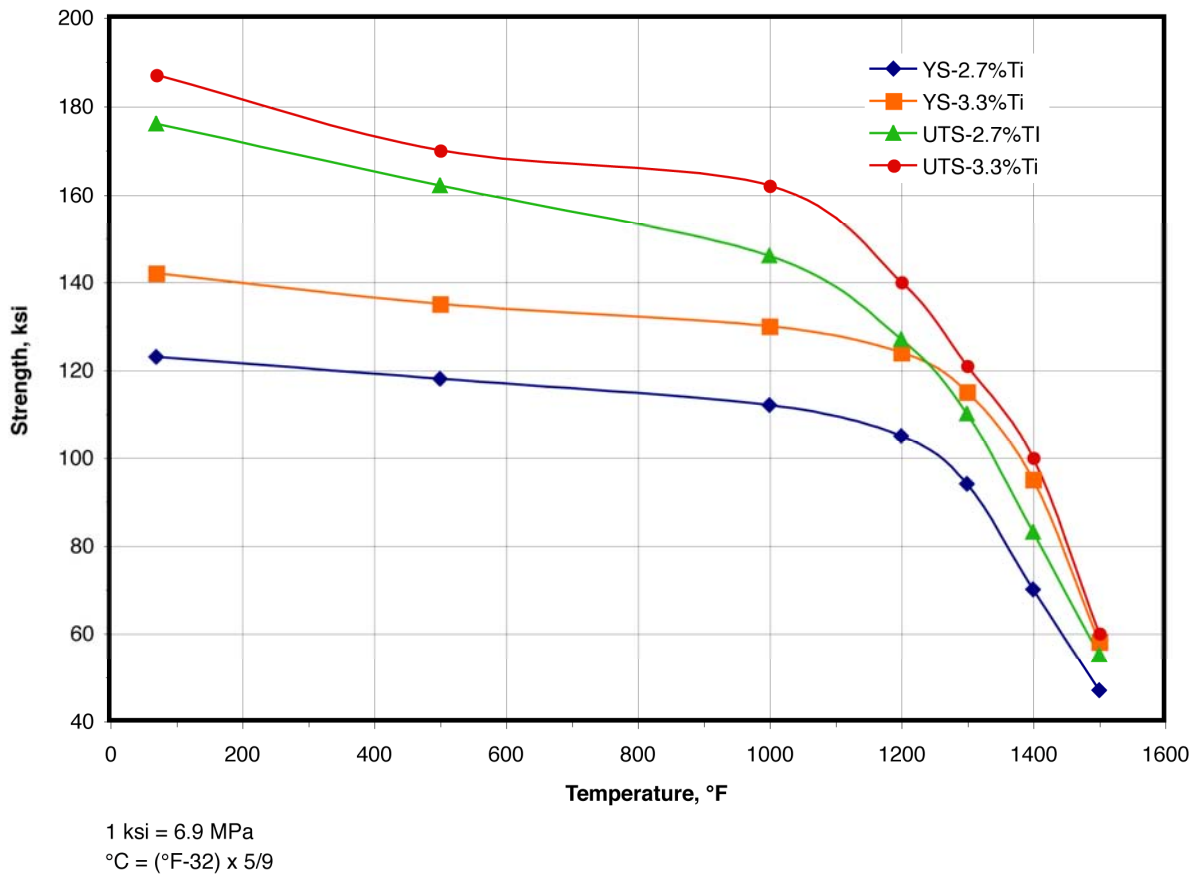


Figure 2-10
Tensile properties of Superalloy W-545 material

Rothman [26] has given physical and mechanical property data for W-545 (UNS S66545). The mean coefficient of linear expansion values were 9.88×10^{-6} per $^{\circ}\text{F}$ (17.78×10^{-6} per $^{\circ}\text{C}$) from room temperature (RT) to 900°F (482°C) and 10.1×10^{-6} per $^{\circ}\text{F}$ (18.18×10^{-6} per $^{\circ}\text{C}$) from RT to 1200°F (649°C).

Figure 2-11 compares the thermal expansion properties for the superalloy stem materials as a function of temperature. Incoloy 901 and Refractalloy 26 have similar expansion characteristics, but the thermal expansion of W-545 is considerably higher. Alloy W-545 has a coefficient of thermal expansion that matches those of austenitic stainless steels. The Charpy impact energy at room temperature was 29.8 ft-lb (40.4 J) for the steel given the B type heat treatment.

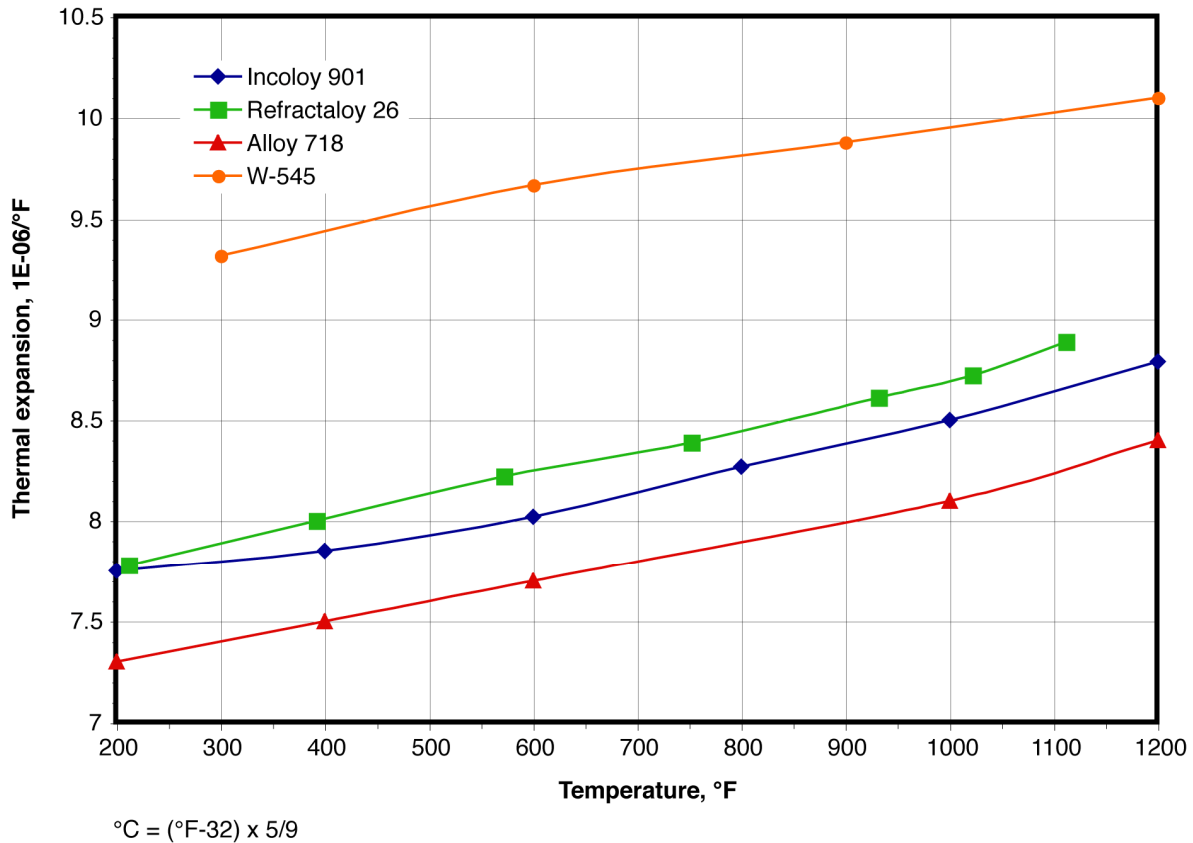


Figure 2-11
Comparison of thermal expansion coefficients for superalloy stem materials

2.6 Damage Mechanisms

This section includes the damage mechanisms for valve stems and a discussion of the failure of two Incoloy 901 material valve stems. The primary damage mechanisms for steam turbine valve stems are:

- Bending
- Wear
- Oxidation
- Solid particle erosion
- Fatigue
- Pin hole connection deformation and cracking

A similar list of damage mechanisms was found in a previous EPRI study to develop steam turbine valve diagnostic testing [27]. The damage conditions are for stems, bushings, seats, and disks. The list in the EPRI study had the following degradation mechanisms:

- Sticking to the valve seat; excessive pull-out
- Wear of the seating surface
- Disc separation from the stem
 - Broken stem
- Excessive friction
 - Corroded stem
 - Oxide growth on valve internal parts in fossil plant applications
- Bent stem
- Loose linkage
- Changes in the spring
 - Rate change
 - Preload change
- Stem misalignment
- Short travel
 - Linkage maladjustment
 - Foreign material on valve seat preventing closure
- Localized stem wear

2.6.1 Bending

Valve stems bend in service because of the steam forces applied to the stem by normal steam flow through the valve and/or as the stem moves through the valve. Bending can also occur due to stress relief at service temperatures of as-fabricated residual stresses in the stem. To prevent bending of the stems during manufacture, the stems are given the stress relief heat treatment with the stem hung vertically. Stems that are significantly bent usually result in valve failure that occurs during the opening or closing of the valve.

To detect bending prior to valve failure, the typical nondestructive inspection techniques of interest are visual and dimensional. One of the primary dimensional tests to detect bending of stems is the total indicated run-out (TIR). Valve stem TIR is defined as the centerline displacement or maximum stem bending relative to the ends of the stem. Procedures for measuring TIR of valve stems are given in the EPRI valve maintenance guidebook [28].

The factors that determine the limits on stem run-out include the following [28]:

- Magnetite oxide scale thickness
- Differential thermal expansion between stem and bushing
- Stem bending
- Machining tolerances for valve stem and the stack-up of clearances for assembled parts

Of the total design clearance, experience indicates that oxide growth accounts for 50% of the loss, bending is 25% of the loss, and 15% is needed for differential thermal expansion.

With regard to the repair of bent stems, although flame straightening could potentially be used, replacement is the prudent and common utility practice. Flame straightening has been recommended when no replacement stems are available [28]. The flame-straightened stem is not considered a permanent repair because it is susceptible to repeat bending.

Bending is due to inelastic deformation. The stresses and strains in a stem are due to the applied thermal and mechanical loadings, and they can be significantly higher than design. This is especially true for cases of off-nominal operation such as steam flow transients and excessive misalignment due to severe bushing or steam wear. The magnitude of the accumulated strain is primarily a function of these applied stresses, the stem-bushing geometry, and the yield strength of the stem material at the operating temperature. Thus, a stem material with a higher yield strength such as Incoloy 901 is expected to be significantly less likely to become bent in service than a lower yield strength material such as Nitralloy 135M. Turbine valve manufacturers are currently recommending material upgrades to higher strength materials as a solution to the bending problem.

2.6.2 Wear

The wear of the valve materials is a primary factor that determines the service behavior of valve stems and bushings. *Wear* is defined as the progressive loss of material from the surface of the part as the result of the relative motion at the surface. Excessive wear of either the stem or the bushing can result in improper alignment of the stem and cause the valve to close improperly. In addition, the increase in diametrical clearance between the stem and bushing increases the probability of stem failure due to bending and vibration or fatigue. To ensure good antigalling and wear properties, nitriding or Malcomizing the critical surface regions is used. Wear tests are used to determine various wear characteristics and evaluate the effectiveness of nitriding and other hardfacing techniques.

Wear tests have been performed on three steam turbine valve materials, ASTM A 355 (Nitralloy 135M), SUS 422 (422 stainless steel) and Nimonic 901 (Incoloy 901) [29]. The materials were tested in the nitrided and unnitrided conditions. The thickness of the nitrided layer was 0.014, 0.008, and 0.002 in. (360, 200, and 50 microns) for ASTM A 355, SUS 422, and Nimonic 901, respectively. The phases found in the nitrided layer were Fe_3N and Fe_4N for A 355, these iron

nitrides and CrN for SUS 422, and only CrN for Nimonic 901. For 135M, aluminum nitrides are also typically found in the diffusion layer of the nitride case. The case hardness values for the three steels were nominally the same.

The wear-resistance tests were performed using a ring-on-disc tribometer at temperatures of 900°F (482°C) and 1000°F (538°C). The ring was tested in accordance with the ASTM A 355 standard at both temperatures, and the disc materials were Type 422 stainless steel at 900°F (482°C) and Nimonic 901 at 1000°F (538°C). The wear characteristics of interest were the wear loss and the coefficient of friction. Plots of weight loss were made and showed significantly lower weight loss for the nitrided steels compared to the unnitrided steels. Specifically, the weight loss reductions for the nitrided compared to the unnitrided were about 40%–60% reduction for A 355 at the two temperatures, 30%–60% reduction for Type 422 stainless steel at the two temperatures, and about 33% reduction at both temperatures for Nimonic 901 material. At 900°F (482°C), the weight loss for the gas-nitrided steels was approximately 1.5 times those for the plasma-nitrided steel. In essence, the limited wear testing confirmed the effectiveness of nitriding in decreasing the amount of wear for nitrided compared to nonnitrided valve stem materials.

2.6.3 Oxidation

Oxidation of the valve stem and bushing causes a significant decrease in the clearance between the stem and bushing. Oxidation is sometimes referred to as *blue blush*. Because of oxidation, measuring the stem-to-bushing clearance and cleaning or de-scaling is routinely performed as part of the valve maintenance activity. The thickness of the oxide scale is a function of the time, temperature, environment, and material. The valve parts that are subject to wear and/or galling have the surfaces nitrided. The composition of the nitrided layer and the thickness are known to affect corrosion behavior.

The oxidation behavior of ASTM A 355 (Nitalloy 135M and SUS 422 (422 stainless steel) in high-pressure water vapor has been studied [30]. The oxidation tests were performed at 541°F (283°C) and 1450 psi (10 MPa) pressure for durations from 500 to 2500 hours. Both the gas-nitriding and plasma-ion-nitriding process were used. The thickness values of the nitrided layers were 0.014 in. (360 microns) for Nitalloy 135M and 0.008 in. (200 microns) for Type 422 stainless steel. The nitrided layer of Nitalloy 135M contained Fe₃N and Fe₄N, and the Type 422 stainless steel nitrided layer had these iron nitrides as well as CrN.

Tests were performed on nitrided and unnitrided steels. For ASTM A 355, the initial weight gain of the nitrided steel was rapid, but the rate of weight decreased significantly after about 1000 hours. The weight gain was linear for the unnitrided A 355 steel. The weight gain after 2500 hours was lowest in the unnitrided steel, intermediate in the plasma-nitrided steel, and highest in the gas-nitrided steel. Results for AISI Type 422 stainless steel were similar and showed higher oxidation rates for the nitrided materials compared to the unnitrided materials and linear oxidation rate for the unnitrided steel. X-ray diffraction results for the nitrided oxidation test specimens showed oxide peaks of Fe₂O₃ for Nitalloy 135M and both Fe₂O₃ and Cr₂O₃ for Type 422 stainless steel.

Toshiba has reported results of an oxidation study on an existing Type 422 stainless steel stem and bushing combination and an improved combination of Incoloy stem and Stellite bushing materials (www.toshiba.com). Results were shown on a plot of scale quantity versus time, and a schematic illustration of the scale growth kinetics is shown in Figure 2-12. Although no dimensions were given for the scale quantity axis, the oxidation kinetics appeared to be the expected parabolic growth kinetics, that is, thickness is proportional to $\sqrt{t}$ (the square root of) time. After 40,000 operating hours, their results showed a decrease of 85% in the scale quantity for the improved combination compared to the existing stem-bushing combination.

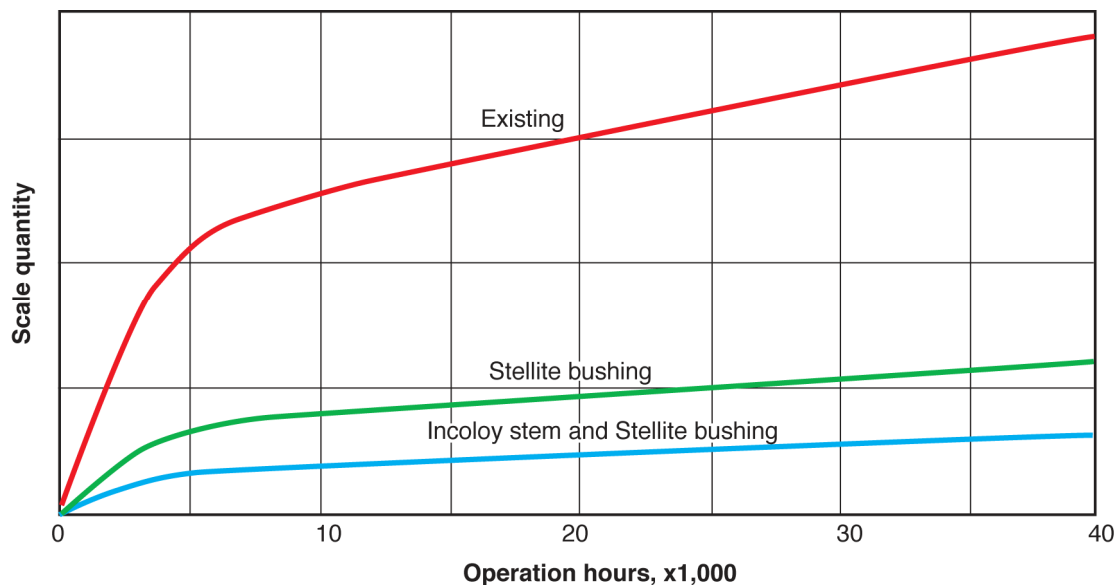


Figure 2-12

Schematic illustration of scale quantity versus time for an existing Type 422 stainless steel stem and bushing combination and an improved combination of Incoloy stem and Stellite bushing material

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The results of the tests performed by Toshiba are in good agreement with the service experiences reported by one utility for Incoloy 901 stems and 422 stainless steel stems and bushings. In the first case, the stem and bushing were installed in 2003 and had operated without disassembly until the valve failed to test properly. Figure 2-13 shows a photograph of a nitrided Incoloy 901 stem after 48,000 hours of service in a GE combined reheat-intercept valve. The nominal operating temperature was 1000°F (538°C). It was reported that the stem had minimal oxidation or oxide scale buildup. The bushing was nitrided 422 stainless steel and had considerable oxide scaling. Photographs of the bushing are shown in Section 3. The oxidation had completely consumed the available clearance of 0.016 in. (0.41 mm), and the valve was removed from service to refurbish the affected valve parts.

In the second case, both the stem and bushing were nitrided 422 stainless steel. The valve was also a GE combined reheat-intercept valve operating at 1000°F (538°C). Figure 2-14 shows a photograph of the 422 stem. The scale was relatively thick and had exfoliated in several areas. The scale thickness filled the clearance between the stem and bushing. The relatively good oxidation behavior of a Stellite bushing is discussed in Section 3.



Figure 2-13
Incoloy 901 stem after 48,000 hours of service with minimal oxide scale thickness



Figure 2-14
Thick and exfoliated oxide scale on nitrided 422 stem

2.6.4 Solid-Particle Erosion

Solid particle erosion is the loss of material on a surface caused by contact with a fluid that contains solid particles. For steam turbine valves, the fluid is steam, and the solid particles are typically exfoliated steamside oxide scales. The growth and exfoliation of steamside oxide scales on ferritic and austenitic boiler tubing have been discussed [4]. There are two types of solid-particle erosion: abrasive erosion where the relative motion of the particles is nearly parallel to the solid surface and impingement erosion where the relative motion of the solid particles is nearly normal to the surface.

There have been numerous papers regarding solid-particle erosion for a large number of environments, particles, and material combinations. In summary, the rate of erosive wear is a function of particle velocity, angle of impact, particle shape and composition, temperature, and the resistance to solid-particle erosion afforded by the surface of the component, that is, the valve part. The particle velocity is the principal operational variable that affects the erosion wear rate. Typically, the rate is proportional to the particle velocity, raised to the power in order of magnitude of 2 to 4.

Solid-particle erosion has been studied for applications to ultrasupercritical power plants [31]. They found that the magnitude of the erosion due to solid particles was primarily a function of the hardness of the particles and the turbine material. Boiler oxide scale is typically harder than the bare turbine base materials. In essence, the erosion metal loss is inversely proportional to the material's hardness. Nitrided materials and chrome-carbide-coated materials are significantly harder than the stem base material.

For stems, the resistance to solid-particle erosion is provided by a surface that has been nitrided or has a Stellite weld overlay. GE nonskirted bypass valve stems have a Stellite inlay. Detailed discussions of Stellite inlays are given in Section 4.2. Several examples of solid-particle erosion of valve stems are discussed in the following paragraphs.

Figure 2-1 shows a photograph of an Incoloy 901 valve stem that was removed from a GE control valve after approximately four years of service at a fossil power plant. Visual examination and dimensional analysis was performed. The stem is approximately 32 in. (0.8 m) in length and has a nominal diameter of 1.5 in. (38.1 mm) in the uniform section. Figure 2-15 shows detailed views of the solid-particle erosion damage found near the pin connection end of the stem and a second position along the length. The erosion damage is not uniform around the circumference or along the length, and there are small patches of material without any apparent wear. The nominal wear is about 0.035 in. (900 microns) at the pin connection end and about 0.010 in. (250 microns) near the center of the uniform section. The eroded surface is highly polished, but it also has a slight unevenness or textured appearance.

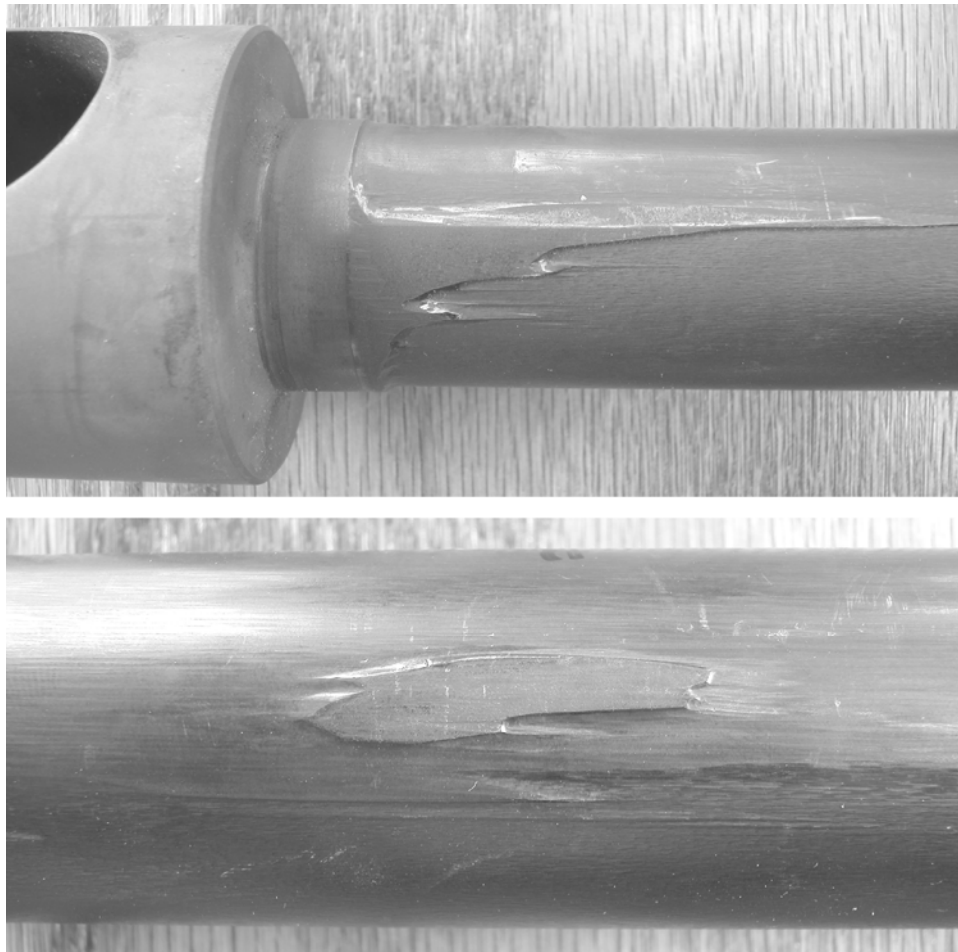


Figure 2-15
Detailed view of the solid-particle erosion damage for Incoloy 901 control valve stem

Figure 2-16 shows a photograph of two valve stems removed from the emergency stop valves (ESV) at a fossil power plant. There are left and right valves, and the solid-particle erosion damage is nearly identical for both stems. The eroded surface has an abraded or gouged appearance.



Figure 2-16
SPE damage for two valve stems removed from the ESV at a fossil power plant
(Courtesy of TVA)

Two examples of solid-particle erosion damage for a GE main stop valve are shown in Figure 2-17. For both stems, the wear is located adjacent to the threaded end of the valve stem. For one stem, the wear is slight and is limited to a small arc of the circumference. For the second stem, the wear is severe, and the stem is apparently approaching failure.

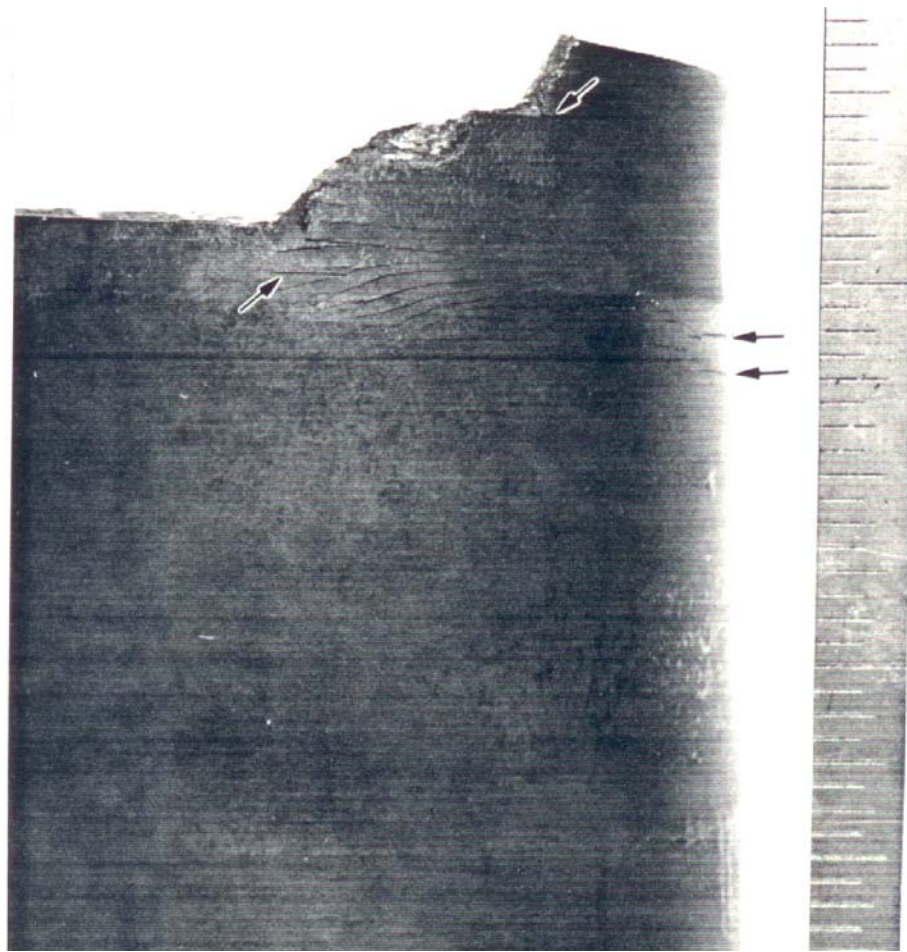


Figure 2-17
Solid particle erosion damage for GE main stop valve stems

2.6.5 Fatigue

Four fatigue failures are discussed in this section. Two of the fatigue failures are for GE control valve stems, which are discussed first. The stem material in both cases was EME. The first stem was approximately 21 in. (0.533 m) long and had been in service approximately six months. It was reported that the valve was frequently used to follow the load from 300 MW to 500 MW. In addition to the frequent cycling, it is also significant that the guide collar (bushing) was loose.

Figure 2-18 shows a photograph of the failed control valve stem, and Figure 2-19 shows a photograph of the fracture surface. The fracture surface is relatively flat over slightly less than half of the stem diameter, and there are beach marks marked by small arrows on the fracture surface. There is also a small, flat fracture region on the opposite side of the large flat fracture surface. These two flat fractures are fatigue cracks. The central angled fracture joining the two flat fatigue cracks is the final ductile overload of the remaining ligament. The fracture is consistent with a high-cycle, bi-direction fatigue failure. The failure is due to an applied cyclic bending moment. There are cracks in the nitride case marked by arrows in Figure 2-19. These case cracks were found to propagate into the EME base metal in several instances as shown in the scanning electron microscope (SEM) photomicrograph in Figure 2-20, and these cracks may be the crack initiation site for the base metal fatigue cracks.



1 inch = 25.4 mm

Figure 2-18
The failed control valve stem
(Courtesy of TVA)

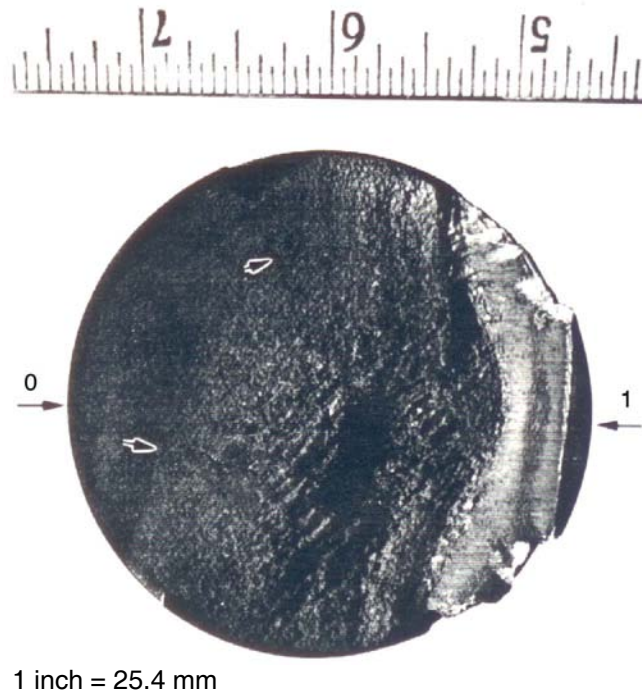


Figure 2-19
The fracture surface
 (Courtesy of TVA)

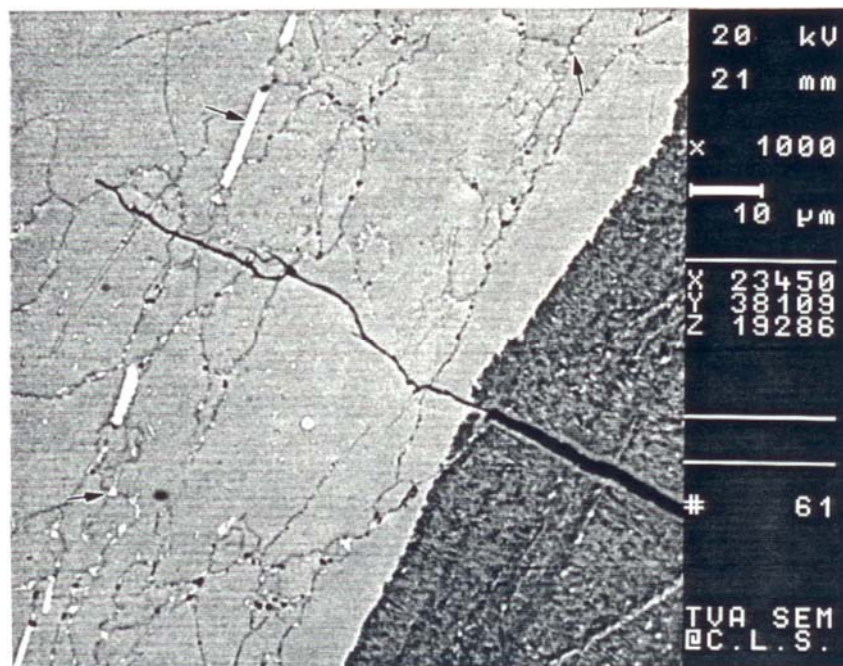
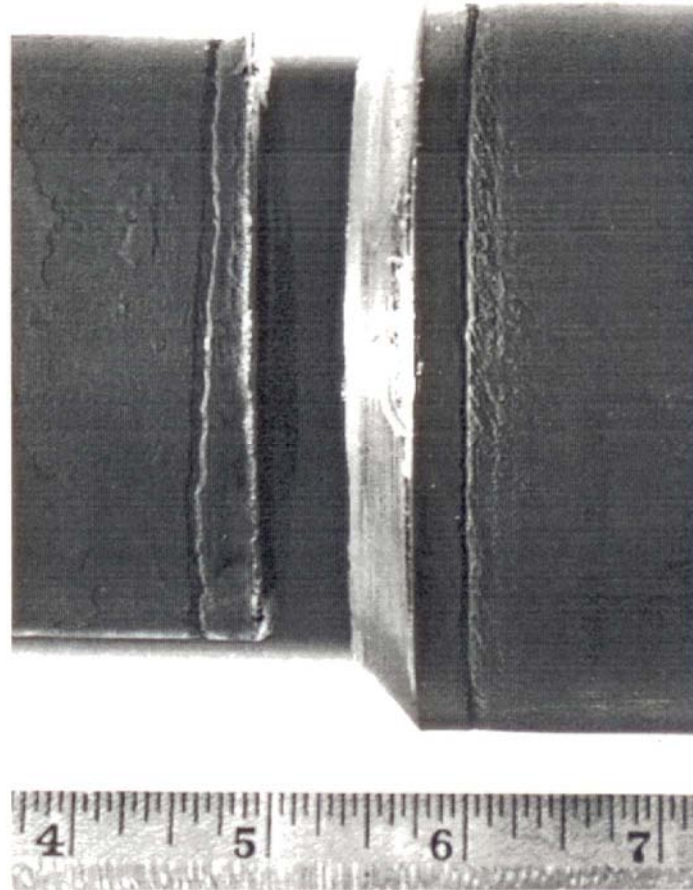


Figure 2-20
SEM photograph of a crack in the nitride coating and the initiation of a transgranular crack in the EME base material
 (Courtesy of TVA)

The second fatigue failure of a control valve stem was located at a change in section size. Figure 2-21 shows a photograph of the failed valve stem. The fracture surface was smooth and flat over the entire surface except for some small ratchet marks located at and adjacent to the OD of the stem. The ratchet marks were found at multiple sites, indicating multiple fatigue crack initiation sites. The change in section had a hardfacing weld overlay, and the cracking initiated in the weld metal. Figure 2-22 shows a cross section through the fracture. Figure 2-23 shows the transgranular cracking in the base and weld metal, which is typical of fatigue failures. Based on the measured chemistry and high cobalt content, the weld metal is probably a Stellite weld metal.



1 inch = 25.4 mm

Figure 2-21
The failure of a control valve stem at a change in section size
(Courtesy of TVA)

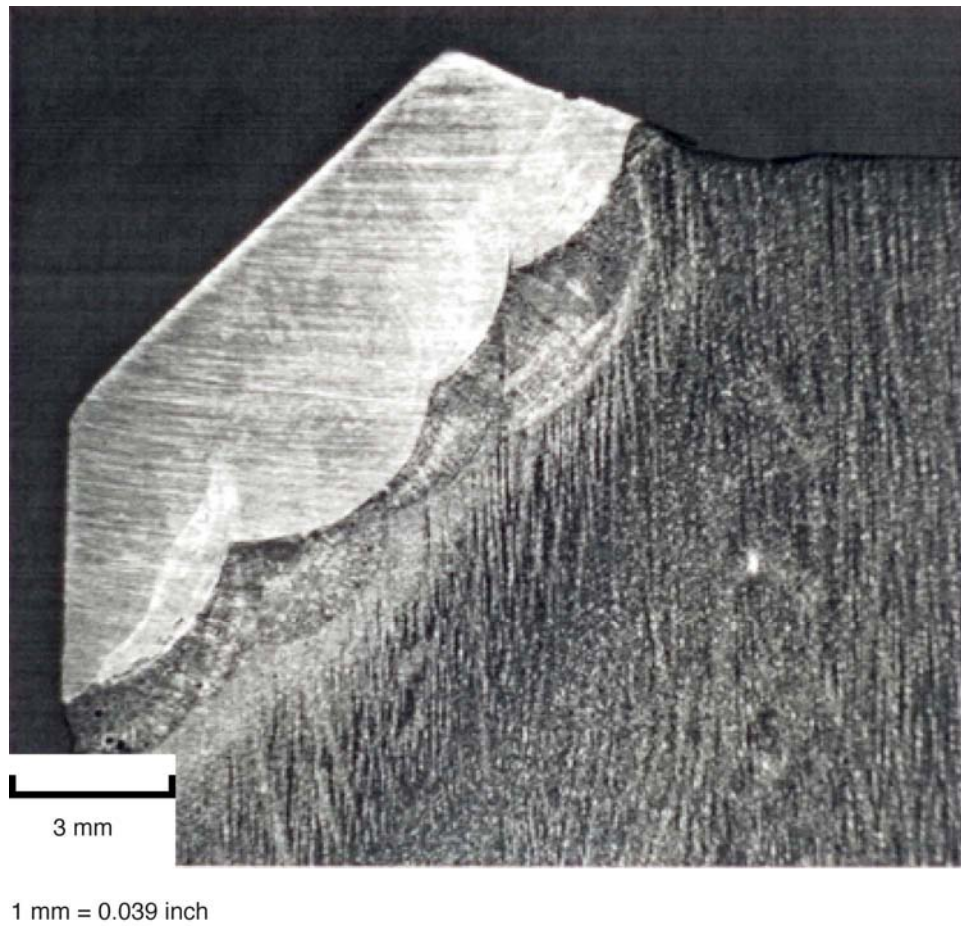


Figure 2-22
Macrostructure at the fatigue crack initiation in the weld metal
(Courtesy of TVA)

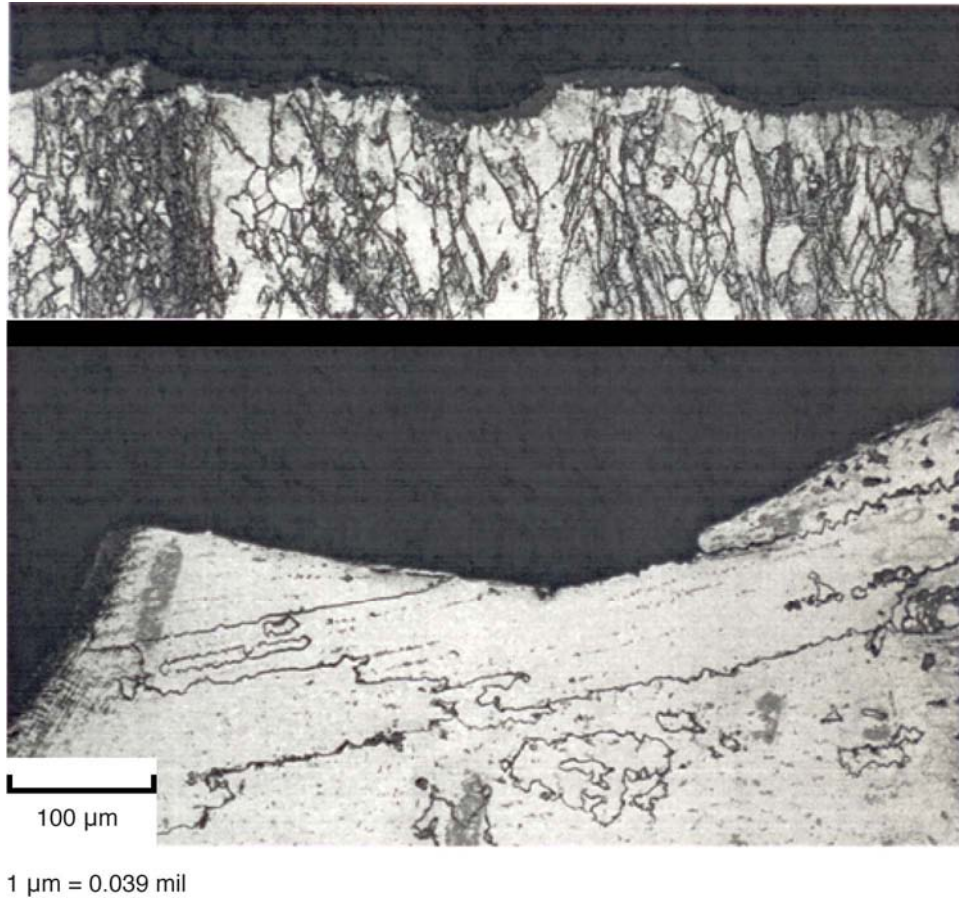


Figure 2-23
Transgranular cracking in the base metal and weld metal
(Courtesy of TVA)

The third fatigue failure was in a carbon steel control valve stem. The stem failed after 18 months of service. Figure 2-24 shows a photograph of the failed stem. The stem failure consisted of two pieces, a smaller diameter (about 2 in. [5.1 cm]) section with external threads and the larger diameter (about 4 in. [10.2 cm]) section with internal threads. The fracture surface was covered by a thin oxide scale, which gave a bronze-to-brown color to the surface.

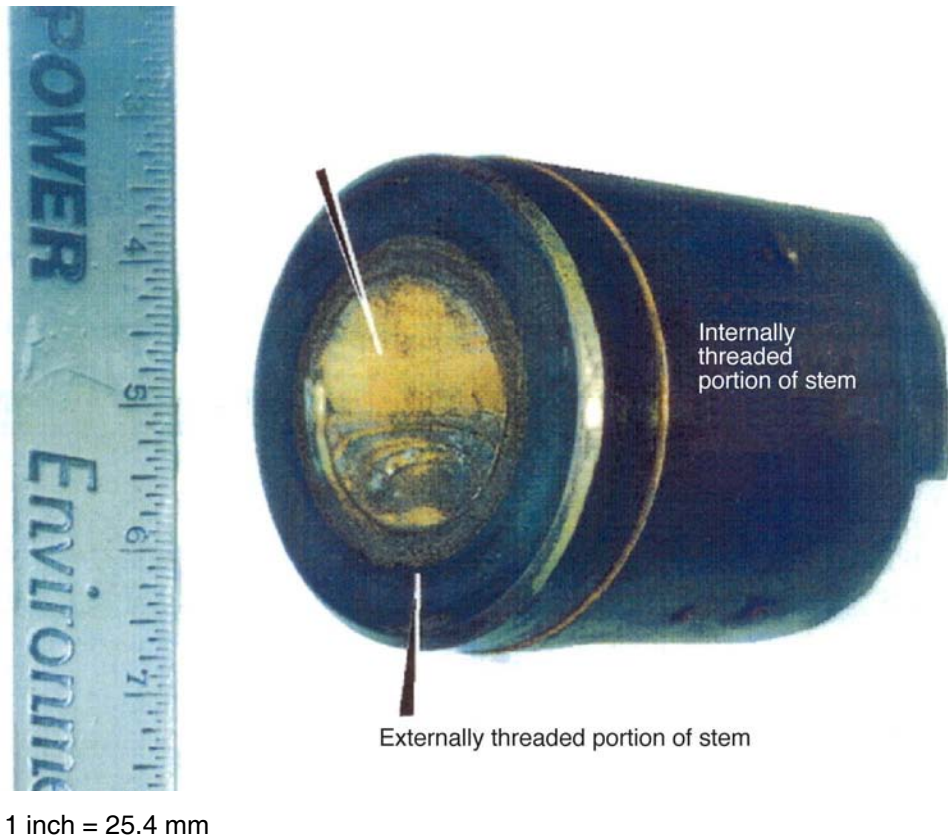
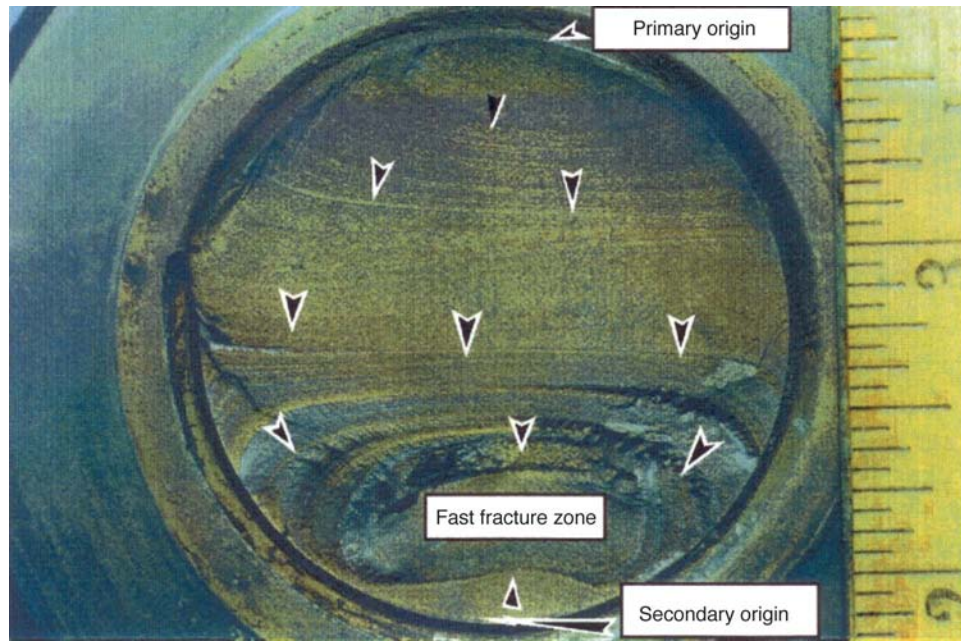


Figure 2-24
Macro view of a failed control valve stem

Figure 2-25 shows a detailed view of the fracture surface and the numerous beach marks that are typical of fatigue. The fracture initiated at two sites, primary and secondary, as shown in the figure. The final fast fracture was a ductile overload failure. The relative size of the final fracture indicates that the applied loads were relatively low. The fatigue cracking initiated at the thread root, which is a stress concentrator.



1 inch = 25.4 mm

Figure 2-25
Beach marks on the fracture surface, typical of low-cycle fatigue

The failure mechanism was mechanical fatigue. Based on the features found on the fracture surface, the failure is due to an applied bending moment, high-cycle and low-strain range, at a stress concentrator of the thread root. The bending was primarily in one direction, but there was a small reversed bending moment.

The final fatigue fracture was at one side of the pin connection hole. Figure 2-26 shows a photograph of the failure for the side with the flat, smooth fracture surface. The other side of the fracture surface was very rough. The rough side of the fracture had evidence of significant plastic deformation including OD distortions and exfoliating oxides.

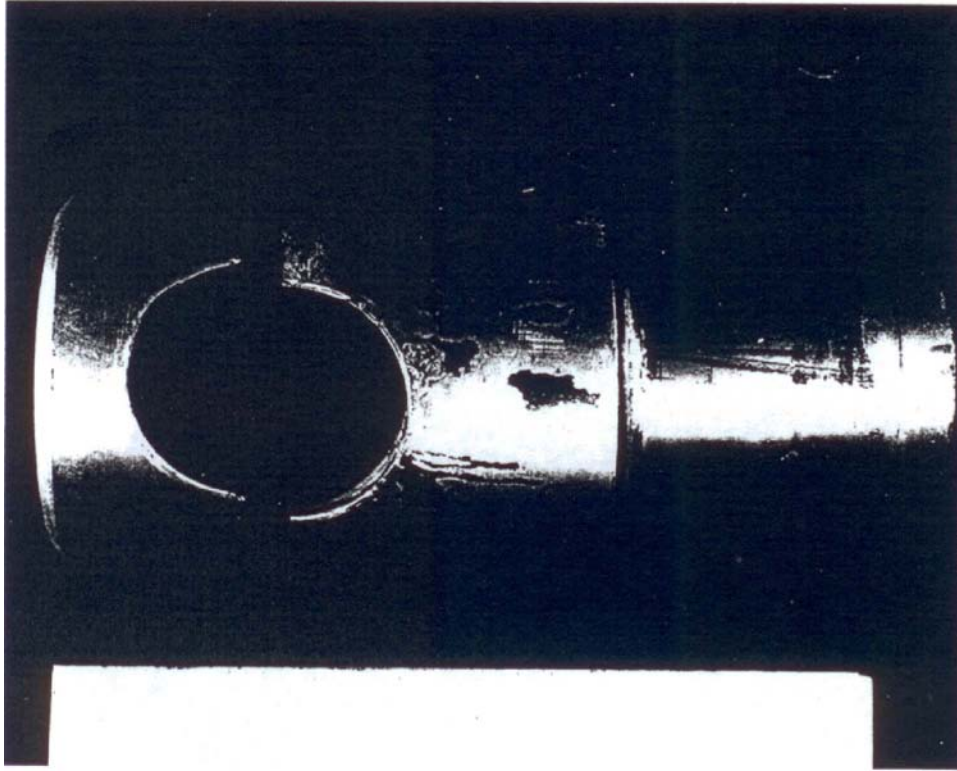


Figure 2-26
Stem failure in the ligaments at a pin hole

Figure 2-27 shows a schematic illustration of the damage distribution at the pin connection hole. Approximately half of the cross section was cracked before the final overload fracture, thus indicating relatively low loads. With regard to crack initiation, the stem material is EME, and cracks were found in the nitrided layer that extends through the case and into the base material. Thus, based on the results of the metallographic examination of the failure, it was concluded that the crack propagation was by high-cycle fatigue, and the case cracks were the initiation sites for the two diametrically opposed fatigue cracks.

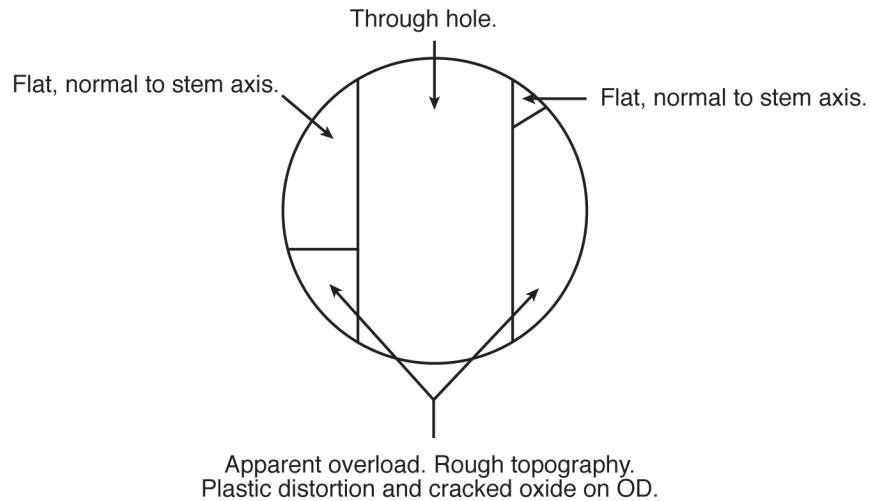


Figure 2-27
Fracture surface showing regions of high-cycle fatigue and ductile overload

2.6.6 Pin Hole Connection Deformation and Cracking

Figure 2-28 shows a photograph of a Nitralloy 135M valve stem. There are cracks at the pin connection, and the ligament is significantly deformed. As a result of the deformation, the pin connection hole is oval, and the ovality is approximately 5.6 % based on the measured diameters of the hole. The root cause of the deformation and cracking in this case is the use of the Nitralloy 135M material at a higher temperature than is allowable for this material. Although the damage was advanced at the pin hole, the stem failed at a change in section size. The fracture surface had ratchet marks, and the stem ultimately failed due to low-cycle fatigue.



Figure 2-28
Pin hole connection deformation and cracking for a Nitralloy 135M valve stem

2.6.7 Incoloy 901 Valve Stem Failures

Failure analysis was performed for two identical Incoloy 901 valve stems that were removed from a combined stop-and-control steam turbine valve [32]. The fracture was in the threaded portion of the stem that had been nitrided. The failure analysis included microstructural examinations, fractography, chemical analysis, Charpy, and tensile testing.

The austenitic microstructure had a duplex grain size, ASTM 5 to ASTM 1 (grain size number), and there was a nearly continuous coating of carbides, identified as (Ti, Mo) C, on the grain boundaries. The nitride layer was about 0.002 in. (50 microns) thick. Dark-field transmission electron microscope (TEM) photographs of the γ particles for the failed Incoloy 901 stem showed that the particles were coherent and had a particle size of about 7.9×10^{-7} in. (20 nm).

The average measured hardness was 42 HRC (414 HV). The measured tensile properties at room temperature were reported in units of MPa and were a yield strength of 90 MPa (13 ksi) and ultimate tensile strength of 120 MPa (17.4 ksi). These strengths are significantly below the expected values for Incoloy 901 and are not consistent with the measured hardness. Resolution of this apparent conflict can be obtained if it is concluded that the correct unit for the tensile measurements was Kgf/mm^2 . Using this assumption, the yield strength is 128 ksi (883 MPa), and the ultimate tensile strength is 171 ksi (1177 MPa). These tensile strengths are at the upper end of the range of values expected for Incoloy 901.

The fracture surface had three zones:

- Origin at the nitrided thread root
- Fast fracture with chevron marks
- Overload final fracture

The fracture is consistent with a notched circular section under a combined tensile and bending stress loading. The fracture mode was intergranular in all three zones of the failure and is consistent with grain boundary embrittlement.

Charpy tests were performed at room temperature with a C or U type notch. The measured impact energy was 9 ft-lb (12.2 J), which is significantly below the nominal value expected for unexposed Incoloy 901 material. Ageing is expected to decrease toughness. Special Metals Corporation [33] has reported Charpy data as a function of exposure time at elevated temperature. The reported operating temperature for the failed stems was about 750°F–840°F (400°C–450°C). At 1022°F (550°C), their data have a decrease in Charpy impact energy from 43 ft-lb (58.3 Nm) after 30 hours to 30 ft-lb (40.7 Nm) after 10,000 hours.

Chemical analysis was performed. The composition of the failed stem was consistent with the specification except for the titanium content of 3.50 %, which is higher than the maximum specified of 3.10%.

Based on the results of the failure analysis, the failure was due to low toughness and the nitrided layer at the root of the thread. The low toughness is associated with the high titanium content, continuous carbide precipitation film on the grain boundaries, and the duplex grain size distribution. To avoid future failures, the recommendation is for special care in manufacturing to limit the maximum grain size to ASTM 3–4, to limit the titanium concentration within specified parameters, and not to nitride the threaded region of the stem.

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3

VALVE BUSHING MATERIALS

3.1 General Discussion

The sealing surfaces for steam turbine valves are on the valve seat and disc. A narrow ring of contact exists between the disc and seat (approximately 0.0625 in. (1.6 mm) in width) that is called the *sealing surface*. Bushings are used to guide the stem and attached disc and to ensure that the disc and seat are in proper alignment. There are usually two bushings per stem, an upper and lower bushing. Bushings have hollow cylinder geometry. The bushings are held in place by the pressure seal heads. Figure 3-1 shows a sketch of a typical control valve bushing.

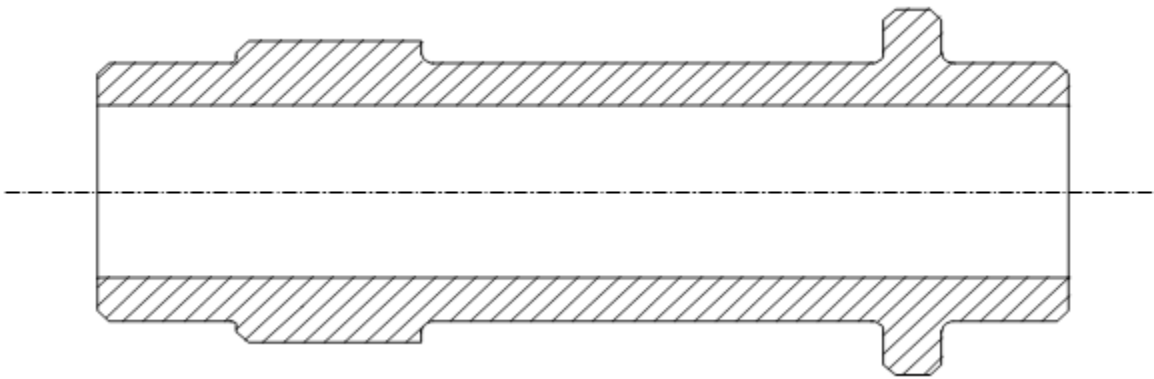


Figure 3-1
Drawing of control valve bushing

The major considerations in material selection for bushings are wear and oxidation. Wear is important because the stem and bushings have very close tolerances, and proper valve operation requires the smooth, unencumbered travel of the stem. Excessive oxidation and thick oxide scales on the bushing decrease the clearance between the stem and the bushing. The EPRI report *Guidelines and Procedures for Turbine Valve Condition Assessment* [1] provides guidelines on measurement of the stem and bushing dimensions. The report contains detailed drawings for the various valve geometries.

To meet the wear requirements, a nitriding process is frequently used to develop a thin, hard, wear-resistant case covering. The wear and oxidation properties of the nitrided bushings are determined by the chemistry and microstructure of the nitrided case. The tensile strength properties of the composite material are determined by the bulk of the material, that is, the core.

The materials used for steam turbine valve bushings in General Electric and Siemens - Westinghouse U.S. fossil power plants are given in Table 3-1. General Electric has also used Stellite liners.

Table 3-1
Bushing materials

General Electric
Nitalloy 135M – (135M Nitrided)
AISI Type 410 Stainless Steel – Nitrided
AISI Type 422 Stainless Steel – Nitrided
Incoloy 901 – Nitrided
347 Stainless Steel
Siemens – Westinghouse
Nitalloy 135M – (135M Nitrided)
AISI Type 422 Stainless Steel – Nitrided
Incoloy 901 – Nitrided
Refractaloy 26 – Nitrided
G18B – Nitrided

The alloys used for bushings on steam turbine valves include the low-alloy Nitalloy 135M, stainless steels, and superalloys. As noted previously, the majority of the alloys used for the valve bushings are the same ones that are used for the valve stems. The two new alloys are AISI Type 347 stainless steel and the G18B alloy, 13Cr-13Ni-10Co-3Nb-2.5W-2Mo.

AISI Type 347 stainless steel is used on the 1050°F (566°C) temperature steam turbine valves, but it has not been used on valves installed after 1962. The G18B alloy (13Cr-13Ni-10Co alloy) has also been used for gas turbine components and was considered as a main steam line piping material for the Eddystone Unit 1 plant [2].

3.2 AISI Type 347 Stainless Steel

AISI Type 347 stainless steel (UNS S34700) is a niobium-stabilized, austenitic stainless steel. The composition of Type 347 stainless steel is given in Table 3-2. Niobium has a strong carbide former, and the niobium carbide precipitation is beneficial to increase creep strengthening and to improve intergranular corrosion resistance.

Table 3-2
Chemical composition of AISI Type 347 stainless steel

Element	Weight Percent
C	0.08
Mn	2.00
P	0.045
S	0.030
Si	1.00
Cr	17.00–19.00
Ni	9.00–13.00
Nb & Ta	10 X C Minimum

The heat treatment for Type 347 stainless steel is solution and water quench. The typical solution temperatures are in the temperature range of 1850°F–2000°F (1010°C–1095°C) for Type 347 and about 2066°F–2192°F (1130°C–1200°C) for Type 347H. The nominal hardness is 88 HRB (150 Brinell), and the room temperature Izod impact strength is 110 ft-lb (149 J) [3]. The mean coefficient of thermal expansion from 32°F to 1202°F (0°C to 650°C) is 10.4×10^{-6} per °F (18.8×10^{-6} per °C).

The specified minimum strength values at room temperature are yield strength of 30 ksi (207 MPa) and ultimate tensile strength of 75 ksi (517 MPa). Tensile tests were performed on nine heats of Type 347H tubing at temperatures from room temperature to 1382°F (750°C) [4]. At room temperature, the yield strengths were from 31.3 to 38.4 ksi (216 to 265 MPa), and the ultimate tensile strength values were from 81.1 to 89.6 ksi (559 to 618 MPa). At 1022°F (550°C), the yield strengths were from 18.4 to 27 ksi (127 to 186 MPa), and the ultimate tensile strength values were from 58.3 to 66.9 ksi (402 to 461 MPa).

Creep-rupture tests have also been performed on the nine heats of Type 347H tubing. The test temperatures were 1112°F, 1202°F, 1292°F, and 1382°F (600°C, 650°C, 700°C, and 750°C) [4]. The test are long-term with typical rupture times greater than 20,000 hours at each temperature and a maximum test time of 56,000 hours at 1292°F (700°C). The rupture properties were analyzed using three time-temperature parameters (Orr-Sherby Dorn, Manson-Succop and Manson-Haferd), and the 100,000-hour rupture strength was calculated. The average 100,000-hour rupture strength at 1112°F (600°C) was from 18 ksi to 18.8 ksi (124.3 MPa to 129.4 MPa).

3.3 G18B Material

The austenitic alloy G18B (13Cr-13Ni-10Co-3Nb-2.5W-2Mo) stainless steel material was developed in the 1940s and has been used as a gas-turbine material for turbine discs, rotor blades, and rotor forgings [5]. The nominal chemical composition of G18B alloy is given in Table 3-3. The standard heat treatment is a solution treatment at 2372°F (1300°C). A lower

solution temperature of 2012°F (1100°C) has also been used, but the creep strengths are about 80% of those developed using the higher solution temperature. The material is also used in the solution treated-aged condition and after warm working. The microstructure is an austenitic matrix with fine carbide particles in the matrix and grain boundaries.

Table 3-3
Chemical composition of G18B stainless steel

Element	Weight Percent
C	0.40
Mn	0.80
Si	1.00
Cr	13.0
Ni	13.0
Co	10.0
Nb	3.00
W	2.50
Mo	2.00

The physical and mechanical properties of the G18B alloy have been discussed in Jessop-Saville's sales literature and several technical articles [2, 5, 6]. The mean coefficient of thermal expansion values are $9.4 \times 10^{-6}/^{\circ}\text{F}$ ($17 \times 10^{-6}/^{\circ}\text{C}$) from 68°F to 932°F (20°C to 500°C) and $10.0 \times 10^{-6}/^{\circ}\text{F}$ ($18 \times 10^{-6}/^{\circ}\text{C}$) from 68°F to 1292°F (20°C to 700°C). At room temperature, the nominal ultimate tensile strength is about 100 ksi (700MPa), and the expected Izod energy is approximately 28 ft-lb (38 J).

A relatively extensive and long-term creep and creep-rupture testing program has been conducted on the G18B alloy. Harris and Bailey [7] briefly reviewed the results of the testing in the discussion section of the paper by Blumberg [2] on the selection of main steam line piping material for the 1200°F (649°C) Eddystone Unit 1 fossil power plant. Creep data are available for time durations up to 80,000 hours, and rupture properties have been obtained for time durations of 35,000 hours. One desirable and unusual characteristic of G18B material is the rupture ductility that increases with increasing rupture time at test temperatures from 1202°F to 1382°F (650°C to 750°C).

A welding electrode was developed for the G18B alloy and was used to construct a large turbine rotor [8]. As part of the development program, metallurgical examinations, tensile, Izod, and creep tests were performed on the weld metal and weldments. The weld metal microstructure had a fine dendritic structure. There was no ferromagnetism detected in the weld deposit, indicating that the interdendritic region consisted of carbides, intermetallic compounds, and austenite, that is, no delta ferrite. The weld metal properties at room temperature were nominally equal to those of the base material. Relatively short-term creep tests were performed on the weldments at

1292°F (700°C), and comparisons with the G18B alloy base material indicated that both the solution-treated and stress-relieved weldments have creep strengths nominally equal to that of the base material.

Siegfried [6] has discussed the smooth bar and notched bar creep-rupture behavior of his Alloy 1 with a composition in weight percent of 13.0Cr-13.0Ni-10Co-3.0(Nb + Ta)-2.5W and 2.0Mo. The material was tested in the solution-treated condition (the solution temperature was not given). The creep tests were performed at temperatures of 1202°F, 1292°F, and 1342°F (650°C, 700°C, and 730°C). The test times were from about 2 hours to 1800 hours for the smooth bars. The test stresses were from about 28.4 ksi to 51.2 ksi (196 MPa to 353 MPa) at 1202°F (650°C) and from 21.3 ksi to 44 ksi (147 MPa to 304 MPa) at 1346 °F (730°C). Metallographic examination of the double-notched bars was used to study the creep-rupture process. In addition, long-term creep tests on blade root specimens were performed.

At 1202°F (650°C), notch weakening was found for the sharp notch with the 0.020 in. (500 microns) radius, but the round notch with a 0.20 in. (5 mm) radius did not show notch weakening. At 1346°F (730°C), notch weakening was found for the sharp notch with the 0.004 in. (100 microns) radius at short rupture times, less than approximately 50 hours. The 0.020 in. (500 microns) sharp notch and the 0.060 in. (1.5 mm) round notch showed notch strengthening at all rupture times. The ductility increased with increasing rupture time, and the change from notch weakening to notch strengthening nominally correlated with the increase in smooth bar rupture ductility.

The microstructure at the root of the notches was a mixture of intergranular and transgranular cracks for the 13Cr-13Ni-10Co alloy. Based on the photomicrograph of the 1202°F (650°C) notched bar specimen, the microstructure is a single-phase austenitic matrix, and there appears to be carbide precipitation both within and at the grain boundaries.

Specimens were annealed under a load of 14.3 ksi (98.7 MPa) at 1292°F (700°C) for times from approximately 300 to 3500 hours. Room temperature tensile tests were performed after the annealing process was performed with load. The ultimate tensile strength values were from approximately 116.6 to 124.7 ksi (804 to 860 MPa) and the yield strengths were from approximately 64.5 to 67.4 ksi (445 to 465 MPa). The values for the reduction in area were from 13% to 33%.

3.4 Damage Mechanisms

The damage mechanisms for bushings are wear and oxidation. Two examples relating to the oxidation damage mechanism for steam turbine valve bushings are discussed. The oxidation behavior of a Stellite inlay bushing and nitrided AISI Type 422 stainless steel bushing have been reported and documented by one utility.

Figure 3.2 shows a photograph of a bushing with a Stellite sleeve after 8000 hours of service. As seen in the photograph, the inside surface of the bushing has the mirror finish typical of an as-installed condition. Based on the surface appearance, it is believed that the oxide scale thickness is minimal, implying very good to excellent oxidation resistance for Stellite. This observation is

in agreement with the oxidation data reported by Toshiba for Stellite bushings and discussed in Section 2. Based on the good to excellent oxidation behavior exhibited by the Incoloy 901 stem and Stellite inlay bushing combination, the utility has increased the maintenance interval for these valves to coincide with that for the balance-of-plant maintenance interval, currently a six-year cycle.

Figure 3.3 shows a photograph of an AISI Type 422 stainless steel bushing after 48,000 hours service in a GE combined reheat-intercept valve at 1000°F (593°C). This is the mating part to the Incoloy 901 stem discussed in Section 2. The stem and bushing were installed in 2003 and had operated without disassembly until the valve failed to test properly. The stem had minimal oxidation, but the bushing had considerable oxide scaling. The scaling of the nitrided Type 422 bushing was such that the available clearance of 0.016 in. (0.41 mm) was completely consumed. Based on the extensive operating interval, the oxidation resistance of nitrided AISI Type 422 stainless steel is considered nominally good.



Figure 3-2
Bushing with Stellite sleeve after 8000 hours service with minimal oxide scale



Figure 3-3
Nitrided 422 stainless steel bushing after 48,000 hours service with thick oxide scale

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4

SEATS

4.1 General Discussion

One of the sealing surfaces for steam turbine valves is the seat. A narrow ring of contact exists between the disc and seat that is the sealing surface. The seat of a steam turbine valve has a hollow cylinder or pipe geometry. Valve seats are installed using a variety of techniques including the following:

- Shrink fitting
- Pins
- Bolting
- Lock rings
- Seal welding

Figure 4-1 shows a photograph of a weld-repaired governor valve seat after machining.



Figure 4-1
Weld-repaired governor valve seat after machining

The major considerations in material selection for seats are galling, wear, oxidation, and thermal expansion. To meet the antigalling and wear requirements of the sealing surface, a welded Stellite inlay is used. The requirements on oxidation and thermal expansion are satisfied using seat material of either the same nominal composition as the valve body material or a higher alloy material.

The typical materials used for steam turbine valve seats in General Electric and Siemens - Westinghouse at U.S. fossil power plants are given in Table 4-1.

Table 4-1
Seat materials

General Electric
1C-1Mo-0.25V
2.25Cr-1Mo
AISI Type 316 H
AISI Type 347 Stainless
Stellite 6 weld inlay at contact points
Siemens-Westinghouse
1Cr-0.5Mo
2.25Cr-1Mo
1Cr-0.5Mo-0.25-V
Stellite 6 weld inlay at contact points

The alloys used for valve seats are diverse and include low-alloy ferritic steels, stainless steels, and a cobalt-based superalloy. Many of these alloys used for the valve seats are also the same ones that are used for the valve discs. Type 347 and Type 316 stainless steel are used on the higher temperature steam turbine valves, that is, 1050°F (566°C). Type 347 was discussed in the section on bushings.

This section discusses each of the seat materials, the typical damage mechanisms for valve seats, and weld repair techniques used to refurbish the seats.

4.2 Stellite 6 Material

Stellite 6 is one of the cobalt-based, wear-resistant alloys that include Stellite 1, Stellite 12, Stellite 21, Haynes alloy 6B, Tribaloy T-800, etc. [1]. Stellite 1, 6, and 12 are derived from the original cobalt-chromium-tungsten alloys introduced by Haynes. Haynes alloy 6B is a wrought version of Stellite 6. The wrought form has increased ductility and homogeneity compared to the cast and weld metal structure of Stellite 6.

Stellite 6 (UNS R30006) is one of the most commonly used cobalt-based alloys. The primary characteristics of interest for Stellite 6 in valve seat and disc applications are the outstanding self-mated antigalling properties, high hardness, and good wear resistance. For valve sealing application, the good antigalling property is of prime importance to develop a leaktight seal. To optimize the antigalling property of Stellite 6, the material is typically used in the self-mating approach where the weld inlay is applied to the contact regions of both the seat and stem. *Galling* is defined as a severe case of scuffing associated with gross damage to the surfaces or failure [2]. *Scuffing* is localized damage that results from solid-phase welding of asperities due to frictional heat. The surface damage is the result of the fracture of the welded asperities.

For valve stem, seat, and disc applications, a weld inlay of Stellite 6 material is typically used. Stellite 6 material is available as casting, powder, welding rod, welding electrode, cored welding wire, and as a powder metallurgy product. The welding rod is AWS specification SFA 5.21 ERCoCr-A. The undiluted weld metal typically has a hardness of about 40–45 HRC. The welding electrodes are commercially available in sizes from 3/32 in. (0.094 in.) (2.6 mm) to 0.25 in. (6.4 mm). The welding electrode (UNS W73006) is ASME/AWS specification of SFA 5.13 ECoCr-A, and the weld metal hardness is 39–43 HRC.

Common welding processes for Stellite alloys include the usual processes of shielded metal arc (SMA), gas tungsten arc (GTA), metal inert gas (MIG), and plasma transfer arc (PTA). The stress relief heat treatment is to heat slowly to 1650°F (900°C) and hold for 2 hours minimum [3]. Table 4-2 compares the composition of the cast material (AMS 5387) and welding consumable (AMS 5788) with the nominal composition given in the *ASM Handbook* for Stellite 6 and 6B.

Table 4-2
Composition of Stellite 6 nominal, cast, and welding consumables

Element	Nominal Stellite 6	Nominal Stellite 6B	Cast	Welding Consumable
Ni	3 Max.	2.5	3.00 Max.	3.00 Max.
Cr	28	30	27.0–31.0	26.0–30.0
W	4.5	4	3.5–5.50	3.50–5.50
Fe	3 Max.	3 Max.	3.00 Max.	3.00 Max.
C	1.2	1.1	0.90–1.40	0.90–1.40
Si	2 Max.	0.7	1.50	0.70–1.50
Mn	1 Max.	1.5	1.00	0.50
Mo	1 Max.	1	1.50	1.00
Co	Balance	Balance	Balance	Balance

The reported tensile properties for the cast material at room temperature are yield strength of 78.5 ksi (649 MPa), tensile strength of 130 ksi (896 MPa), and an elongation of 1%. The tensile strengths for investment castings at room temperature are yield strength of 96 ksi (662 MPa), tensile strength of 115 ksi (792 MPa), elongation of 3%, and reduction of area of 3% [3]. The Izod energy (smooth, unnotched sample) was 4 ft-lb (5.4 J) at room temperature for the investment castings. For a two-layer weld deposit, the tensile strength was 110 ksi (758 MPa), and the elongation was 1%.

The mean coefficient of thermal expansion for Stellite 6 is 8.36×10^{-6} per $^{\circ}\text{F}$ (15×10^{-6} per $^{\circ}\text{C}$) from room temperature to 1000°F (538°C) [3]. Figure 4-2 compares the coefficient of thermal expansion for Stellite 6 and the wrought version of Stellite 6B as a function of temperature. Also shown for comparison in Figure 4-2 are the thermal expansion data for 1CrMoV, 12%Cr steels, Refractaloy 26, and Type 316 materials.

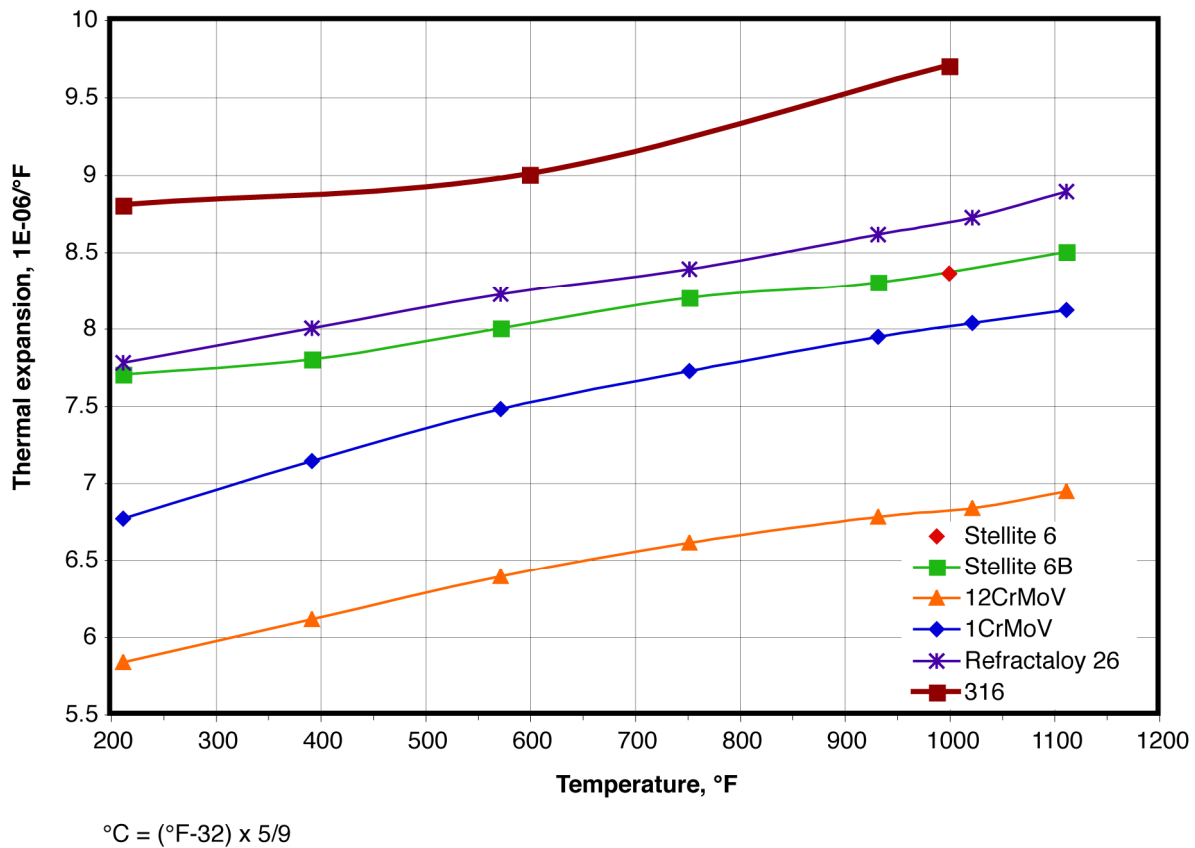


Figure 4-2
Coefficient of thermal expansion for Stellite 6 and 6B as a function of temperature

The simple formula for the calculation of the thermal stress in a dissimilar metal weld is shown in Equation 4-1 [4];

$$S = E \Delta\alpha \Delta T$$

Equation 4-1

Where:

S is the stress.

E is Young's modulus.

$\Delta\alpha$ is the difference in thermal expansion coefficient

ΔT is the temperature difference between the stress free temperature (typically assumed as room temperature) and the operating temperature.

Based on this formula, significantly larger stresses are expected for the welding of 12%Cr steels and the austenitic stainless steels such as Type 316 than for the CrMoV and nickel base alloys. Because of the thermal expansion stresses and the interface structure, a butter layer is sometimes used as the initial weld bead to join dissimilar metal welds (DMWs). For the case of a DMW consisting of modified 9Cr-1Mo base metal, Grade 91, and Stellite 6 weld metal, Velan (2002) has suggested the use of Inconel 625 as the intermediate weld material to lower the thermal expansion stresses.

Figure 4-3 shows a plot of the hardness as a function of temperature based on the Deloro Stellite technical database (<http://www.stellite.com/Technical/AlloyDatabase/tabid/262/Default.aspx>). The data are shown for sand castings, resin shell castings, and Stellite 6B material. The hardness data for Stellite 6B material are from the *ASM Handbook* [5]. The hot hardness value is relatively high, up to the service temperature of about 1112°F (600°C). For weld inlay applications of Stellite 6 material, the effect of dilution on the weldment chemistry and properties is important. Figure 4-4 shows the effect of iron content on the hot hardness of Stellite 6 weldments. At room temperature, there is no effect of dilution. However, as the temperature increases, the effect of the iron content on the reduction in hardness increases.

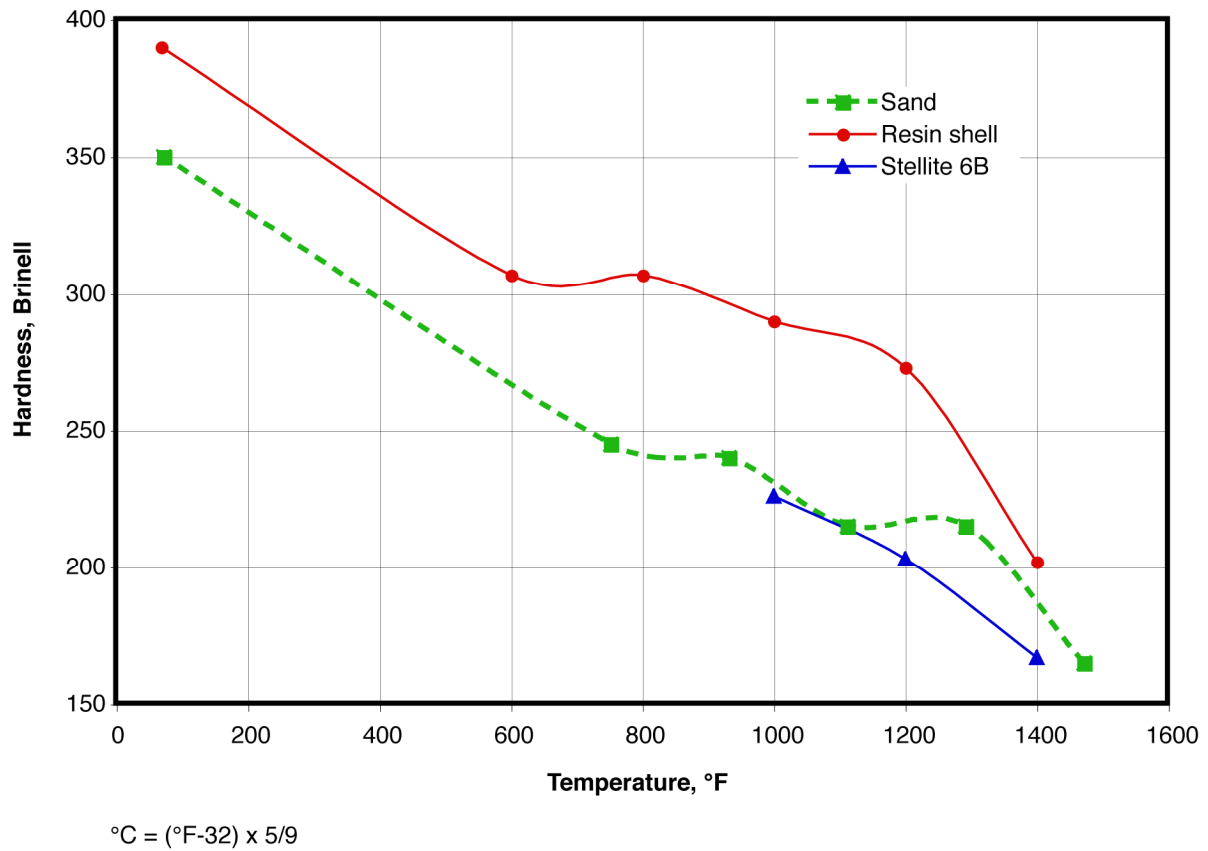


Figure 4-3
Hardness as a function of temperature for cast Stellite 6 and wrought Stellite 6B

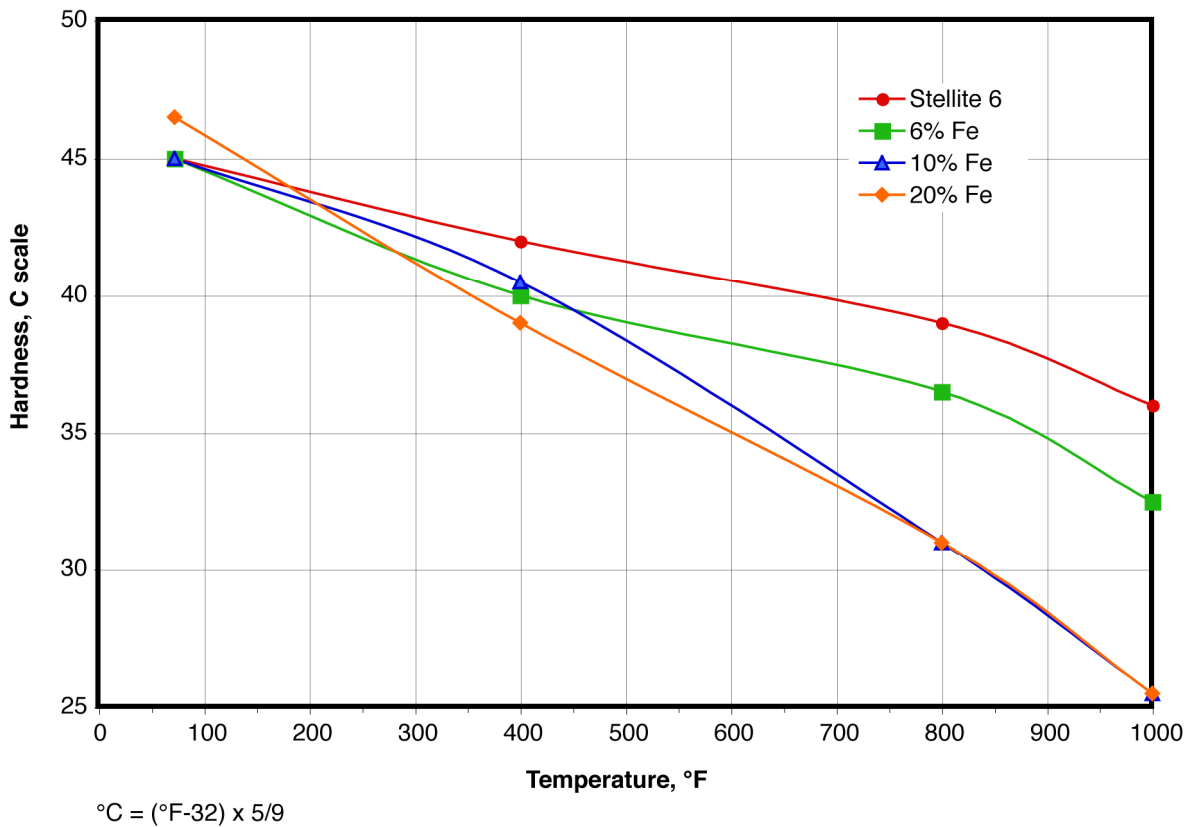


Figure 4-4
Effect of iron content on hardness of Stellite 6 weld deposits as a function of temperature

The microstructures of the various cobalt-based wear-resistant alloys were shown in the *ASM Handbook* [1, 6]. The microstructures were for two-layer GTA weld deposits of Stellite 1, 6, 12, and 21 [1] and PTA two-layer deposits of ERCoCr-C (Stellite 1), ERCoCr-A (Stellite 6), and ERCoCr-E (Stellite 21). The microstructure of a Stellite 6 weld inlay for a steam turbine valve disc is shown in Figure 4-5. The microstructure consists of cobalt-rich, single-phase dendrites and eutectic mixture in the interdendritic regions. The carbides in the matrix are predominantly the M_7C_3 (chromium rich) type. In essence, the microstructure is hard particles embedded in a softer matrix. Tungsten contributes to the solid solution hardening of the matrix.

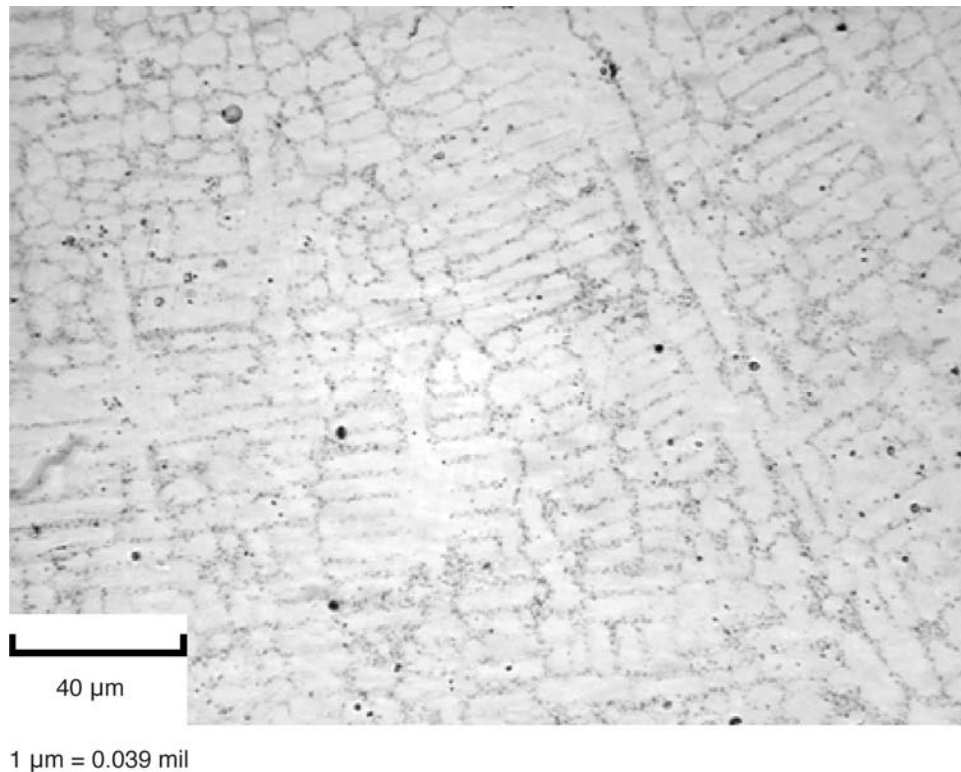


Figure 4-5
Microstructure of Stellite 6 weld metal

The types of wear discussed with reference to the cobalt-base alloys were abrasive wear, sliding wear, and erosive wear [1]. The microstructures and abrasive wear properties of Stellite 6 hardfacing welds have been studied [7]. The welds were deposited using manual metal arc (MMA), tungsten inert gas (TIG), and laser cladding. The microstructures and hardness developed in the welds are a function of the heat input, dilution, and freezing rate for the various processes.

The scale of the microstructure and magnitude of dilution were found to decrease in the order MMA, TIG, and laser cladding (in order of decreasing heat input). The hardness increased in the same order. The abrasive wear resistance is related to the difference in hardness of the abrasive and the component surface. For alumina abrasive (significantly harder than Stellite 6), the wear resistance increased in the order MMA, laser cladding, and TIG. The MMA samples have a coarser microstructure and a lower hardness and are expected to have a lower wear resistance. The difference in mean wear rate for the TIG and laser cladding sample was small.

For valve seats, sliding wear and erosive wear are potential damage mechanisms. Sliding wear occurs when two surfaces are forced together and move relative to each other. The types of sliding wear are fretting, galling, and subsurface fatigue. Of these, galling is of primary importance in the selection of the material for the mating surfaces on the steam turbine seat and disc.

Galling is associated with high contact stresses, such as those found at the seat-to-disc contact area during valve closure. The stresses are sufficiently high in the metal surfaces for galling so that the oxide scale is removed and metal-to-metal contact is possible. Galling and welding are similar processes. The welding process requires scale removal from the sample surface, metal-to-metal contact, and a source of heat. For galling, the heat source is the frictional heating developed by one surface rubbing against another. In essence, the asperities or high spots on one mating surface are welded to the other mating surface to produce the galling damage. Galling is similar to the induction heating and pressure welding process where the parts are heated by induction coils and the mating surfaces forced together under high pressure. Opening the valve results in the fracture of the welded asperities and removal of the material from either the seat or disc.

Galling data were measured for the cobalt-based wear-resistant materials and compared to Hastelloy C-276 and Nitronic 60 (a stainless steel reported to have good galling resistance) [1]. The materials were self-mated. The tests were conducted at a force of 6000 lb (26.7 kN) by twisting cylindrical pins back and forth 10 times through a 120° arc. Results of the tests showed that all of the commonly used cobalt wear-resistant alloys have exceptional resistance to galling.

The primary erosive wear of interest for the steam turbine seat is solid particle erosion (SPE). As noted previously, the rate of SPE is dependent on several factors, including particle velocity; impingement angle; and the shape, size, and hardness of the particles. The SPE resistance of Stellite 6 material is near the middle of the range for various hardfacing alloys and coatings. Several alloys and/or alloy-coating combinations are significantly better than Stellite 6 for SPE including Stellite plus 20% TiC, Stellite 720, Tribaloy 720, and Stellite plus 50% CrC. The chromium carbide coating approach has been shown to be useful for steam turbine stem applications and is discussed in Section 7 in this report.

4.3 AISI Type 316H Stainless Steel Material

Type 316H is an austenitic stainless steel. Type 316 has a molybdenum alloy addition to improve corrosion resistance and creep strength when compared to Type 304 stainless steel. The H version of 316 is intended for elevated temperature applications where optimal creep strength is required. Table 4-3 gives the composition of Type 316H material. The major difference in compositions between standard 316 and 316H is the carbon content, which is a maximum of 0.08 for standard 316. Type 316 and 316H are available in a variety of product forms (bars, forgings, plates, and sheets), and a typical bar specification is ASTM A276.

Table 4-3
Composition of AISI Type 316H stainless steel

Element	Weight Percent
C	0.04–0.10
Mn	2.00
Si	1.00
Cr	16.0–18.0
Ni	10.0–14.0
Mo	2.0–3.0
P	0.045
S	0.03

The specified minimum tensile properties of annealed Type 316H are a yield strength of 30 ksi (207 MPa) and an ultimate tensile strength of 75 ksi (517 MPa). The mean coefficient of thermal expansion from room temperature to 1000°F (538°C) is 9.7×10^{-6} per °F (17.5×10^{-6} per °C). Annealed austenitic stainless steels have good impact toughness even at cryogenic temperatures. At room temperature, the Charpy V-notch impact energy of 316 is 65 to 100 ft-lb (88 to 134 J).

The initial microstructure of Type 316H is an austenite matrix with inclusion stringers and annealing twins. Long-time exposure at elevated temperatures results in precipitation of carbides and other phases such as sigma phase. Sigma phase is known to decrease creep ductility and can also affect rupture strength.

Tensile and creep-rupture properties have been reported by the National Institute for Material Science (NIMS) of Japan for 316H tubes [8]. Testing has also been performed for Type 316 bar [9] and plate material. The typical heat treatment for Type 316 and 316H stainless steel is a solution heat treatment and either an air or water quench depending on the section size. The time for the solution heat treatment is typically 1 hour per inch (1 hour per 25 mm) of thickness, and the solution temperatures range from about 1900°F to 2150°F (1040°C to 1175°C). The hardness values in the NIMS creep data sheets were from 73 to 80 HRB for the Type 316H tubes and from 78 to 84 HRB for the Type 316 bars. Parametric analysis of the creep-rupture data in the NIMS database for Type 316H tubes was performed. The average stress for rupture in 100,000 hours at 1112°F (600°C) was 17.5 ksi. (121 MPa).

4.4 1.25Cr-0.5Mo and 2.25Cr-1Mo Alloy Materials

The low-alloy Cr-Mo ferritic steels are widely used in elevated temperature applications because of their relatively low cost and good properties—tensile, creep, and oxidation [5]. In addition, the lower thermal expansion and higher thermal conductivity compared to austenitic steels make them attractive for thermal cycling operation.

The steels are available in many product forms: bars, tubes, pipes, plates, forgings, and castings. The compositions of the wrought low-alloy ferritic steels are not strongly dependent on product form, and typical compositions for the ASME pipe specifications of 1Cr-0.5Mo, 1.25Cr-0.5Mo, and 2.25Cr-1Mo are given in Table 4-4. The ASTM specifications are nominally the same as the ASME specification except they begin with the letter “A”. The minimum specified strengths for these pipe materials are a yield strength of 30 ksi (207 MPa) and a tensile strength of 60 ksi (415 MPa). The chemical compositions and strength levels of the plate materials are slightly different than those for the pipe material. For example, the 2.25Cr-1Mo plate specification of SA-387 Grade 22-Class 1 has the same minimum yield strength of 30 ksi (207 MPa), but the minimum specified tensile strength is from 60 to 85 ksi (415 to 485 MPa).

Table 4-4
Specified compositions of low-alloy ferritic pipe materials

Element	SA-335-P11	SA-335-P12	SA-335-P22
C	0.15 Max	0.15 Max	0.15 Max
Mn	0.3–0.61	0.3–0.61	0.3–0.60
P (Max)	0.03	0.045	0.03
S (Max)	0.03	0.045	0.03
Si	0.5–1.0	0.5 Max	0.5 Max
Cr	1–1.5	0.8–1.25	1.9–2.6
Mo	0.44–0.65	0.44–0.65	0.87–1.13
Fe	Balance	Balance	Balance

The microstructures of the low-alloy ferritic steels are either ferrite-pearlite or ferrite-bainite. The microstructure depends on the heat treatment. The two primary types of heat treatment are (1) annealed and (2) normalized and tempered.

The typical annealing heat treatment consists of heating to temperatures in the range of 1650°F–1760°F (900°C–960°C) and holding for approximately 1 hour per inch (25 mm) of thickness, followed by furnace cooling to 1100°F (593°C), and then air cooling. Annealed steels have the ferrite-pearlite microstructure.

The normalized and tempered (N&T) heat treatment consists of two steps:
(1) normalizing by heating to temperatures in the range of 1650°F–1760°F (900°C–960°C) and holding for approximately 1 hour per inch (25 mm) of thickness followed by air cooling
(2) tempering at temperatures of about 1180°F–1275°F (640°C–690°C) for 1Cr-1/2Mo and 1.25Cr-1/2Mo steel and about 1200°F–1335°F (650°C–725°C) for 2.25Cr-1Mo. The microstructure of the N&T low-alloy ferritic steels is ferrite-bainite.

There are matching-composition welding consumables for the low-alloy ferritic steels. The welding consumable choices include bare wire, electrodes, and flux cored electrodes. For 1.25Cr-0.5Mo, the typical welding electrodes are AWS 8018-B2 with normal carbon content or the low-carbon version AWS 8018-B2L. For 2.25Cr-1Mo, the typical welding electrodes are AWS 9018-B3 with normal carbon content or the low-carbon version AWS 9018-B3L. Cleaning of the weld joint prior to welding is required. Preheat and postweld heat treatments are typically used. The preheat temperature is about 400°F–600°F (204°C–315°C), and postweld stress-relief heat treatment temperatures are in the range of 1200°F–1300°F (649°C–704°C) for 1Cr-0.5Mo alloy and in the range of 1250°F–1375°F (677°C–746°C) for 2.25Cr-1Mo alloy.

There are numerous publications concerning the low-alloy CrMo ferritic steels. Two reviews are typical of the type of information available. EPRI has a 2-1/4Cr-1Mo alloy handbook [10] that is a relatively comprehensive summary of the mechanical and physical properties. In addition, the microstructure, heat treating, and oxidation behavior are given in the handbook. The elevated temperature properties of low-alloy ferritic steels are reviewed in the *ASM Handbook* [5]. The 2.25Cr-1Mo material was selected as one of the primary materials for the breeder reactor; consequently, significant materials characterization testing was performed in the United States by the national laboratories. The mechanical test results cited in the ASM review include short-term tests, long-term tests, fatigue tests, creep-fatigue tests, ductility, and toughness tests.

In addition to these reviews, ASTM has published data series for the low-alloy ferritic alloys and the National Institute for Materials Science (formerly National Research Institute for Metals) has published data sheets for 1.25Cr-0.5Mo and 2.25Cr-1Mo tube and plate materials. Both the ASTM data series and the NIMS data sheets have the tensile and creep-rupture data for multiple heats of material over a wide range of temperatures and stresses. Rupture data analysis results and microstructure characterization are also given in the NIMS data sheets.

With regard to steam turbine valve damage, one of the most important properties of the low-alloy ferritic alloys is the steamside oxide scale growth and exfoliation. The exfoliated oxide scale from the ferritic tubing in the boiler is the primary source of solid particles for the SPE damage to the steam turbine valves and blades. Several EPRI reports discuss the growth and exfoliation of oxide scales [11, 12].

The initial isothermal growth of oxide scale is parabolic with time. The initial oxide scale has a duplex structure consisting of a dense inner layer and less dense or porous outer layer. For scale grown in a heat flux that is typical of reheat and superheat tubing, the scales become laminated and multilaminated, and the growth rate becomes linear with time.

Single duplex-layer scales are not generally susceptible to exfoliation or spalling. Multi-layered or multi-laminated scales are susceptible to exfoliation. The exfoliation generally occurs between the outer layer (less dense) of the inner portion of the multi-layered scale and the inner layer (dense) of the outer portion. The exfoliation tendency for multi-layered scales is because the outer layers in a multi-layered scale grow under stress.

The EPRI tube manual provides information on a rating scale to evaluate the magnitude of the exfoliation and the conditions required for exfoliation [12]. The exfoliation rating scale goes from a rating of 1 for mild to 5 for severe exfoliation. The rating roughly corresponds to the area fraction of surface exfoliated. The ratings and the corresponding area fraction pairs are the following:

1. 0%
2. (Mild) – 4%
3. (Moderate) – 14%
4. (Severe) – 32%
5. (Very severe) – 41%

As expected, the higher the exfoliation rating, the greater the amount or weight of magnetite that is released.

Operational stresses are a source of strain that causes exfoliation. The lists of operational-related strains are the following:

- Cooling strains associated with differential thermal contraction
- Removal of steady heat flux
- Thermal shock, such as frequent or long duration soot blower operation in fossil plants
- Oxide/oxide transformation
- Tubing system bending strains

Scale thickness and tube metal temperature also play a role in steamside scale exfoliation. Exfoliation typically occurs at a critical scale thickness as a function of applied strain.

The thermal stresses in a Stellite weld depend on the difference in coefficient of thermal expansion between the materials being joined. The mean coefficient of thermal expansion for 2.25Cr-1Mo is given in the EPRI handbook as a function of temperature, and the value is $7.82 \times 10^{-6}/^{\circ}\text{F}$ ($14.1 \times 10^{-6}/^{\circ}\text{C}$) from room temperature to 1000°F (538°C) [10].

4.5 1Cr-0.5Mo-0.25V and 1Cr-1Mo-0.25V Alloy Materials

The physical metallurgy of the chromium-molybdenum-vanadium steels and the development of the turbine rotor and casing materials have been reviewed by Viswanathan [13] and also by Klueh [5]. For rotors, 1Cr-1Mo-0.25V was developed in the 1950s and has continued as an industry standard since that time. The microstructure of Cr-Mo-V steel depends on the heat treatment and section size. For rotors, a normalizing and tempering heat treatment is used, and the typical microstructure is a tempered bainite, specifically, upper bainite.

The materials used for turbine casings changed as the steam temperatures increased and as improved materials/refined compositions became available. For casings, the materials changes were from C-0.5Mo to 1Cr-0.5Mo and from 0.5Cr-0.5Mo-0.25V to 1Cr-1Mo-0.25V. Because of reheat cracks in the heat-affected zone of 0.5Cr-0.5Mo-0.25V, specifications were made to control residual element content, and improved welding procedures were implemented. As a replacement for the 0.5Cr-Mo-V, several manufacturers began using 2.25Cr-1Mo based on perceived higher creep ductility, low-cycle fatigue, and weld repair properties compared to 1Cr-Mo-V casing steel. The maximum operating temperatures were 1000°F (540°C) for 2.25Cr-1Mo and 1050°F (566°C) for 1Cr-1Mo-0.25V and 0.5Cr-0.5Mo-0.25V. The typical microstructure of the casing materials was reported to be ferrite-pearlite [13].

The common turbine and valve casing materials are cast materials and typically are specified by the ASTM A217 and ASTM A356 specifications. The ASTM A217 cast steels include the 1.25Cr-0.5Mo Grade WC6 and the 2.25Cr-1Mo Grade WC9 materials. The ASTM A356 specifications cover a range of steels including carbon steel, CrMo steels, and CrMoV steels [14]. The 1.25Cr-0.5Mo is ASTM A356 Grade 6, and the 2.25Cr-1Mo is ASTM A356 Grade 10. The 1Cr-1Mo-0.25V casting material specification is A356 Grade 9 [2]. There is also a 1Cr-1Mo-0.25V rotor forging material specification of ASTM A470 Grade 8. The forging material has a higher carbon content and tensile strength than the casting grade of 1CrMoV. Table 4-5 gives the nominal chemical compositions of several Cr-Mo-V casing materials. Similar compositions were found for 0.5Cr-0.5Mo-0.25V and 1Cr-1Mo-0.25V turbine piping [15, 16]. The 1Cr-0.5Mo-0.25V steel is common in many countries and is found in cast and wrought forms.

Table 4-5
Compositions of Cr-Mo-V casing materials

Element	0.5Cr-0.5Mo-0.25V	A356 Grade 9	A356 Grade 10
C	0.10–0.15	0.13–0.20	0.20 Max
Mn	0.40–0.60	0.50–0.90	0.50–0.80
P (Max)	--	0.035	0.035
S (Max)	--	0.030	0.03
Si	0.45 Max	0.20–0.60	0.6 Max
Cr	0.40–0.60	1.00–1.50	2.00–2.75
Mo	0.40–0.605	0.90–1.20	0.90–1.20
V	0.22–0.28	0.20–0.35	--
Fe	Balance	Balance	Balance

The minimum specified tensile requirements for A356 Grade 9 material are a yield strength of 60 ksi (414 MPa) and a tensile strength of 85 ksi (586 MPa). The typical heat treatment for A356 Grade 9 material is to normalize it at 1875°F–1925°F (1025°C–1050°C) and temper it at 1275°F–1350°F (690°C–730°C). Tensile and creep-rupture properties are given in the NIMS data sheet for multiple heats of steel castings [17]. The hardness values for the castings on the Rockwell B scale range from 96 to 101 HRB.

The values of the coefficient of thermal expansion were measured for the 1Cr-0.5Mo-0.25V bolting steel over a range of temperatures, and similar values are expected for all of the low-alloy CrMoV steels including 1Cr-1Mo-0.25V steel [18]. A plot of the thermal coefficient of expansion is shown in Figure 4-2, and at 1022°F (550°C) the value is $8.05 \times 10^{-6}/^{\circ}\text{F}$ ($14.5 \times 10^{-6}/^{\circ}\text{C}$).

4.6 Damage Mechanisms

The damage mechanisms for seats were discussed in an EPRI study that developed steam turbine valve diagnostic testing [19]. The damage conditions were given for stems, bushings, seats, and discs. For seats, the list had the following degradation mechanisms:

- Sticking to the valve seat; excessive pull-out force
- Wear of the seating surface
- Short travel due to foreign material on the valve seat preventing closure

The sticking of the valve seat refers to the change in the angle between the disc and the seat due to SPE. Because the seat angle has increased, the normal force between the valve disc or plug and the seat is increased. The wear of the sealing surface is the SPE damage mechanism. The decreased travel due to foreign material on the valve seat has also been reported for steam turbine valves in Japan [20].

Their survey of operating damage mechanisms in steam valves found a relatively high frequency of occurrence for particle clamping (foreign material on valve seat) and also reported many cases of SPE damage. To decrease the tendency for particle clamping, they developed a double-stepped seat design with an inclined flow entry. Based on the results of this study, the primary damage mechanisms identified for steam turbine valve seats are the following:

- SPE
- Stellite weld metal cracking

Several examples of these damage mechanisms are discussed in this section, and the weld repair for the Stellite weld metal cracking is discussed in Section 4.7.

Both SPE and Stellite weld metal cracking were found in the seat of the control valves at a large fossil unit, 850–900 MW. The turbine was a General Electric cross compound turbine, and the main steam temperature was 1050°F (566°C). There were four control valves, and significant SPE was found in the mating discs (discussed in Section 5) as well as the seats. The time in service was estimated as three years, based on the typical maintenance schedule.

Figures 4-6 and 4-7 show the SPE damage found in control valves 1 and 3, respectively. The SPE damage has resulted in significant metal loss and gouged regions for valve 1, which is more severe than the damage found in valve 3. For valve 3, the SPE damage is in the Stellite weld metal at the upper-left side of the figure. The cutting or gouging due to the SPE is oriented in the radial direction, transverse to the Stellite weld.



Figure 4-6
Detailed view of solid particle erosion in the seat of control valve 1



Figure 4-7
Solid particle erosion in the seat of control valve 3

Figure 4-8 shows a photograph of the SPE damage and Stellite weld metal cracking in the seat of control valve 2. There are three transverse weld metal cracks that were detected by liquid penetrant examination. The erosion damage for valve 2 appears to be more severe than that found in the seat of control valve 3 and less severe than that in valve 1. It is the utility's practice to repair transverse weld metal cracks that are in close proximity, such as those shown in the figure. Results of a detailed metallographic examination of cracking in the Stellite weld inlay are discussed in Section 5 on the disc damage mechanism examples.



Figure 4-8
Solid particle erosion and transverse weld metal cracks in the Stellite inlay on the seat of control valve 2

The accumulation of the SPE is related to the amount of entrained particles in the steam as well as the steam quality. The damage rate is typically high on initial valve opening since the quantity of particles is expected to be higher initially, and the steam is expected to have a higher moisture content.

One additional factor in the SPE damage accumulation rate is the number of valves used for admission of steam to the turbine. Higher damage levels are expected for partial arc admission compared to full arc admission operations. The subject turbine was converted in 1999 to full arc admission.

Figure 4-9 shows a photograph of Stellite weld metal cracking in the bypass valve seat of an emergency stop valve. Liquid dye penetrant examination revealed cracking in the circumferential and radial directions. The circumferential cracking is over about 180° and is relatively severe in regions based on the amount of bleedout. No metallographic examinations were performed in this case. However, based on an examination of Stellite weld metal cracking on a disc, the circumferential cracking is expected to be either adjacent to the fusion interface in the Stellite weld metal or at the fusion interface.



Figure 4-9
Stellite weld metal cracks in the bypass valve seat of an emergency stop valve

4.7 Repairs

Weld repairs to damaged/cracked steam turbine valve seats are routinely performed. The decision to repair or replace depends on economics, the nature of the damage, and the location/extent of the damage. For SPE and Stellite weld metal cracking in the seat, weld repairs are usually possible, if access and sufficient undamaged material are available. Two examples of weld repairs are briefly discussed here, but no detailed inspection or welding procedures are given.

Based on the results of inspections and assessments for the damaged control valve seats discussed above, weld repairs were performed. One of the first steps is to remove the damaged material and prepare the area for welding. Figure 4-10 shows the weld prep that was machined on one of the valve seats. The area was cleaned and repair welding was performed using Stellite 6 weld metal. Figure 4-11 shows the completed weld repair.



Figure 4-10
Machined weld prep for the control valve seat repair



Figure 4-11
Weld repair beads on the control valve seat

Figure 4-12 shows a seat for a Westinghouse governor valve that has been weld repaired. The weld repairs are performed in the field, and specialized equipment is needed to perform the machining. Figure 4-13 shows the machining of the governor valve seat. The machined seat is shown in Figure 4-1. Final inspections, bluing, and lapping are the final steps that are required prior to returning the valve seat to service.



Figure 4-12
Weld-repaired seat for a Westinghouse governor valve



Figure 4-13
Machining of a governor valve seat

With regard to applications in nuclear plants, there is an effort to reduce the shutdown dose rates of the light water reactors. A primary contributor to high shutdown doses is the presence of cobalt. As seen in Table 4-1, cobalt is the major element of Stellite. The volume of cobalt that is released during normal operation has a significant effect on radiation field buildup. For this reason, there is an effort to reduce or eliminate cobalt-based hardfacing alloys in nuclear units.

One way to reduce the amount of cobalt released from the turbine valve seats is to perform seat repairs away from the turbine casing. Thus, the valve seat should be removed, and the machining and welding performed outside the valve casing. Also, minor repairs to the seats should not be made with the seat in place. Additional information on this topic can be found in the EPRI report *Radiation Field Control Manual* (1003390).

4.8 References

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5

MAIN AND BYPASS VALVE DISCS

5.1 General Discussion

The mating sealing surfaces for steam turbine valves are the seat and the disc. The sealing surface is a narrow ring of contact between the disc and the seat. As discussed in the previous section, the contact regions for both the seat and the disc are Stellite 6. Most of the disc is made from an alloy that is similar or identical to the valve body material. The disc typically has a semi-hemispherical (actually less than a half of a sphere) or truncated cone geometry in the mating surface region. A sketch of a typical steam turbine disc is shown in Figure 5-1.

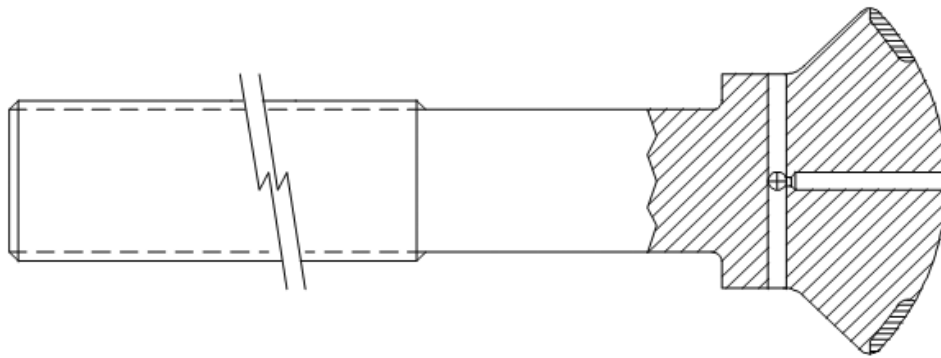


Figure 5-1
Sketch of a typical steam turbine valve disc

The major considerations in material selection for discs are the same as those for seats and include antigalling, wear, oxidation, and thermal expansion. The needed antigalling and wear properties for the sealing surface are attained using a welded Stellite inlay on the disc material. The required oxidation and thermal expansion properties are obtained by using a material for the disc that is nominally the same as the valve body.

The materials used for steam turbine main and bypass valve discs in General Electric and Siemens-Westinghouse at U.S. fossil power plants are given in Table 5-1.

Table 5-1
Main and bypass valve disc materials

General Electric
Nitalloy 135M (135M Nitrided)
1Cr-1Mo-0.25V
2.25Cr-1Mo
AISI Type 316 H Stainless Steel
AISI Type 347 Stainless Steel
Stellite 6
Siemens-Westinghouse
1Cr-0.5Mo
2.25Cr-1Mo
Stellite 6

The alloys for valve discs include Nitalloy, low-alloy ferritic steels, stainless steels, and a cobalt-based superalloy. The alloys used for the valve discs are the same ones that are used for the valve seats except for Nitalloy 135M. The metallurgy and physical properties have been discussed for all of these materials in Section 4. Thus, this section gives information on the damage mechanisms and repairs for discs.

5.2 Damage Mechanisms

The primary damage mechanisms for the main and bypass valve discs are SPE and Stellite weld metal cracking. Several examples of SPE and a typical Stellite weld metal cracking case are discussed in this section.

5.2.1 Solid Particle Erosion

The steamside oxide scale is the primary solid particle responsible for SPE. Screens are used to trap the larger foreign particles prior to their entry into the seat-disc area of the valve. Figure 5-2 shows several foreign objects captured by a throttle valve strainer. Depending on the magnitude and amount of the scale and the time in service, the screens or strainer can become clogged. Figure 5-3 shows a stop valve strainer that was plugged and removed from service.



Figure 5-2
Boiler foreign objects caught in a throttle valve strainer



Figure 5-3
Stop valve strainer plugged by an excessive amount of foreign objects and oxide scale

Two main stop and bypass valve discs or plugs were removed from a large 750-MW fossil unit. The valves were labeled A and B, and the damaged/failed valve discs are shown in Figure 5-4. The General Electric valve design had a skirt to protect the valve stem, and the skirt is missing for the A valve. There is an antirotation lug on the disc seen in the bottom of the figure for disc A. The SPE damage is evident on the surface of the discs in the region between the Stellite weld inlay and the skirt. The erosion is found around the entire circumference, and the damage has the appearance of arc cutting.



Figure 5-4
Failed discs with significant solid particle erosion damage. The discs were removed from a General Electric main stop and bypass valve.
(Courtesy of TVA)

Based on the experience at this unit, the discs have a relatively short service life. Thus, in order to avoid failure, the discs are inspected at about nine month intervals and replaced as needed. In addition to the failure of the main stop and bypass valve disc, there was significant damage to the valve stem, despite the skirted design of the valve.

To mitigate the erosion problem, design and material coating approaches were implemented. Figure 5-5 compares the geometry of the old valve disc design (two golden-colored discs) and the new design. The major change is in the skirt region for the disc. The old design had a uniform cylindrical skirt, but the skirt for the new design is a tapered conical section. The skirt on the new design has a high-velocity oxyfuel or high-velocity oxygen fuel (HVOF) chromium carbide coating that is intended to provide significantly improved SPE resistance compared to the uncoated or bare disc material.



Figure 5-5
Comparison of old and new main stop bypass valve disc designs
(Courtesy of TVA)

In addition, the valve stem shown in Figure 5-6 has a chromium carbide coating at the threaded end connection to the disc. Based on the erosion damage of the old design, the length of the chromium carbide coating is about 2.25 in. (5.7 cm). The coated stem and disc shown in Figures 5-5 and 5-6 were removed after about nine months of service and show no evidence of significant SPE damage.



1 inch = 25.4 mm

Figure 5-6
Chromium carbide coated (HVOF) stem for a main stop and bypass valve
(Courtesy of TVA)

Figures 5-7 and 5-8 show the SPE damage to General Electric control valve discs 1 and 2. These discs are the mating pieces for the damaged control valve seats that were discussed in Section 4. The turbine is a cross-compound turbine, and the unit is 850–900 MW. The operating temperature is 1050°F (566°C), and the time in service is approximately three years.

The damage is found around the entire circumference of the disc and is associated with the full arc admission operation for the control valve. The cutting or erosion of the surface is not uniform, but it is significantly deeper in selected regions as documented in the photographs. Weld repair of this type of SPE damage is possible, but cost (usually justified for discs of this size) is the determining factor.



Figure 5-7
Solid particle erosion damage in control valve disc 1
(Courtesy of TVA)



Figure 5-8
Solid particle erosion damage in control valve disc 2
(Courtesy of TVA)

Figure 5-9 shows the SPE damage for a General Electric main stop valve bypass valve disc. This is also for a cross-compound turbine at a 500-MW plant. The main steam temperature is 1050°F (566°C).

Three relatively deep solid particle eroded regions can be seen in the center of the figure for the disc. No detailed metallographic examinations were performed for any of the solid particle eroded discs.



Figure 5-9
Solid particle erosion damage for a General Electric stop valve bypass valve
(Courtesy of TVA)

5.2.2 Stellite Weld Metal Cracking

Stellite weld metal cracking was found in three discs for the governor valves. There are four discs in each of the two governor valves for a total of eight discs for the unit. Figure 5-10 shows a sketch of one of the governor valves. The four valves work together to control the steam flow to the turbine. The enlarged view shows the location of a typical valve seat and disc that have the weld inlay.

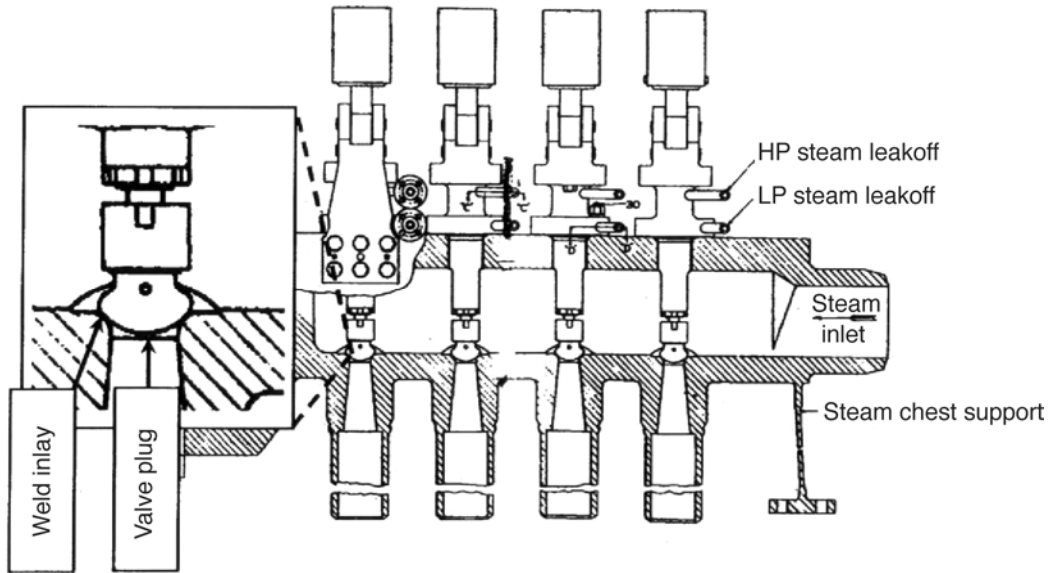


Figure 5-10
Sketch of governor valve and detailed view of valve disc with Stellite weld inlay
 (Courtesy of TVA)

Following the failure of the weld inlay for three discs, all eight of the valve discs were replaced. The failures were in discs 1, 7, and 8. The failure appearance of all three discs was nominally the same, and disc 8 was submitted for metallographic examination. The examination techniques were visual, EDS (energy dispersive spectrometer) chemical analysis of the weld, hardness, and optical metallography. In addition, alloy analysis of the disc base material was performed.

Figure 5-11 shows disc 8 in the as received condition. The weld metal is missing from portions of the disc and other portions are cracked. The fracture surface has an appearance similar to a lack of fusion appearance where the fracture appears to follow the weld beads. Lack of fusion appearance usually indicates that the fracture location is relatively close to or at the fusion interface.



Figure 5-11
Photograph of Stellite weld metal failure for governor valve disc, The sample is shown in as-received condition.
(Courtesy of TVA)

Figure 5-12 shows the two sets of cracks: circumferential and transverse. The primary cracking is the circumferential cracking, and this cracking was found around the entire circumference of the disc. The secondary cracking was the transverse cracks that were found at several locations. Based on the results of the visual examination, the disc was sectioned and ground.

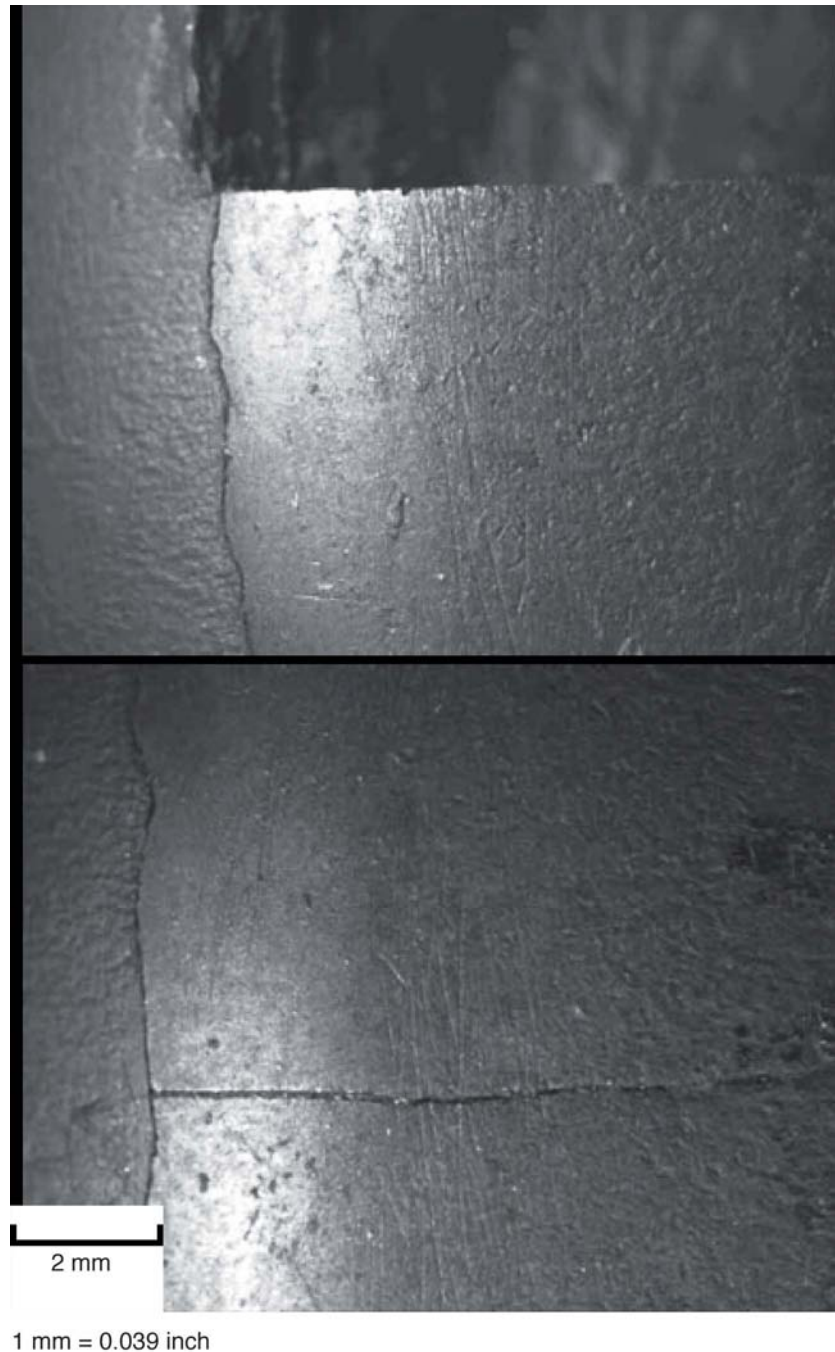


Figure 5-12
Circumferential and transverse weld metal cracking in a governor valve disc
(Courtesy of TVA)

Figure 5-13 shows a cross section through the failed disc and the circumferential cracking in the weld inlay. A more detailed view of one of the weld inlay cracked regions is shown in Figure 5-14. The majority of the crack length was in the root pass weld bead, and there was no evidence of the cracking extending into the base material. As seen in Figure 5-14, the circumferential cracking initiates at the toe of the weld.



Figure 5-13
Cross section of a valve disc showing weld inlay regions
(Courtesy of TVA)

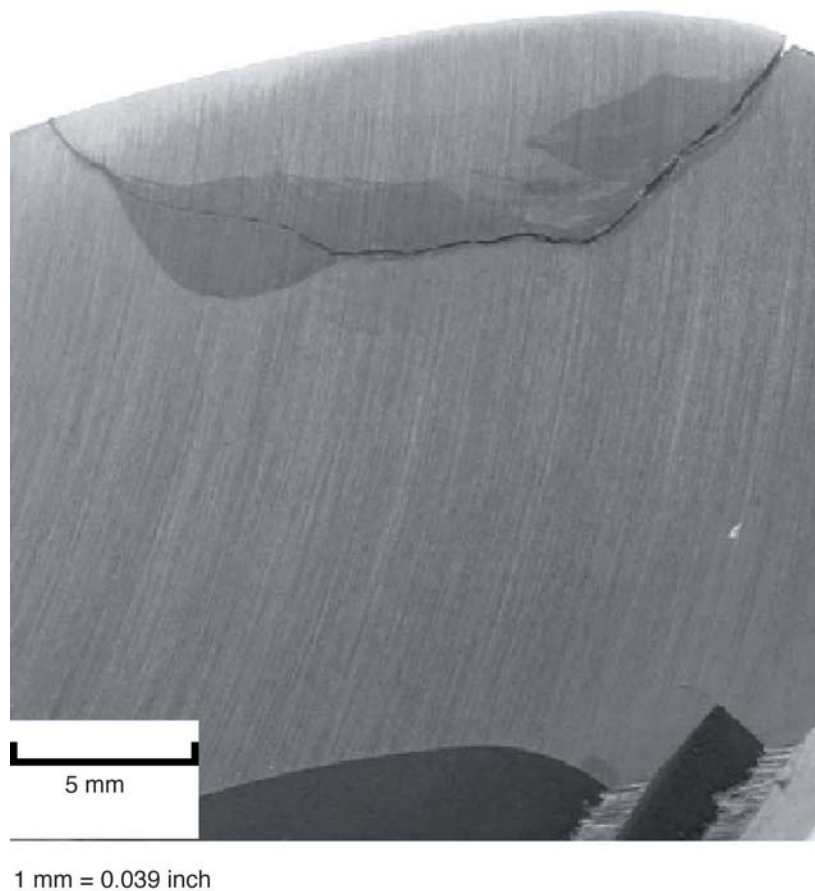


Figure 5-14
Macro view of circumferential cracking adjacent to a fusion interface in weld metal
(Courtesy of TVA)

Figure 5-15 shows the cracking at the toe of the weld. This cracking is adjacent to the fusion interface but is clearly within the weld metal. The cracking is closer to the interface initially, and the distance of the fracture from the fusion interface varies from about 0.0005 to 0.001 in. (about 15 to 30 microns).

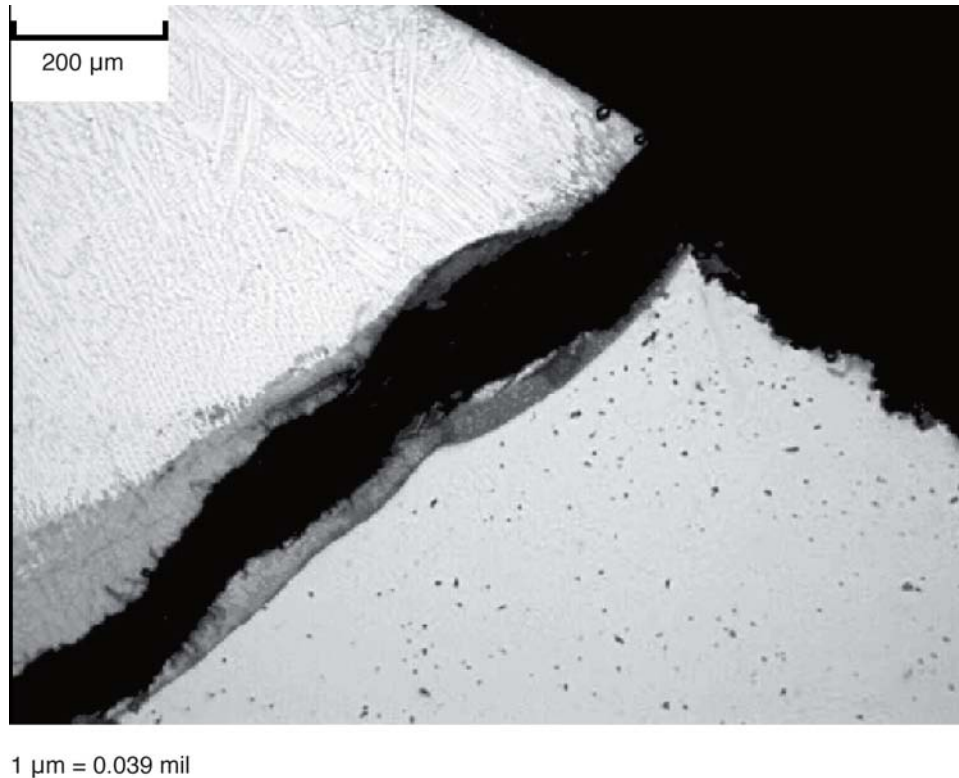


Figure 5-15
Crack initiation site at the toe of a weld
(Courtesy of TVA)

EDS chemical analysis and hardness testing was performed for the weld metal. Figure 5-16 shows the macrostructure of the weld in the area selected for testing. The weld at this position consists of three beads that are numbered 1–3, counting from the outermost to the innermost weld bead. The measured chemical compositions of the weld beads are given in Table 5-2. The nominal composition of undiluted Stellite 6 weld metal and Type 410 stainless steel are also given in the table.

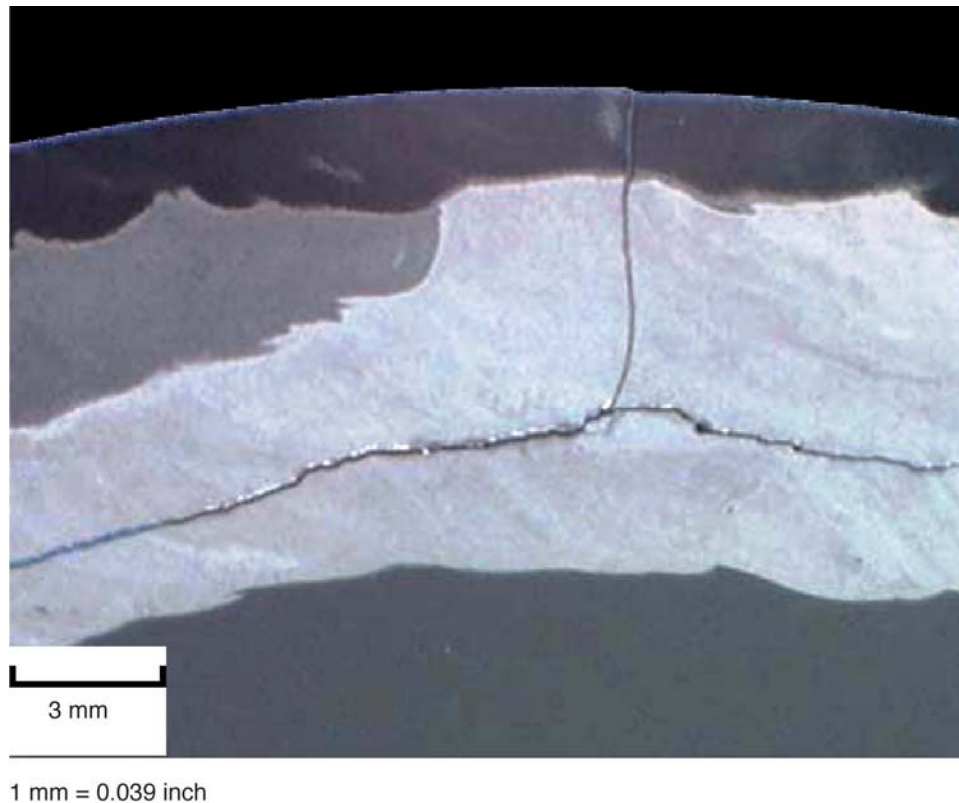


Figure 5-16
Weld beads used in EDS chemical analysis and hardness measurements
 (Courtesy of TVA)

The hardness values for the weld beads were 59–60 HRC, 45–46 HRC, and 48–49 HRC for weld beads 3, 2, and 1, respectively. Weld beads 1 and 2 have hardness values in the range expected for Stellite 6 welds, but the innermost bead 3 is significantly harder than the other beads.

Table 5-2
Weld bead compositions

Element	Bead 1	Bead 2	Bead 3	Stellite 6	410 SS
Co	49.6	39.1	29.6	61	0
Cr	29.5	26	25.7	28	12
W	4.1	3.7	3.3	4.5	0
Fe	15.5	30.2	40.2	3	88

The basic question for any failure analysis is *why did the failure occur?* Several possible failure mechanisms and contributing factors are viable. The conclusion given in the report is based on the high levels of iron found in the welds and the maximum limit of 3% iron for the Stellite materials such as Stellite 6 and Stellite 21. The analysts considered the iron levels too high to be the result of dilution. Thus, it was concluded that the brittle failure (consistent with the high

hardness of the root pass weld) was the result of the use of a Fe-Co type weld material that is inferior to the Stellite materials that are typically used for this application. To study the question of dilution, calculations were performed to estimate the level of dilution.

Dilution is defined as the change in composition of a weld filler metal caused by the admixture of the base metal or previously deposited weld metal. Figure 5-17 shows a bead on a plate weld, and the definition of weld metal dilution is based on areas A (above the surface of the plate) and B (below the surface of the plate) [1].

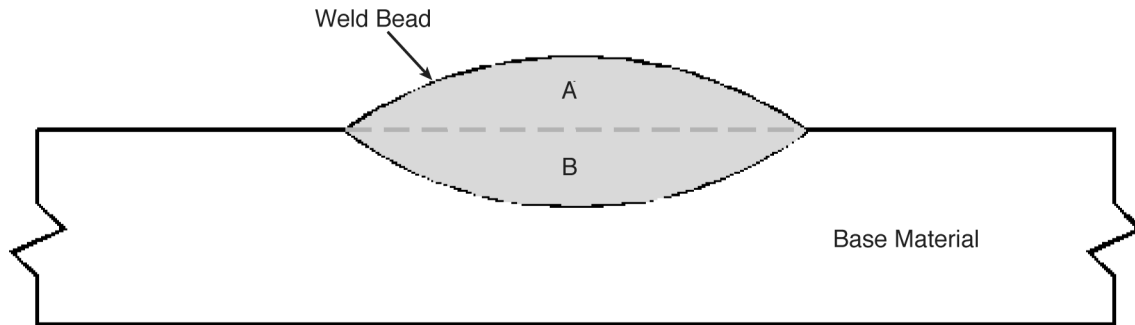


Figure 5-17
Weld metal dilution for a bead on a plate weld

Dilution is defined by Equation 5-1.

$$\text{Dilution} = B/(A + B) \quad \text{Equation 5-1}$$

In essence, dilution is the area fraction of base metal. Several conditions were used in the dilution calculation. First, the area fractions and volume fractions are expected to be equal. Second, the sum of the area fraction of the base and the area fraction of the weld is 1 as given in Equation 5-2.

$$V_{FW} + V_{FB} = 1 \quad \text{Equation 5-2}$$

Where:

V_{FW} is the volume fraction of the weld metal.

V_{FB} is the volume fraction of the base metal.

The composition of the weld bead, C , is given in Equation 5-3.

$$C = V_{FW}C_W + V_{FB}C_B \quad \text{Equation 5-3}$$

Where:

C_W is the composition of the weld metal.

C_B is the composition of the base material.

Using the two equations given above, the following relation in Equation 5-4 is obtained:

$$C - C_W = V_{FB}(C_B - C_W) \quad \text{Equation 5-4}$$

The objective is to find the best value for the dilution (V_{FB}) based on chemistry. The least squares regression method was used

Using the above equation and the compositions for weld bead 3, Stellite 6 weld metal, and Type 410 stainless steel base material given in Table 5-2, a linear least squares regression analysis was performed. The results of the analysis for weld bead 3 gave a value for dilution of 0.456, and a standard error of the estimate (SEE) in composition of 3.695.

Figure 5-18 compares the calculated and observed composition for weld bead 3 based on the results of the dilution calculation. Similar regression analyses were performed for the other weld beads, and the results are given in Table 5-3.

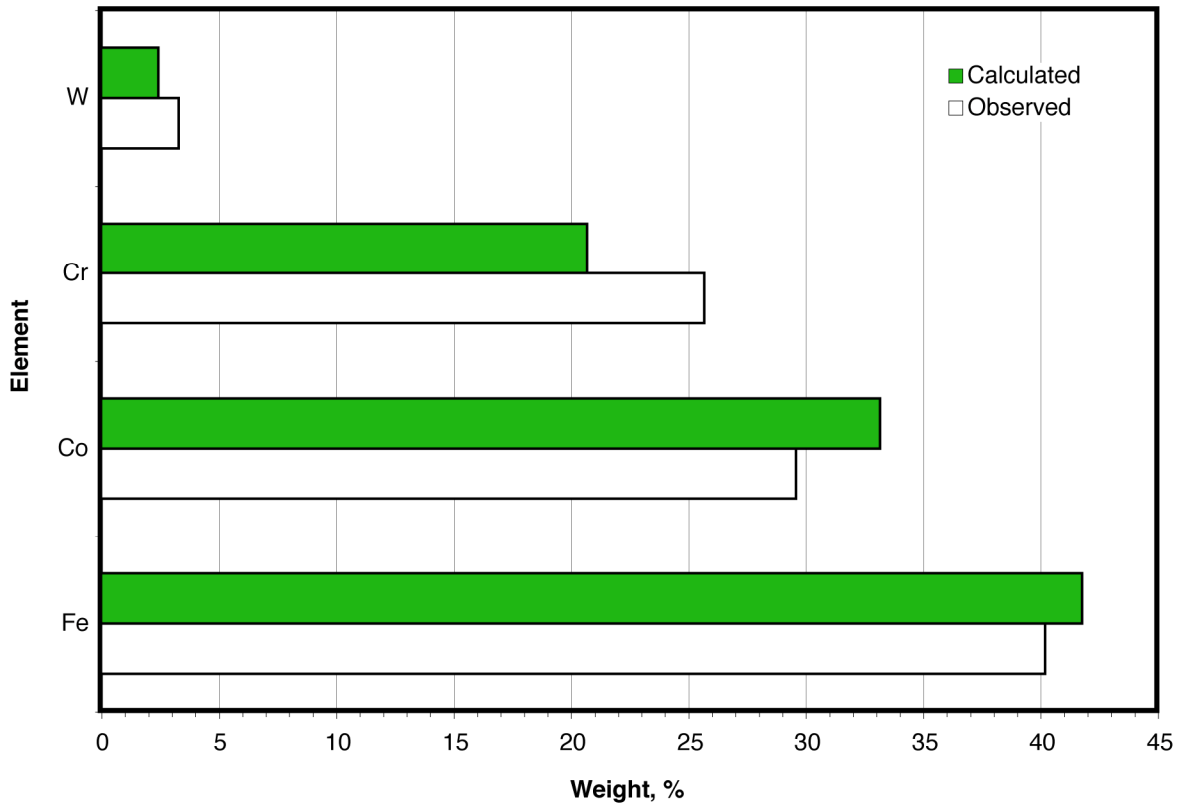


Figure 5-18
Comparison of the calculated and observed composition of weld bead 3 based on a dilution calculation

Table 5-3

Values for weld metal dilution based on a regression analysis of energy-dispersive-spectrometer- (EDS-) measured compositions

Base	Weld	Weld Bead	VFB	SEE
Type 410	Stellite 6	3	0.456	3.695
Bead 3	Stellite 6	2	0.718	0.510
Bead 2	Stellite 6	1	0.480	1.544

Based on the results of the regression analysis for weld metal dilution and the measured composition of the beads, it is believed that the weld metal was Stellite 6.

A definitive failure analysis is beyond the scope of the current review. Nevertheless, several factors are believed to have contributed to the failure. First, the microstructure very near to the fusion interface in Stellite 6 welds (within about 6 micro-inches (6×10^{-6} in.) [150 nm]) is complex, based on the characterization study of Burke et al.[2]. The crack location, about 0.0005 to 0.001 in. (10 to 30 microns) from the interface, is well beyond the microstructurally complex zone very near the interface. This crack location is consistent with the effect of the iron dilution on the properties of Stellite weld metal and a partially mixed zone adjacent to the interface. Second, high thermal expansion stresses are expected for the 12% Cr base material to Stellite DMWs (dissimilar metal welds), based on the difference in thermal expansion for the two materials.

5.3 Repairs

The weld repair of discs is possible and is routinely performed. Weld repairs have been done by a variety of sources including OEMs, turbine component repair facilities, and service shops of utilities. The repairs are essentially part manufacturing and require procedures for welding, heat treating, and machining. For SPE damage, a weld build-up repair is often used. Figure 5-19 shows a disc with an extensive weld build-up repair.



Figure 5-19
Disc with a weld build-up repair

5.4 References

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6

PRESSURE SEAL HEADS

6.1 General Discussion

The pressure seal heads hold the bushings in place and are typically welded to the valve body. The geometry of the pressure seal heads for steam turbine valves is a hollow cylinder.

The primary considerations in material selection for the pressure seal heads are oxidation and thermal expansion. The oxidation and thermal expansion requirements are satisfied using a material for the pressure seal head that is nominally the same as the valve body.

The materials used for the pressure seal heads in the steam turbine valves of General Electric and Siemens-Westinghouse at U.S. fossil power plants are given in Table 6-1.

Table 6-1
Pressure seal head materials

General Electric
1Cr-1Mo-0.25V
2.25Cr-1Mo
AISI Type 316 H Stainless Steel
AISI Type 347 Stainless Steel
Siemens-Westinghouse
1Cr-0.5Mo
2.25Cr-1Mo

Because the metallurgical information for the pressure seal head materials has been discussed previously, this section discusses only the damage mechanisms and repair techniques.

6.2 Damage Mechanisms and Repairs

Circumferentially oriented cracks have been found at tight radius locations on the pressure seal heads. Only visual examination of the cracks has been performed; consequently, no definitive failure mechanism has been determined. The typical repair for these cracks is to recontour or radius the damaged area with a larger radius than the original design. Based on the field repairs, the depth of the cracks is shallow. One possible failure mechanism is thermal-mechanical fatigue. Weld repairs have been performed on stainless steel pressure seal heads for the case of repeated cracks in the radius regions.

7

ALTERNATIVE MATERIALS

7.1 General Discussion

Based on service experience, literature reviews, and the results of oxidation tests, several alternative valve part materials were selected as potential alternative valve materials. The oxidation tests were conducted on both the current and candidate valve part materials and coatings.

The alternative materials discussed in this section are for the stems and bushings. The alternative materials for the steam turbine stems and lift rods are the following:

- Inconel 718 – nitrided
- Thermal spray coating (HVOF) of chromium carbide applied to 422 stainless steel,
- National Aeronautics and Space Administration (NASA) PS304 self-lubricating coating
- Maglon enhanced vacuum coating

The alternative materials for the bushings are solid Stellite 6 and weld build-up Stellite. The alternative materials for steam turbine valves are summarized in Table 7-1.

Table 7-1
Alternative materials for steam turbine valve parts

Stems
Inconel 718 – Nitrided
Chromium Carbide Coating on 422 Stainless Steel
Lift Rods
NASA PS304 Self-Lubricating Coating
Maglon Enhanced Vacuum Coating Process
Bushings
Solid Stellite 6
Weld Build-Up Stellite

This section discusses results of the oxidation testing, the metallurgical structure and properties of Inconel 718, the solid and weld build-up Stellite bushings, and the three coating materials named in Table 7-1.

7.2 Oxidation Tests on Bare and Coated Valve Materials

TVA initiated a program designed to increase the time between overhauls (TBO) and reduce the costs of steam turbine valve parts. In order to increase the TBO, valve materials with a longer life are required. A review of TVA's outage and maintenance reports revealed three problem areas for high-temperature steam turbine valves:

- Oxide buildup in clearance openings, resulting in binding
- Bending or distortion of valve parts
- Wear of mating surfaces

Improvements in the life of valve parts can be obtained through the use of materials with better oxidation and wear properties than those given by the currently available materials and coatings. The current industry standard for hardfacing or coating materials used to produce a wear-resistant surface for valve parts is nitriding or Malcomizing.

One of the first steps in the TVA program was to identify candidate material and coatings that were expected to provide improved wear and oxidation properties. Many of the coatings selected were proprietary, and the data properties were not available. Thus, TVA decided to conduct oxidation tests on materials of interest to rank the various alloy and coating options and provide a basis for selection of alternative materials and coatings for plant application. Three of the alternative materials given in Table 7-1 were selected based on the results of the oxidation testing and other engineering considerations.

Oxidation tests were performed on a variety of steam turbine valve materials [1]. The tests were conducted at 1200°F (649°C) in air, and the maximum test time was 1000 hours. To determine the effect of the nitrided surface and various coatings, the tests were conducted on bare alloys and the same alloys that were nitrided and had various coatings applied to the outside surface of the test samples. The steam turbine valve materials and coatings are given in Table 7-2.

Table 7-2
Turbine valve materials and coatings for oxidation study

Valve Materials	Coatings
F22 – 2.25Cr-1Mo	Nitride
135M	Turbine Metal Technology (TMT) 2413A Aluminide
AISI Type 347H Stainless Steel	TMT 2813L NiAl
AISI Type 410 Stainless Steel	TMT Super 300
AISI Type 422 Stainless Steel	TMT Boride (1568)
Nitronic 60	Sermatech diffused coating (SDC) boride (1577)
Incoloy 901	
Inconel 718	
Refractaloy 26	
Stellite 6B	

All of the coatings except the nitride were applied using proprietary chemical vapor deposition (CVD) techniques. The 2413A aluminide coating is an aluminum diffusion coating; the expected thickness is in the range of 0.00015–0.0035 in. (3.8–89 microns). The TMT 2813L is a low-temperature diffusion coating of Ni-Al, approximately 0.0005–0.0008 in. (13–20 microns) in thickness. The Super 300 is a manufacturer's trade name, and the nominal thickness is 0.008–0.035 in. (200–890 microns). The boride coatings are diffusion coatings of boron, and the nominal thickness is about 0.001–0.0035 in. (25–89 microns).

The oxidation test samples were cylinders that were 0.5 in. (12.7 mm) in diameter and 2 in. (50 mm) long. Not all combinations of alloy and coating were tested. Those material and coating combinations selected for testing were considered to offer a high probability of improvement.

The test samples were placed in ceramic crucibles, weighed, and then held for 125 hours at 1200°F (650°C) in the furnace. The samples were allowed to cool in the furnace, removed, and weighed again. The total accumulated test time was 1000 hours.

Results of the oxidation tests are shown in Figure 7-1 and 7-2. The results for 135M show that the nitrided steel has better oxidation resistance than the bare material, as expected. The 2813L coating essentially eliminated oxidation in air, and the other coatings were also effective.

The control material was the forged 2.25Cr-1Mo F22 material. For the F22 material, the oxidation behavior of the nitrided material was slightly worse than the bare material, and the bare F22 material was slightly worse than the nitrided 135M material. The 2813L coating essentially eliminated the oxidation of the 135M and F22 materials at these test conditions.

For the AISI Type 347H stainless steel, there was essentially no weight gain for the bare or coated steel. Figure 7-2 shows the plot for weight gain in percent versus time for the 135M (bare and nitrided), 2.25Cr-1Mo (bare and nitrided), 422 stainless steel (nitrided), and Incoloy 901 material (nitrided). The oxidation kinetic is linear for all except a possible parabolic rate for the nitrided 135M material. Linear oxidation kinetics are expected for the nonprotective oxide scales.

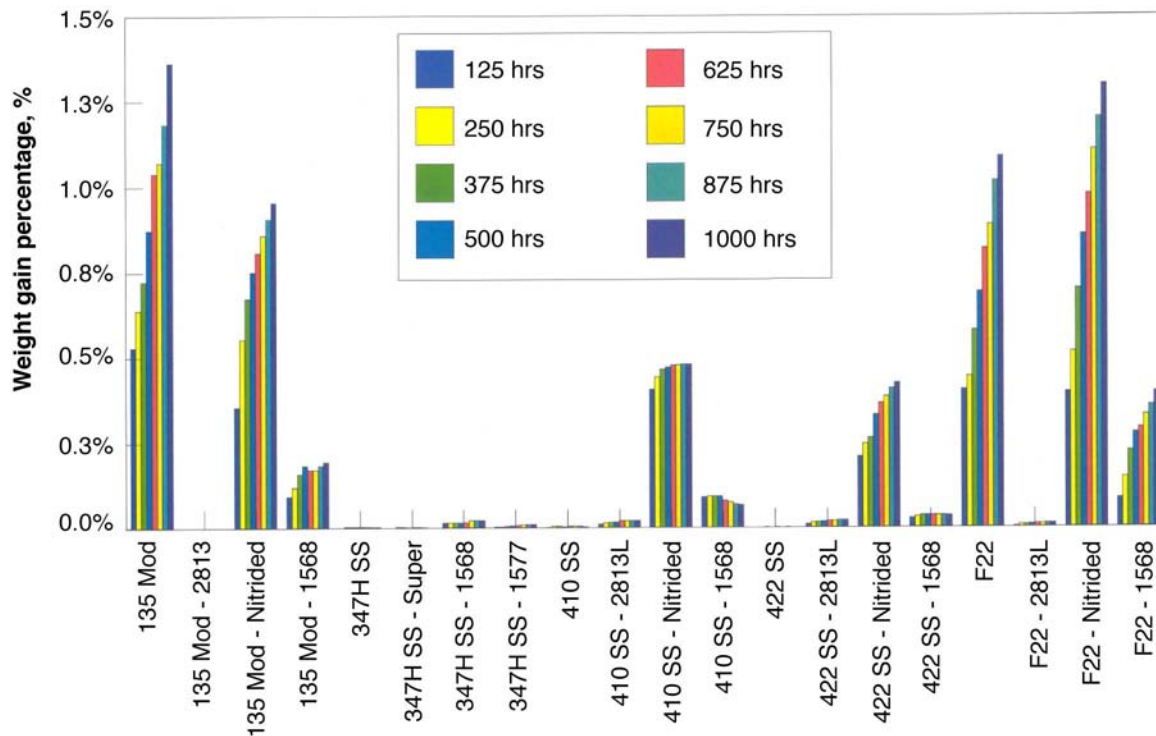


Figure 7-1
Weight gain for low-alloy and stainless steels at 1200°F (650°C) for bare and coated steels
 (Courtesy of TVA)

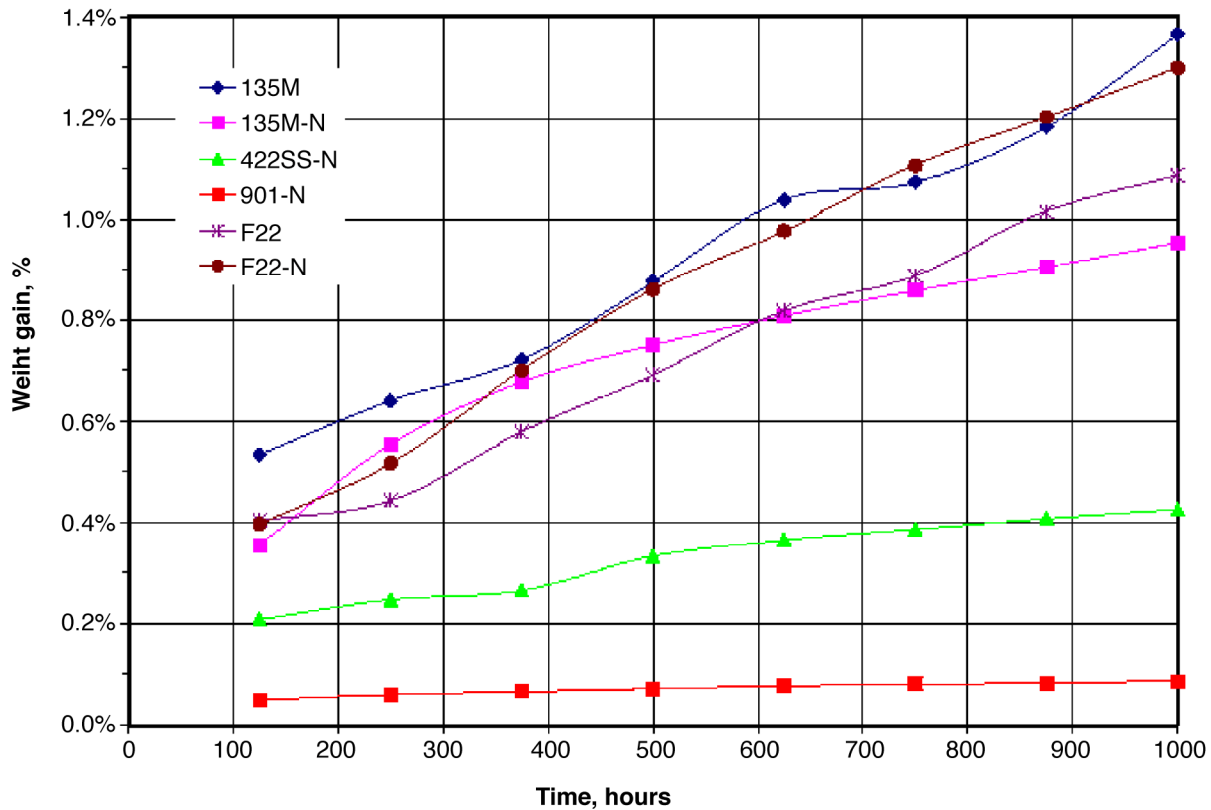


Figure 7-2
Weight gain versus time for bare and nitrided steels

For the martensitic stainless steels (AISI Type 410 and 422), the nitrided steel had the highest weight gain, as expected (based on the iron nitrides in the nitrided layer as discussed in Section 2), and—somewhat unexpectedly—the bare steel had slightly better oxidation resistance than the coated steels. The 2813L coating provided oxidation resistance about equal to that of the uncoated martensitic stainless steels. The improved oxidation behavior of the bare AISI Type 422 indicated that the use of 422 without a nitride coating would provide improved service for stems. To provide wear protection and some possible additional oxidation resistance, an HVOF coating was applied to the AISI Type 422 stainless steel. This HVOF 422 stainless steel is one of the alternative materials that has been applied in service and is discussed in detail in Section 7.4.

The results of oxidation tests on the four superalloys and the Nitronic 60 stainless steel showed that all of these materials had very good oxidation resistance at 1200°F (649°C). The maximum weight gain was about 0.1% for nitrided Incoloy 901. Based on the oxidation test results and the mechanical and physical properties, Inconel 718 was selected as an alternative material for stems in steam turbine valves.

7.3 Inconel 718 Material

Inconel 718 (UNS N07718) or Alloy 718 is precipitation-hardening nickel-based alloy. The chemical composition of Alloy 718 is given in Table 7-3. The matrix is the nonmagnetic gamma phase (face-centered cubic unit cell) found for all nickel-based superalloys. The typical elements found in solid solution are iron, cobalt, molybdenum, and chromium. The two precipitation strengthening phases are γ' (ordered face-centered cubic structure with formula $\text{Ni}_3(\text{Al}, \text{Ti})$) and γ'' . The γ'' phase is the primary strengthening particle for Alloy 718 and has the formula $\text{Ni}_3(\text{Nb}, \text{Al}, \text{Ti})$. The γ'' phase has an ordered body-centered tetragonal crystal structure and is coherent with the gamma matrix. The strengthening due to the γ'' phase is partly the result of the large mismatch strain in the range of 2% with the gamma matrix.

Table 7-3
Composition of Alloy 718

Element	Alloy 718
C	0.08 Max.
Mn	0.35 Max.
Si	0.35 Max.
Ni (plus Co)	50.00–55.00
Cr	17.00–21.00
Nb (plus Ta)	4.75–5.50
Mo	2.80–3.30
Ti	0.65–0.80
Al	0.20–0.80
Co	1.00 Max
P	0.015 Max.
S	0.015 Max.
Cu	0.30 Max.
B	0.006 Max.
Fe	Balance

The physical and mechanical properties were briefly reviewed in an ASM data sheet and an EPRI bolting guideline [2, 3]. There have been two heat treatments used for Alloy 718 [2]. The usual heat treatment produces a fine grain size and a material with high tensile strengths and good high-cycle fatigue properties. The heat treatment has three steps:

1. Anneal at 1700°F–1850°F (925°C–1010°C), and air cool or faster cooling.
2. Age at 1325°F (720°C) for 8 hours, and furnace cool to 1150°F (620°C).
3. Hold at 1150°F (620°C) for a total aging time of 18 hours, and then air cool.

Because of the precipitation reactions, the alloy has a size change following aging, a contraction of about 0.008 in/in (0.008 mm/mm). The second heat treatment has a higher annealing temperature compared to the first, which produces a coarser grain size microstructure than the first heat treatment. The steps for the second heat treatment are:

1. Anneal at 1900°F–1950°F (1035°C–1065°C) and air cool or faster cooling.
2. Age at 1400°F (760°C) for 10 hours, and furnace cool to 1200°F (650°C).
3. Hold at 1200°F (650°C) for a total aging time of 18 hours, and then air cool.

Alloy 718 is available from many manufacturers (for example, Carpenter, Haynes, and Allvac) in a variety of product forms (bars, forgings, rings, strips, sheets, and plates) and to AMS, ASTM and ASME specifications. The bar and forging specifications are ASTM B 637, AMS 5662 (solution treated), AMS 5663 (solution and precipitation treated), and AMS 5664. The General Electric specification for bars, forgings, and rings is GE B50TF15A.

The specified minimum tensile properties for the bars and forging given the lower temperature solution and aging heat treatment (ASTM B 637, AMS 5662, and AMS 5663) are a tensile strength of 180 ksi (1241 MPa), a yield strength of 150 ksi (1034 MPa), an elongation of 6%–12%, a reduction of area of 8%–15%, and a hardness of 35 HRC (331 HB). The specified minimum tensile properties for the bar and forging, given the higher temperature and aging solution heat treatment (AMS 5664), are a tensile strength of 180 ksi (1241 MPa), a yield strength of 150 ksi (1034 MPa), an elongation of 10–12%, a reduction of area of 12%–15%, and a hardness of 37 HRC (341 HB).

Both the ASM data sheet and the EPRI guide provide a summary of the physical and mechanical properties including density, thermal conductivity, coefficient of thermal expansion, modulus of elasticity, tensile properties, and ASME allowable stress values [2, 3]. The mean coefficient of thermal expansion as a function of temperature is given in Table 7-4. The coefficient of expansion for all of the superalloy materials that are used as stem materials was shown in a plot in Section 2. The tensile strengths and elongation of Inconel 718 is given in Table 7-5. The values are given as a function of temperature for a bar material given the precipitation hardening heat treatment with the lower solution temperature of 1800°F (982°C) [2].

Table 7-4
Physical properties of Alloy 718 material

Temperature	Temperature	Coefficient of Thermal Expansion From 70°F (21°C) to Temperature	
°F	°C	10 ⁻⁶ /°F	10 ⁻⁶ /K
-320	-196	5.9	10.6
70	21	--	--
200	93	7.3	13.1
400	204	7.5	13.5
600	316	7.7	13.9
1000	538	8.1	14.6
1200	649	8.4	15.1
1400	760	8.9	16.0
1600	871	9.5	17.1
1800	982	9.8	17.6
2000	1093	10.0	18.0

Table 7-5
Average tensile properties of Alloy 718 material

Temperature °F (°C)	Tensile Strength ksi (MPa)	Yield Strength ksi (MPa)	Elongation %
70 (21)	210 (1448)	175 (1207)	22
400 (204)	198 (1365)	163 (1124)	20
800 (427)	191 (1317)	156 (1076)	19
1000 (538)	185 (1276)	155 (1069)	18
1200 (649)	168 (1158)	149 (1027)	19

Many research projects have been performed on Inconel 718 by the U.S. national laboratories; universities; and various steam turbine, gas turbine, and jet engine manufacturers. In addition, several themed and continuing symposia have been devoted to superalloy 718; superalloys in general; and superalloys 718, 625, and various derivatives. The Minerals, Metals, and Materials Society (TMS) has published these conference proceedings and has made copies of many of these publications available on their website for free downloads. The results of typical U.S. national laboratory studies include reviews on the fatigue properties [4], creep and rupture properties [5], fatigue crack propagation [6], and welding [7]. One advantage of Alloy 718 is that it can be welded in either the solution or the aged condition.

With regard to steam turbine stems, TVA has installed Inconel 718 stems on two emergency stop valves at one fossil plant. The Inconel 718 stems are nitrided for antigalling and wear resistance. The valve stem vendor has reported that Inconel 718 does not take the nitriding treatment as well as Incoloy 901. The Inconel 718 stems were installed in 2002, and they have been inspected at two subsequent valve outages. Results of the inspections revealed no evidence of significant service-induced damage such as excessive oxidation/scaling, excessive run out or bending, or cracking.

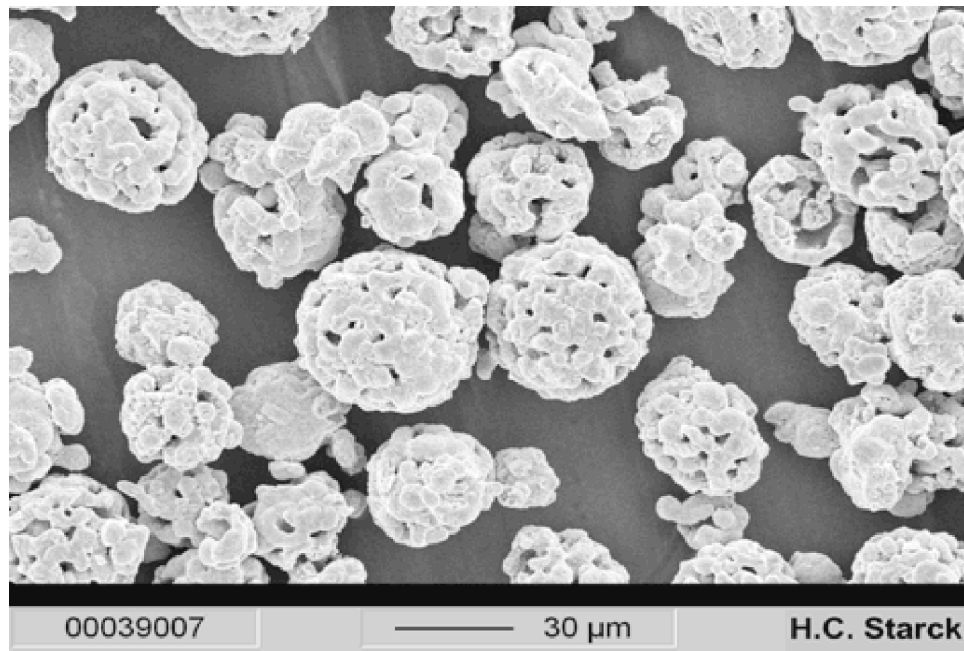
7.4 HVOF Chrome Carbide Coating

Prior to discussing the application of the chrome carbide coating for steam turbine valve stems, a general discussion of thermal spray coatings and HVOF coating microstructures and the results of several studies on coating properties and microstructure are included.

Thermal spray is the term applied to a number of processes that are used to apply metallic or nonmetallic coatings to the surface of a component [8]. Based on the energy source used to heat the coating materials, the processes are in three categories:

- Flame spray
- Electric arc spray
- Plasma arc spray

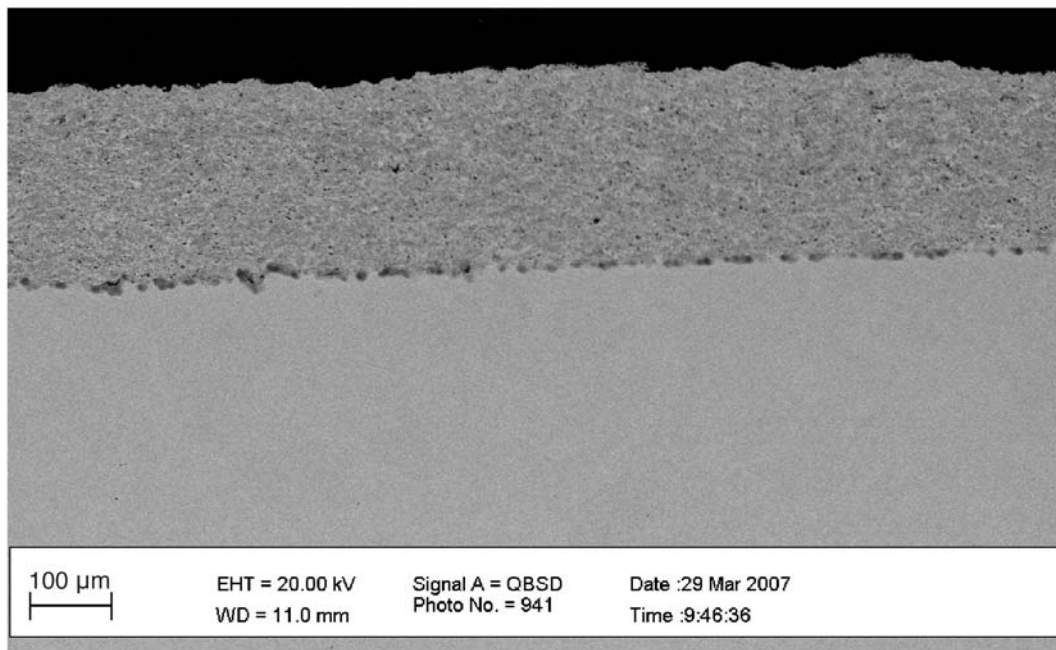
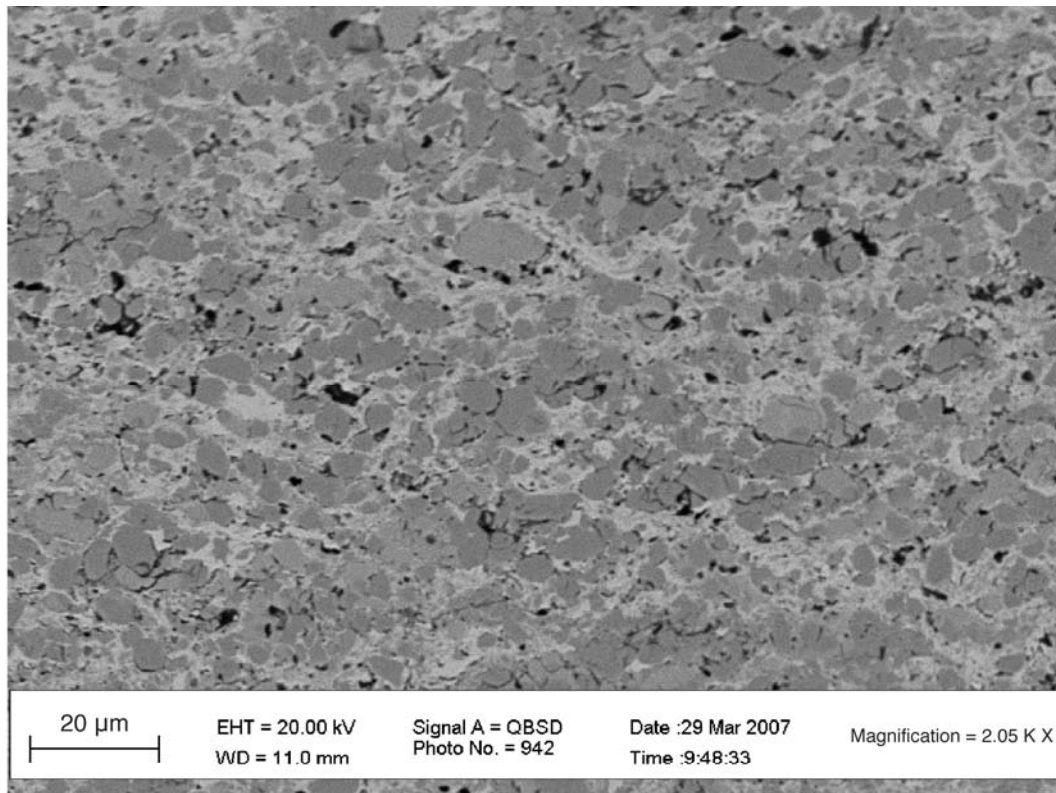
The HVOF process used for the steam turbine valve stem application is one of the flame spray processes. In all of these processes, the coating material, typically fine particles or wire, was heated to temperatures near or above the melting temperature and then propelled rapidly onto the component surface. Figure 7-3 shows a photograph of the Cr_3C_2 – NiCr agglomerated and sintered particle mixture used for the steam turbine valve stem application. The combustion jet temperature for HVOF is about 4500°F–5600°F (2500°C–3100°C).



1 μm = 0.039 mil

Figure 7-3
Photograph of the Cr₃C₂ – NiCr agglomerated and sintered particle mixture

The acceleration is achieved through the process gas or atomization jets [8]. The particle impact velocity for the HVOF process is about 2000–3500 ft/s (610–1060 m/s). As the molten or semimolten particles impact the surface, a bond is formed and a layered or lamellar structure is developed. The individual particulates are termed *splats*, and the cooling rate for these splats is very high, typically greater than 10^6 K per second. Figure 7-4 shows the lamellar microstructure consisting of splats for the HVOF chrome carbide coating on AISI Type 422 stainless steel. The microstructure has dark oxide inclusions, voids/porosity, and partially melted particles. The long axis of the splats and the oxide inclusions are parallel to the component surface.



1 μm = 0.039 mil

Figure 7-4
Lamellar microstructure consisting of splats for the HVOF chrome carbide coating on AISI Type 422 stainless steel.
 (Courtesy of TVA).

Davis [8] has compared the process parameters and expected coating properties for the various thermal spray processes. On a scale of 1 to 10 (low to high), the HVOF process had a rating of 8 for adhesive strength and 5 for cost. The other properties for the HVOF process were a very high cohesive strength for the coating and an oxide content of 0.2%. The oxide content for HVOF coatings is typical of the high-velocity processes done in air.

Mann and Prakash [9] have studied the friction and wear characteristics of high-temperature coatings for the application to a steam turbine valve spindle or stem. The techniques used to provide wear-resistant surfaces include stelliting, nitriding, and thermal spray coatings. The thermal spray coating materials were chrome carbide (Cr_3C_2), chrome oxide, NiCrAlY, and $\text{Al}_2\text{O}_3 + \text{NiAl}$. All stelliting, nitriding, and thermal spray coatings were applied to X20CrMoV121 steel, a 12Cr-1Mo-0.3V (CrV) martensitic stainless steel. The thermal spray coatings were applied using the plasma spray process and the detonation gun process. Gas nitriding was used, and the thickness of the nitrided layer was 0.010 in. (250 microns). The stelliting welding was performed using the shielded arc process with Stellite Grade 6 electrodes, and the thickness of the weld deposit (three layers) was about 0.25 in. (6-7 mm).

The friction and wear tests were conducted at 1022°F (550°C) by rubbing the coated CrV steel against graphite-filled Stellite steel [9]. Based on the results of the testing, they concluded that chromium carbide coating by plasma spraying was superior to all other coatings except chromium oxide for the graphite lubrication conditions. The graphite fills in the pores, and the volume percent porosity is greater for the plasma-sprayed chrome carbide than for the detonation gun chrome carbide. The thermal cycling behavior of the chrome carbide coated CrV steel was significantly better than that for the chrome oxide coated material. Chromium carbide coated spindles have been in service on steam turbine valves for four years, and the service experience has been good.

Quets et al. [10] reported the results of SPE and fatigue tests on chrome carbide coated AISI Type 422 stainless steel. The chrome carbide coating is UCAR LC-1H and consists of 80% chromium carbide and 20% nicrome. The chrome carbide coating was applied by a detonation gun at 1022°F (550°C). The SPE resistance of chrome carbide coated AISI Type 422 at low impingement angles (15° and 30°) is significantly greater than that of uncoated AISI Type 422 stainless steel and a chromium carbide (FeCrAlY) coating applied by a plasma torch.

Tension-compression fatigue tests were conducted at 1000°F (538°C) on chrome coated and uncoated Type 422 stainless steel fatigue samples [10]. The fatigue strength of the coated samples was approximately 10%–15% lower than that for the uncoated Type 422 stainless steel. This reduction in fatigue strength for coated Type 422 stainless steel is greater at higher cyclic stresses than at longer fatigue lives and was reported to be within the design-allowable variation for many steam turbine components.

Metallurgical examination of the failed fatigue specimens revealed a difference in the cracking behavior for the coated and uncoated samples. The uncoated samples had a single dominant fatigue crack, but the coated specimens had multiple crack initiation sites. It was concluded that the reduced fatigue life is the result of the nucleation and growth of these multiple fatigue cracks for the coated material. Chromium carbide coatings have low ductility even at 1022°F (550°C),

and the cracking of the coating is apparently due to applied cyclic strains greater than the strain to fracture for the coating. Case cracks were also found for the fatigue failures of austenitic stainless steel EME stems in the current study.

The effect of heat treatment or service at elevated temperatures on the properties and microstructure of thermal spray coatings is important in selecting the proper coating material for an application. Murthy et al. [11] studied the effect of a 1.5-hour heat treatment at 1112°F (600°C) on the microstructure and erosion behavior of the $\text{Cr}_3\text{C}_2 - 20\%$ (NiCr) coating that is used for the steam turbine stem application. They used the pulsed detonation gun process to apply the thermal spray. The coatings produced by HVOF and pulsed detonation gun processes are expected to be similar. The velocities are similar for the detonation gun and HVOF processes, but the flame temperature is higher for the detonation gun process, about 7000°F (3900°C) versus 5600°F (3100°C). In addition to the erosion tests, they measured porosity, hardness, fracture toughness, and coating adhesion strength.

The microstructure was characterized using x-ray diffraction, SEM, and TEM [11]. The microstructure of the as-coated material was complex and consisted of chrome carbide particles embedded in a binder phase that is mostly amorphous. The heat treatment resulted in the formation of nanocrystalline grains and fine carbide precipitation. The effect of the heat treatment on the properties of the coating were the following:

- The hardness increased from 850 to 1100 Vickers.
- The indentation fracture toughness increased from 3.2 to 4.1 ksi in^{1/2} (3.5 to 4.5 MPa m^{1/2})
- The porosity increased from 0.65% to 1.49%. This increase in porosity was noted to be contrary to that reported for the coating deposited by the HVOF process.
- The tensile bond strength increased slightly from 6.7 to 7.5 ksi (46 to 52 MPa) (within the range of error for the measurement).

The SPE tests were conducted at impact angles of 30, 60, and 90 degrees [11]. The erosion tests were conducted until a steady state erosion rate was established. The results were evaluated based on the ratio of the volume loss of the as-sprayed coating to the heat-treated coating. The plot of this ratio showed a strong dependence on impact angle with values of about 1.4 at 30° to about 2.4 at 90° [11]. Thus, heat treatment significantly increases the erosion resistance of the chrome carbide coating. They concluded that the improved erosion resistance of the heat-treated coating is the result of the improved binder strength and toughness that are related to several microstructural features, that is, the nanocrystalline phases, the fine carbide precipitates, and the sintering of the intersplat boundaries.

The microstructure of the chrome carbide coating on a AISI Type 422 stem is shown in Figure 7-4. The thickness of the chrome carbide coating is about 0.010 in. (250 microns) in this case. Manufacturing the coated stem requires the following steps:

1. Machining the AISI Type 422 bar stock to the proper dimensions
2. Stellite welding (when necessary)
3. Heat treating

4. Grit blasting
5. Chrome carbide coating
6. Final machining

The grit blasting is performed (typically with aluminum grit) to roughen the surface for better adhesion of the coating. Figure 7-5 shows a photograph of a typical chrome coated AISI Type 422 stem in the as-manufactured condition. In this case, the stem has a Stellite weld that is shown in Figure 7-6. The chrome carbide coating does not cover the entire length of the stem, but it has been applied only to those areas that need wear and erosion resistance.



1 inch = 25.4 mm

Figure 7-5
Chrome carbide coated Type 422 stainless steel stem
(Courtesy of TVA)

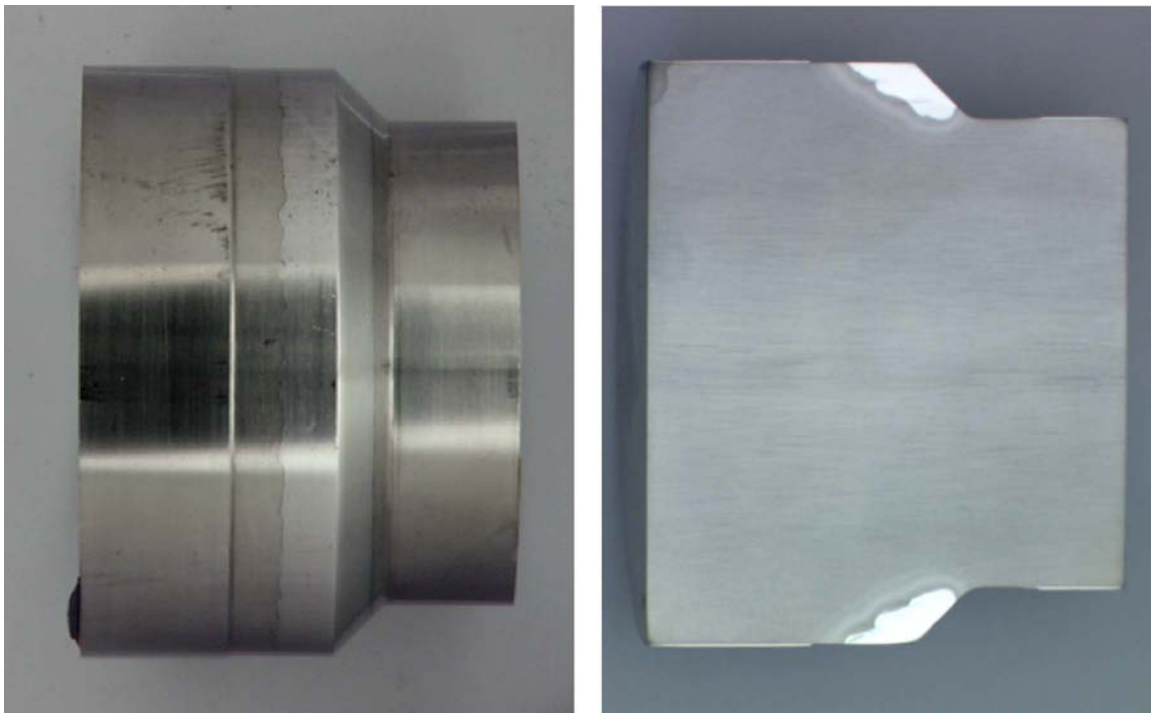


Figure 7-6
Stellite weld for chrome carbide coated stem at the transition in diameter
(Courtesy of TVA)

TVA has installed chrome carbide coated stems on control valves, main stop valves, and governor valves. The total number of stems is estimated at about 30. The stems have performed well, but several problems have occurred: reverse engineering design errors in one case and an excessive foreign object loading in another.

7.5 NASA PS304 Material

NASA has developed several high-temperature solid lubricant materials that are applied by the plasma spray process [12]. One of these materials, PS304, has a low coefficient of friction and good wear resistance up to a temperature of 1200°F (650°C). In addition, the thermal expansion coefficient of PS304 material is similar to that of most nickel-based superalloys.

The nominal composition of PS304 material is given in Table 7-7. PS304 material is an engineered material that consists of a high chrome-nickel matrix or binder, chrome oxide, and two solid lubricants (silver and eutectic fluorides). The matrix has good high-temperature oxidation resistance and strength properties. The chrome oxide is primarily used to harden the matrix, but it also a good solid lubricant above 932°F (500°C). Silver is the primary solid lubricant up to about 842°F (450°C), and the eutectic fluoride mixture is useful at temperatures above 752°F (400°C).

Table 7-6
Nominal composition of PS304 material (weight %)

	80%Ni-20%Cr	Cr₂O₃	BaF₂/CaF₂	Ag
PS304	60	20	10	10

Based on the oxidation, antigalling, and wear-resistance properties for the PS304 material coating and results of laboratory tests, PS304 material coating was applied to two steam turbine lift rods [13]. The rods were Waspaloy, and the operating temperature was 1005°F (540°C). The lift rods were slightly less than 2 in. (47 mm) in diameter and about 35.8 in. (0.91 m) long. The coating was applied to the shank section of the lift rods, about 19.7 in. (0.50 m) in length. A bond coat of METCO 443 was used before the PS304 coating was applied.

The lift rods were inspected after 8500 hours of service. Results indicated that the surface was protected. A lubricous glaze layer (consisting of chrome oxide, silver, and the fluorides) had formed on the coated surface and effectively protected the surface of the lift rod from wear and galling. The lift rods have been in service three years at the time of the paper (2004), and results indicate that the coating is functioning effectively [13].

7.6 Maglon Process

Maglon is a patented process for applying a thin metallic film to the surface of a component. Texas Utilities (TU) Electric has used the Maglon process to coat threaded fasteners and valve stems [14]. The term *engineered surfaces* is used to describe the approach used to develop the desired properties of the component surface for the application. For bolting and steam turbine stem applications, low friction, antigalling and wear resistance are required. To develop these desirable surface properties, a soft material approach was used.

The engineered surface consists of distinct layers. The layers are identified by their chemical symbol and begin with the substrate. The layers are separated by slashes, and the symbols are hyphenated if the layer is an alloy. The typical engineered surface consists of a base layer that adhered strongly to the component material, an intermediate or transition layer, and the working surface at the outermost layer. For typical bolting and valve stem applications requiring galling resistance, the engineered surface coating is very thin, about 0.4 to 4 microinches (1000 angstroms to 10,000 angstroms) and typically consists of layers of Ni/Cr/Au or Ni/Ag-Pd.

Service experience for bolting applications with Maglon-treated surfaces has shown that the soft metal surfaces improve the margin against galling substantially. TU Electric has Maglon-treated the stems of a few valves to lower friction at the sliding interface between the stem and the packing. Service experience indicates that the Maglon-treated valve stems appear to perform more reliably than untreated stems.

7.7 Solid Stellite and Weld Build-Up Bushings

Based on the results of the oxidation testing discussed in Section 7.2 and the stated objective to extend the time between outages, TVA decided to install solid Stellite bushings in the governor, intercept, and throttle valves on the 150-MW Westinghouse turbines. There were ten total bushings, four for the governor valve lower bushing, two for the intercept valve leakoff bushing, two for the throttle valve lower bushing, and two for the throttle valve upper bushing. The bushings were cast Stellite 6 materials. Although there were some initial problems in obtaining a sound casting, essentially discontinuity free castings were obtained. Figure 7-7 shows a photograph of a cast solid Stellite 6 bushing. The bushings have been in service since 2001, and there have been no significant service-related problems reported.

As an alternative to solid Stellite bushings, several suppliers are offering bushings with a Stellite weld buildup, which have been used by one utility. Thermal cycling tests have been performed on the weld buildup Stellite bushings, and results indicate good service performance is expected.

The bushing is a composite that consists of the bushing base material, an intermediate Inconel transition weld or “butter” layer, and the Stellite weld layer on the inside diameter of the valve bushing. Figure 7-8 shows photographs of a valve bushing coupon given to the utility for evaluation. The coupon was obtained from a nonOEM supplier. It was part of their development process, and the coupon has the base, the Inconel transition weld, and a Stellite weld buildup that

is typical of the as-manufactured valve bushing. The compositions of the materials were not supplied to the utility, and no chemical analyses have been performed. However, the Stellite weld metal is believed to be Stellite 6.



Figure 7-7
Cast solid Stellite 6 bushing
(Courtesy of TVA)

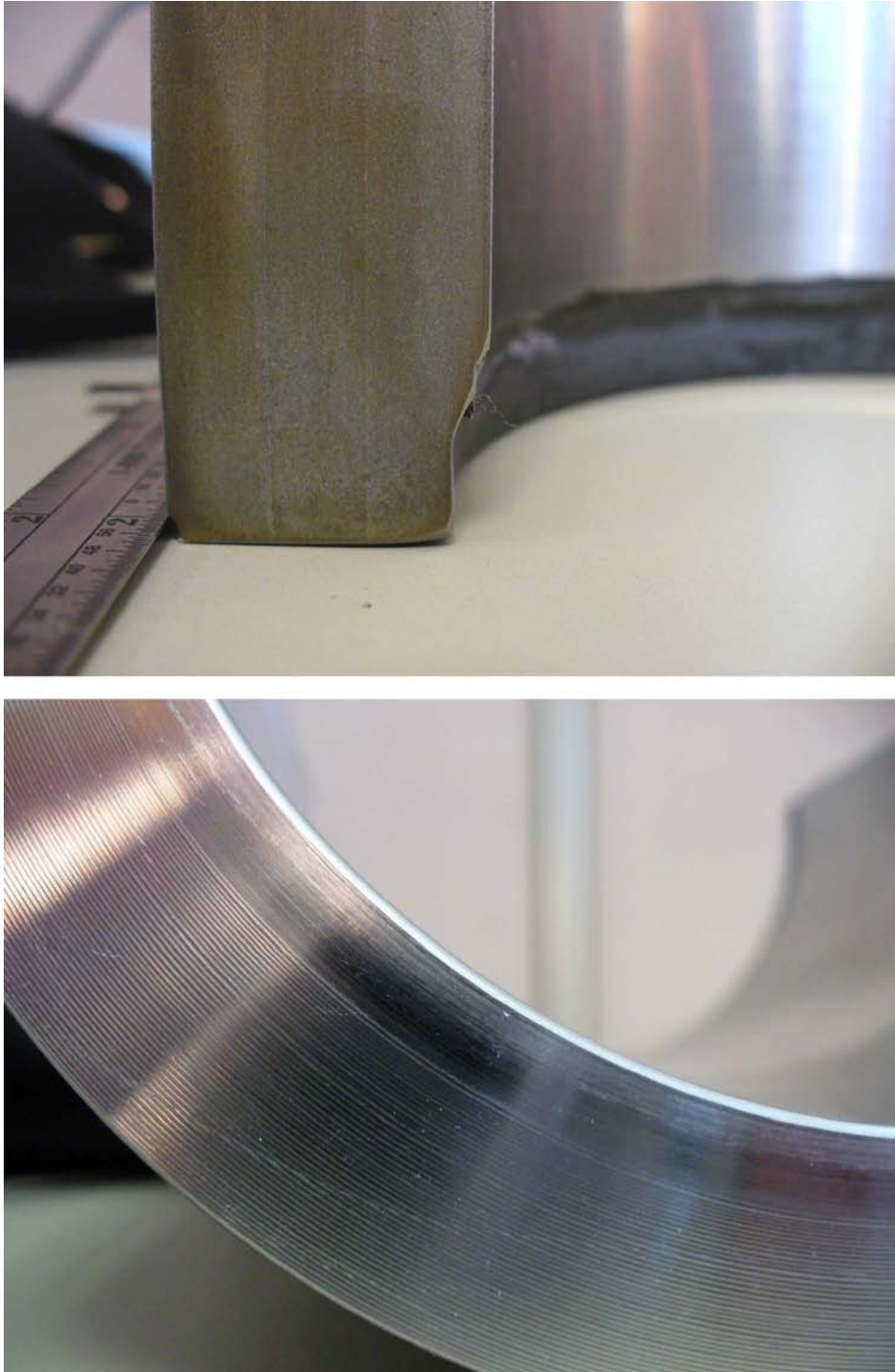


Figure 7-8
Weld buildup Stellite bushings

7.8 Alternative Material Considerations and Recommendations

Currently, several steam turbine OEMs are recommending and performing steam turbine valve material upgrades to increase reliability and potentially increase the time between outages. The recommended stem material is typically Incoloy 901, and the bushing materials are AISI Type 422 stainless steel, solid Stellite, and weld buildup Stellite. When material upgrades such as these are undertaken, consideration of the oxidation properties, thermal expansion, and thermal conductivity of the alternative material combinations is required in order to select the proper clearances for the selected stem and bushing materials.

Based on the results of this report and the nonproprietary OEM recommendations, the following recommendations are made:

- The Nitralloy 135M stems and bushings should be replaced on a planned schedule as the outage schedule permits. The material upgrades should be consistent with utility objectives and cost constraints. Viable material choices for the upgrades include AISI Type 422 stainless steel, Incoloy 901, and Alloy 718 for stems and AISI Type 422 stainless steel and solid or welded Stellite 6 for bushings. Nitriding or other suitable surface antigalling and wear protection techniques are recommended.
- The tendency for fatigue crack initiation in the nitrided case of EME stems observed in this study may indicate a generic problem. Additional studies regarding service experience and fatigue testing of bare and nitrided EME materials are recommended.
- The frequency and consequence of Stellite weld metal cracking and failure of the seat and disc weld inlay is cause for concern. Additional studies are recommended to determine the nature of the cracking, including the failure mechanism, and to develop suitable methods (for example, butter layers) to eliminate or mitigate the cracking/failure.
- SPE is a continuing and costly problem for valve stems, seats, and discs. For steam turbine valve applications, an evaluation of new erosion-resistant coatings such as EPRI's nano-coating should be performed. In addition, studies are recommended to develop design and other material-based solutions for SPE of the affected steam turbine valve parts.
- Longer term steam oxidation studies are recommended to develop improved materials, coatings, and surface modifications for steam turbine valve materials.
- Based on the good oxidation resistance found for the boride diffusion coated materials, additional study is recommended to develop boride coated valve materials. One significant problem is the very high temperatures required for the boride diffusion coating and the effect on base material properties.

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A

GLOSSARY

The essential tools of technical communication are technical words and phrases that are both useful and unique to each specific science or study. The glossary of terms is an attempt to clearly define the terminology and meanings that are used in the metallurgical guide. The words and phrases are from several different fields of study including metallography, heat treating, wear, welding, and steam turbines. The definitions are taken from the sources given in references 1–6.

A

abrasion

The process of grinding or wearing away the surface using abrasives and the scratching of the surface due to abrasive wear.

abrasive

A substance that usually consists of small, hard, and irregularly shaped particles that is capable of removing material from another material or substance.

abrasive wear

The removal of surface material when hard particles slide or roll across the surface under stress or pressure.

adhesive wear

The removal of surface material by the welding together and subsequent shearing of minute areas of two surfaces that are in intimate contact and slide across each other under pressure.

age hardening

Hardening by aging that follows rapid cooling or cold working.

aging

The change in material properties that occurs at ambient or slightly elevated temperatures after hot working, heat treating, or cold working. The property change is often due to a phase change such as precipitation that does not alter chemical composition.

AISI

The American Iron and Steel Institute, an association of North American steel producers.

alloy

A substance that has metallic properties and is composed of two or more chemical elements of which at least one is an elemental metal.

alloying element

An element added to a metal to change the structure and properties of the material. The following list gives the alloying elements commonly found in steels and the chemical symbol for the element:

- Aluminum (Al), antimony (Sb), and arsenic (As)
- Boron (B)
- Calcium (Ca), carbon (C), chromium (Cr), cobalt (Co), and copper (Cu)
- Lead (Pb)
- Manganese (Mn), molybdenum (Mo)
- Nickel (Ni), niobium (Nb) or columbium (Cb), and nitrogen (N)
- Phosphorus (P)
- Silicon (Si) and sulfur (S)
- Tin (Sn), titanium (Ti), and tungsten (W)
- Vanadium (V)

alpha iron

A solid phase of pure iron that is stable below 1670°F (910°C), has a body-centered cubic lattice, and is ferromagnetic below 1415°F (768 °C).

AMS

Aerospace Materials Specification.

anisotropy

Having different values of a property in different directions.

annealing

A generic term denoting a treatment, heating to and holding at a suitable temperature, followed by cooling at a suitable rate. Annealing is used primarily to soften metallic materials, but also to produce desired changes simultaneously in other properties or in the microstructure. When applied only for the relief of stress, the process is called stress relieving or stress-relief annealing. In ferrous alloys, annealing is carried out above the upper critical temperature, but the time-temperature cycles vary widely in maximum temperature attained and cooling rate used, depending on the composition, material condition, and desired results. In nonferrous alloys, annealing cycles are designed to remove part or all the effects of cold working (recrystallization may or may not be involved), cause complete coalescence of precipitates from the solid solution in relatively coarse form, or both, depending on the composition and material condition.

anneal to temper

A final partial anneal that softens a cold-worked nonferrous alloy to a specified level of hardness or tensile strength.

artifact

A false feature such as a scratch or a piece of dust on a metallographic specimen that can be erroneously interpreted as a real feature.

ASM

American Society for Metals.

ASTM

American Society for Testing and Materials International.

asperities

Small-scale irregularities on a surface.

austenite

Generally, a solid solution of one or more alloying elements in a face-centered cubic iron (γ-iron). Specifically, in carbon steels, the interstitial solid solution of carbon in γ-iron.

austenitic grain size

The size attained by the grains in steel when heated to the austenitic region; may be revealed by appropriate etching of cross sections after cooling to room temperature.

austenitizing

Forming austenite by heating a ferrous alloy into the transformation range (partial austenitizing) or above the transformation range (complete austenitizing). The term implies complete austenitizing when used without qualification.

AWS

American Welding Society.

axis

The edge of the unit cell of a space lattice.

B

bainite

A transformation product of ferrite and a fine dispersion of carbide, generally formed below 840°F–930°F (450°C–500°C). Upper bainite is an aggregate that contains parallel lath-shaped units of ferrite, produces the so-called feathery appearance in optical microscopy, and is formed above approximately 660°F (350°C). Lower bainite, which has an acicular appearance similar to tempered martensite, is formed below approximately 660°F (350°C).

banded structure

A segregated structure consisting of alternating bands of different physical morphology or chemical composition aligned in filaments or plates parallel to the direction of working.

beach marks

Beach marks or clamshell marks are characteristic markings found on the cyclically grown portion of a fatigue fracture surface. Beach marks document the location of the crack front at various positions during the growth of the crack.

body centered

A cubic crystallographic structure with equivalent lattice points at corners of the unit cell and at its center. In steel, ferrite is a body-centered cubic phase.

bonnet

A cover of the valve body.

bright annealing

Annealing in a protective medium to prevent discoloration of the bright surface.

brittle fracture

A rapid fracture with little or no plastic deformation.

brittleness

The tendency of a material to fracture without significant plastic deformation.

bushing

A cylinder-shaped piece used to guide and align the stem to ensure accurate positioning of the disc and seat.

C

carbide

A compound of carbon and one or more metallic elements.

case

The portion of a ferrous alloy extending inward from the surface, whose composition has been altered during case hardening. The composition of the case material is measurably altered from the core material's original composition, and the case has a higher hardness value than the core.

case hardening

A generic term covering several processes applicable to steel that change the chemical composition of the surface layer by the absorption of carbon, nitrogen, or both and that by diffusion create a concentration gradient.

cast structure

The metallographic structure of a casting characterized by shape and orientation of grains as well as by segregation of impurities.

cementite

A hard, brittle compound of iron and carbon, Fe_3C , or iron carbide. It has the orthorhombic crystal structure. In steels, the chemical composition is typically changed by the presence of manganese, chromium, molybdenum, and other carbide-forming elements.

chevron marks

Chevron marks are the vee-shaped marks found on a fracture surface. The point of the vee indicates the fracture initiation site.

cleavage

The fracture of a crystal by crack propagation across a crystallographic plane of low index.

cleavage fracture

A fracture, usually of a polycrystalline metal, in which most of the grains have failed by cleavage, resulting in bright reflecting facets. Cleavage fracture is typically a brittle fracture mode.

coarse grains

Grains larger than normal for the particular wrought metal or alloy or of a size that produces a surface roughening known as orange peel or alligator skin.

coherent precipitate

A precipitated particle of a second phase whose lattice maintains registry with the matrix lattice. Because the lattice spacings are usually different, strains often exist at the interface.

cold-worked structure

A microstructure resulting from the plastic deformation of a metal or alloy below its recrystallization temperature.

columnar structure

A coarse structure consisting of parallel, elongated grains formed by unidirectional growth that is most often observed in castings, but is sometimes seen in structures.

constituent

A phase or combination of phases that occurs in a characteristic configuration in an alloy microstructure.

continuous phase

The phase that forms the background or matrix in which the other phase or phases may be dispersed.

cooling rate

The average slope of the time-temperature curve taken over a specified time and temperature interval.

core

In a ferrous alloy that has undergone case hardening, that portion of the alloy structure that is not part of the case. Typically considered to be the portion that (a) appears light when etched, (b) has an unaltered chemical composition, or (c) has a hardness value lower than that of the case.

coring

The variation in composition between the center and surface of a unit of structure, such as a dendrite, a grain, or a carbide particle that results from non-equilibrium growth over a temperature range.

crystal

A solid composed of atoms, ions, or molecules arranged in a pattern that is periodic in three dimensions.

crystal system

One of seven groups into which all crystals may be divided: triclinic, monoclinic, orthorhombic, hexagonal, rhombohedral, tetragonal, and cubic.

CVD

Chemical vapor deposition.

D**decarburization**

The loss of carbon from the surface of a ferrous alloy as a result of heating in a medium that reacts with carbon.

dendrite

A crystal with a treelike branching pattern. It is most evident in cast metals slowly cooled through the solidification range.

dendritic segregation

The inhomogeneous distribution of alloying elements through the arms of dendrites.

diffusion

1) The spreading of a constituent in a gas, liquid, or solid that tends to make the composition of all parts uniform. 2) The spontaneous movement of atoms or molecules to new sites within a material.

dilution

The change in chemical composition of a weld filler metal due to the mixture with the base material or previous weld beads.

disc

A moveable component located inside the valve body that can partly or completely block the flow through the valve. The disc is moveable so it can control flow.

dislocation

A linear imperfection present in a crystalline array of atoms. The generation and movement of dislocations are the processes that control inelastic strain accumulation. The two basic types of dislocation recognized are edge and screw.

disordered structure

The crystal structure of a solid solution in which the atoms of different elements are randomly distributed relative to the available lattice sites.

DMW

Dissimilar metal weld.

duplex grain size

A structure with two grain sizes in substantial amounts, with one grain size appreciably larger than the others.

ductility

The ability of materials to plastically deform without fracturing. Ductility is typically measured as elongation or reduction in area as measured in laboratory tests.

E

EDS

Energy dispersive spectrometer.

electron microscope

An electron-optical device that produces a magnified image of an object. Detail may be revealed by selective transmission, reflection, or emission of electrons by the object.

electron microscopy

The study of materials by means of an electron microscope.

elongated grain

A grain with one principal axis significantly longer than either of the other two axes.

embedded abrasive

Fragments of abrasive particles forced into the surface of a work piece during grinding, abrasion, or polishing.

embrittlement

The reduction in normal ductility of a metal, due to either physical or chemical change.

EPRI

Electric Power Research Institute.

equiaxed grain structure

A structure in which the grains have approximately the same dimensions in all directions.

erosion

The loss of material from a solid surface due to relative motion in contact with a fluid that contains solid particles.

ESV

Emergency stop valve.

etchant

A chemical solution used to etch a metal to reveal structural details.

etching

Subjecting the surface of a metal to preferential chemical or electrolytic attack to reveal structural details for metallographic examination.

exfoliation

The detachment of brittle scale (typically magnetite) that is observed in superheat and reheat boiler tubes because of thermal cycling.

F

face-centered

Having atoms or groups of atoms separated by translations of $1/2, 1/2, 0$; $1/2, 0, 1/2$; and $0, 1/2, 1/2$ from a similar atom or group of atoms. The number of atoms in a face-centered cell must be a multiple of 4.

fatigue

A fracture under repeated or fluctuating stresses with a maximum value less than the tensile strength of the material. Fatigue cracks initiate at discontinuities or stress concentrated locations, and the fatigue cracks grow under the action of the cyclic stresses.

FATT

Fracture appearance transition temperature. This is the temperature of a Charpy impact test where the fracture has a 50% brittle and 50% ductile appearance.

ferrite

Generally, a solid solution of one or more elements in body-centered cubic iron. In plain carbon steels, ferrite is the interstitial solid solution of carbon in alpha-iron. Below the Curie temperature, ferrite is magnetic.

ferrite-pearlite banding

An inhomogeneous distribution of ferrite and pearlite aligned in filaments or plates parallel to the direction of working.

fractography

A descriptive treatment of a fracture, especially in metals, with specific reference to photography of the fracture surface.

friction

A resting force tangential to the common boundary between two bodies when one body moves relative to the surface of the other under an external force.

G

GADS

Generating Availability Data System

galling

A severe form of scuffing associated with gross damage to the surface or failure.

gamma iron

A solid nonmagnetic phase of pure iron that is stable from 1670°F to 2550°F (910°C to 1400°C) and possesses the face-centered cubic lattice. It is also known as *austenite*.

GE

General Electric.

grain

An individual crystal in a polycrystalline metal or alloy, including twinned regions or subgrains.

grain boundary

An interface separating two grains at which the orientation of the lattice changes from that of one grain to that of the other. For small changes in orientation, the boundary is sometimes referred to as a *sub-boundary structure*.

grain coarsening

A heat treatment that produces excessively large austenitic grains.

grain growth

An increase in the grain size of a metal, usually as a result of heating at an elevated temperature.

grain size

A measure of the areas or volumes of grains in a polycrystalline metal or alloy, usually expressed as an average when the individual sizes are fairly uniform. In metals containing two or more phases, the grain size refers to that of the matrix unless otherwise specified. Grain size is reported in terms of number of grains per unit area or volume, average diameter, or as a number derived from area measurements.

graphite

The polymorph of carbon with a hexagonal crystal structure.

graphitization

The formation of graphite in iron or steel.

GTA

Gas tungsten arc.

H

hardenability

The relative ability of a ferrous alloy to form martensite when quenched from a temperature above the upper critical temperature.

hardening

Increasing hardness by a suitable treatment that usually involves heating and cooling.

hardness

The resistance of metal to plastic deformation, usually by indentation. Indentation hardness is measured by various hardness tests including Brinell, Rockwell, and Vickers.

HAZ

Heat-affected zone.

HB

Hardness Brinell.

heat-affected zone

The portion of the base metal that was not melted during brazing, cutting, or welding, but whose microstructure and mechanical properties were altered by the heat.

homogenizing

Holding at a high temperature to eliminate or decrease chemical segregation by diffusion.

hot-worked structure

The structure of a material worked at a temperature higher than the recrystallization temperature.

hot working

Deformation under conditions that result in recrystallization.

HP

High pressure.

HRC

Hardness Rockwell C.

HV

Hardness Vickers.

HVOF

High-velocity oxygen fuel (oxyfuel).

I**ID**

Inside diameter.

impingement

The process resulting from a continuous succession of impacts between a solid surface and solid particles in a liquid.

impurities

Undesirable elements or compounds in a material.

inclusions

Particles of foreign or nonmetallic material found in a metallic matrix. The particles are usually compounds such as oxides, sulfides (such as manganese sulfide), or silicates, but may be any substance foreign to and essentially insoluble in the matrix.

interdendritic

Located within the branches of a dendrite or between the boundaries of two or more dendrites.

intergranular

Between the crystals or grains of a metal.

intergranular cracks

Cracks or fractures that occur between the grains or crystals in a polycrystalline aggregate.

interstitial solid solution

The type of solid solution that sometimes forms in alloy systems with two elements of widely different atomic sizes. Elements of small atomic size, such as carbon, hydrogen, and nitrogen often dissolve in solid metals to form this solid solution. The space lattice is similar to that of the pure metal, and the atoms of carbon, hydrogen, and nitrogen occupy the spaces or interstices between the metal atoms.

IP

Intermediate pressure.

isothermal annealing

Austenitizing a ferrous alloy, then cooling to and holding at a temperature at which austenite transforms to a relatively soft ferrite-carbide aggregate.

ISO

International Standards Organization.

isothermal transformation

A phase change that takes place at any constant temperature.

isotropic

Having equal values of properties in all directions.

L

lap

A surface imperfection on worked metal caused by folding over a fin overfill or similar surface condition, then impressing this into the surface by subsequent working without welding it.

lath martensite

Martensite formed partly in steels containing less than approximately 1.0% C and solely in steels containing less than approximately 0.5% C, as parallel arrays or packets that are lath shaped.

lattice

1) A space lattice is a set of equal and adjoining parallelopipeds formed by dividing space by three sets of parallel planes, the planes in any one set being equally spaced. There are seven ways of dividing space corresponding to the seven crystal systems. The unit parallelopiped is usually chosen as the unit cell of the system. 2) A point lattice is a set of points in space located so that each point has identical surroundings. There are 14 ways of arranging points in space, corresponding to the 14 Bravais lattices.

longitudinal direction

The direction parallel to the direction of maximum elongation in a worked material.

LP

Low pressure.

M

macroetching

Etching a metal surface to accentuate gross structural details, such as grain flow, segregation, porosity, or cracks, for observation by the unaided eye or at magnification to about 25X.

macrograph

The graphic reproduction of the prepared surface of a specimen at magnifications of about 10X–25X. When photographed, the reproduction is a photomacrograph.

macroscopic

A term that indicates something is visible either with the naked eye or at low magnification, about 10X–25X.

macrostructure

The structure of metals as revealed by macroscopic examination of the etched surface of a polished specimen.

magnetite

The oxide of iron of intermediate valence, which has a composition close to the stoichiometric composition of Fe_3O_4 .

magnification

The ratio of the length of a line in the image plane to the length of the same line in the object. Magnifications are usually expressed in linear terms and in units called diameters.

martensite

A generic term for microstructures formed by diffusionless phase transformation in which the parent and product phases have a specific crystallographic relationship. Martensite is characterized by an acicular pattern in the microstructure in ferrous and nonferrous alloys. In alloys in which the solute atoms occupy interstitial positions in the martensitic lattice, such as carbon in iron, the structure is hard and highly strained; however, if the solute atoms occupy substitutional positions, such as nickel in iron, the martensite is soft and ductile. The amount of high-temperature phase that transforms to martensite upon cooling depends to a large extent on the lowest temperature attained, there being a distinct starting temperature (M_s) and a temperature at which the transformation is essentially complete (M_f), which is the martensite finish temperature.

martensitic

A plate-like constituent that has an appearance and a mechanism of formation similar to that of martensite.

matrix

The continuous or principal phase in which another constituent is dispersed.

mechanical polishing

The method used to producing a reflecting surface with abrasive particles.

metallography

The science dealing with the constitution and structure of metals and alloys as revealed to the unaided eye or by using such tools as low-power magnification, optical microscopy, electron microscopy, and diffraction or x-ray techniques.

microcrack

A crack of microscopic size.

microetching

The development of a suitable microstructure for microscopic examination at magnification typically greater than about 25 X.

micrograph

The graphic reproduction of the prepared surface of a specimen at magnifications greater than 25 X.

microscope

An instrument capable of producing a magnified image of a small object.

microstructure

The structure of prepared surface of a metal as revealed by a microscope at magnifications above 10X–25X. A photograph of this image is a photomicrograph.

MIG

Metal inert gas.

MMA

Manual metal arc.

MW

Megawatt.

N

NASA

National Aeronautics and Space Administration.

NERC

North American Electric Reliability Council.

NIMS

National Institute for Materials Science.

nitriding

A case-hardening process that introduces nitrogen into the surface layer of a ferrous material by holding it at a suitable temperature in a nitrogenous atmosphere, usually ammonia or molten cyanide of appropriate composition. Quenching is not required to produce a hard case.

nominal area of contact

An area bounded by the periphery of the region where macroscopic contact between two bodies occurs.

normalizing

Heating a ferrous alloy to a suitable temperature above the transformation range, then cooling in still air to a temperature substantially below the transformation range.

notch brittleness

The measure of susceptibility of a material to brittle fracture at the location of a stress concentrator.

nucleation

The initiation of a phase transformation at discrete sites, the new phase growing from nuclei.

nucleus

The first structurally stable particle capable of initiating recrystallization of a phase or the growth of a new phase. It is separated from the matrix by an interface.

O

OD

Outside diameter.

OEM

Original equipment manufacturer.

order-disorder transformation

A phase change among two solid solutions with the same crystal structure, but in which the atoms of one phase (disordered) are randomly distributed; in the other, the different kinds of atoms occur in a regular sequence upon the crystal lattice, that is, in an ordered arrangement.

ordered structure

The crystal structure of a solid solution in which the atoms of different elements seek preferred lattice positions.

overaging

Aging under conditions of time and temperature greater than those required to obtain maximum change in a certain property.

overheating

In ferrous alloys, heating to an excessively high temperature so that the properties/structure undergo modification. The resulting structure is very coarse grained.

oxidation

The combination of a substance with oxygen or a reaction with an increase in valence resulting from a loss of electrons.

oxide-type inclusions

Oxide compounds occurring as nonmetallic inclusions in metals, usually as a result of deoxidizing additions. In wrought steel products, they may occur as a stinger formation composed of distinct granular or crystalline-appearing particles.

P

pearlite

A metastable eutectoid-transformation product consisting of alternating lamellae of ferrite and cementite resulting from the transformation of austenite.

phase

A physically homogeneous and distinct portion of a material system.

phase diagram

A graph of the temperature and composition limits of phase fields in an alloy system as they actually exist under the specific conditions of heating or cooling (synonymous with constitutional diagram). A phase diagram may be an equilibrium diagram, an approximation to an equilibrium diagram, or a representation of metastable conditions of phases.

photomicrograph

A micrograph made by photographic means.

plasticity

The capacity of a metal to deform non-elastically without rupturing.

plate martensite

Martensite formed partly in steel containing more than approximately 0.5% C and solely in steel containing more than approximately 1.0% C as lenticular-shaped plates on irrational habit planes near $(225)_A$, or $(259)_A$ in high-carbon steels ($>0.9\%$ C).

polishing

A mechanical, chemical, or electrolytic process or combination thereof that is used to prepare a smooth, reflective surface suitable for microstructural examination and that is free of artifacts or damage introduced during prior sectioning or grinding.

polycrystalline

An aggregate of more than one crystal and usually a large number of crystals.

porosity

The measure of holes in a solid, with the holes not necessarily connected to each other.

precipitation

The separation of a new phase from solid or liquid solution, usually with changing conditions of temperature, pressure, or both.

precipitation hardening

Hardening caused by precipitation of a constituent from a supersaturated solid solution.

precipitation heat treatment

Various artificial aging conducted at elevated temperatures in which a constituent precipitates from a supersaturated solid solution.

process annealing

A heat treatment used to soften metal for further cold working.

pressure seal head

A component that holds the valve bushings in place and is typically welded to the valve body. The geometry of pressure seal heads for steam turbine valves is a hollow cylinder.

proeutectoid carbide

Primary crystals of cementite formed directly from the decomposition of austenite exclusive of that cementite resulting from the eutectoid reaction.

proeutectoid ferrite

Primary crystals of ferrite formed directly from the decomposition of austenite exclusive of that ferrite resulting from the eutectoid reaction.

PTA

Plasma transfer arc.

Q**quantitative metallography**

The determination of specific characteristics of a microstructure by quantitative measurements on micrographs or metallographic images. Quantities include volume concentration of phases; grain size; particle size; mean free path between like particles or secondary phases; and surface area to volume ratio of microconstituents, particles, or grains.

quenching

A rapid cooling treatment for steel that follows holding at a predetermined temperature. The cooling rate is usually specified to ensure that the desired microstructure and properties are obtained.

quench hardening

In ferrous alloys, hardening by austenitizing, then cooling at a rate so that a substantial amount of austenite transforms to martensite.

R**random orientation**

The condition of a polycrystalline aggregate in which the orientations of the constituent crystals are completely random relative to each other.

ratchet marks

Indications found on fracture surfaces where there are multiple fatigue crack origins that grow and link up. They are steplike junctions between adjacent fatigue cracks.

recrystallization

(1) A change from one crystal structure to another, such as that occurring upon heating or cooling through a critical temperature. (2) The formation of a new, strain-free grain structure from the structure existing in cold-worked metal.

recrystallization temperature

The approximate minimum temperature at which recrystallization of a cold-worked metal occurs within a specified time. This temperature is normally about one-third of the absolute melting point temperature of the alloy.

residual elements

Small quantities of elements present in an alloy that were not added intentionally.

Rockwell hardness

A standard measure of hardness that is expressed as a number related to the depth of residual penetration of a steel ball or diamond cone. The five scales are designated by letters A to H; the B and C scales are the most common.

RT

Room temperature.

S

scanning electron microscope

An electron microscope in which the image is formed by a beam operating in synchronism with an electron probe scanning the object. The intensity of the image-forming beam is proportional to the scattering or secondary emission of the specimen where the probe strikes it.

scoring

The marring or scratching of a smooth surface. It is most often caused by sliding contact with a mating member that has a hard projection or embedded particle on its surface.

scratch

A groove produced in a surface by an abrasive point.

scuffing

Localized damage caused by the occurrence of solid-phase welding between sliding surfaces without local surface melting.

seam

An unwelded fold or lap on the surface of metal that appears as a crack. This is usually the result of defects in casting or working that have not been welded shut.

SEE

Standard error of the estimate.

segregation

The nonuniform distribution of alloying elements, impurities, or phases. Segregation develops in casting because of the primary crystallization of one phase and the concentration of other elements in the remaining liquid.

SEM

Scanning electron microscope.

shear bands

Bands in which deformation has been concentrated inhomogeneously in sheets that extend across regional groups of grains. The bands form on planes of maximum shear stress and carry most of the deformation at large strains.

shortness

A form of brittleness in metal. It is designated as *cold*, *hot*, and *red* to indicate the temperature range in which the brittleness occurs.

sigma phase

The hard, brittle nonmagnetic intermediate Fe-Cr phase that forms at elevated temperatures in Fe-Cr-Ni and Ni-Cr-Fe alloys. The specifics of formation depend on time, temperature, and composition.

silicate-type inclusions

Inclusions composed essentially of silicate glass, normally plastic at forging and hot-rolling temperatures that appear in steel in the wrought condition as small elongated inclusions that are usually dark in color.

slag

A nonmetallic product resulting from the mutual dissolution of flux and nonmetallic impurities in smelting and refining operations.

slip

Plastic deformation by the irreversible shear displacement (translation) of one part of a crystal relative to another. The deformation typically takes place in a definite crystallographic direction and usually on a specific crystallographic plane.

slip band

A group of parallel slip lines so closely spaced as to appear as a single line when observed under an optical microscope.

SMA

Shielded metal arc.

solid solution

A solid crystalline phase that contains two or more chemical species. Concentrations may vary between limits imposed by phase equilibrium.

solute

The component of a liquid or solid solution that is present to the lesser or minor extent; the component that is dissolved in the solvent.

solution

A phase existing over a range of compositions in a chemical system.

solution heat treatment

A heat treatment in which an alloy is heated to a suitable temperature, is held at that temperature long enough to cause one or more constituents to enter into solid solution, then is cooled rapidly enough to hold these constituents in solution.

solvent

The component of a liquid or solid solution that makes up the majority of the solution; the component that dissolves the solute.

spalling

Separation of particles from a surface in the form of flakes.

SPE

Solid particle erosion.

stainless steel

Grades of steel that contain that contain more than about 9% chromium, with or without additional alloying elements. Stainless steels are resistant to corrosion and oxidation and maintain strength at elevated temperatures.

steam turbine

A machine that converts the high-temperature, high-pressure thermal energy of steam into rotational mechanical energy.

stem

A rod or similar-shaped piece spanning the inside and outside of a valve, translating motion to control the internal disc from outside the valve.

strain aging

Aging induced by cold work.

strain hardening

An increase in hardness and strength caused by plastic deformation at temperatures below the recrystallization range.

stress relieving

Heating to a suitable temperature, holding long enough to reduce residual stresses, then cooling slowly enough to minimize the development of new residual stresses.

stringer

A microstructural configuration of alloy constituents or foreign nonmetallic material lined up in the direction of working.

structure

For crystals, the shape and size of the unit cell and the location of all atoms within the unit cell. With regard to microstructure, the size, shape, and arrangement of phases.

sub-boundary or sub-grain structure

A network of low-angle boundaries, usually with misorientations less than 1° within the main grains of a microstructure.

subcritical annealing

An annealing treatment in which steel is heated to a temperature below the A_1 temperature, then cooled slowly to room temperature.

subgrain

A portion of a crystal or grain slightly different in orientation from adjoining portions of the same crystal.

submicroscopic

Below the resolution of the microscope.

substitutional element

An alloying element with an atomic size and other features similar to the solvent that can replace or substitute for the solvent atoms in the lattice and form a significant region of solid solution.

substitutional solid solution

A solid solution in which the solvent and solute atoms are located randomly at the atom sites in the crystal structure of the solution.

substrate

The layer of metal underlying a coating, regardless of whether the layer is base metal.

sulfide-type inclusions

In steels, nonmetallic inclusions composed essentially of manganese iron sulfide solid solutions (Fe, Mn) S. They are characterized by plasticity at hot rolling and forging temperatures and, in the hot-worked product, appear in color as dove-gray elongated inclusions.

SUS

Steel Use Stainless (from the Japanese Industrial Standards).

swabbing

The wiping of the specimen surface with a cotton ball saturated with etchant to remove reaction products simultaneously.

S-W

Siemens-Westinghouse.

T

TBO

Time between overhauls.

TEM

Transmission electron microscope.

tempered martensite

The decomposition products that result from heating martensite below the ferrite-austenite transformation temperature. Under the optical microscope, darkening of the martensite needles is observed in the initial stages of tempering. Prolonged tempering at high temperatures produces spheroidized carbides in a matrix of ferrite. At the higher resolution of the electron microscope, the initial stage of tempering is observed to result in a structure containing a precipitate of fine ϵ iron carbide particles. At approximately 500°F (260°C), a transition occurs to a structure of larger and elongated cementite particles in a ferrite matrix. With further tempering at higher temperatures, the cementite particles become spheroidal, and they decrease in number and increase in size.

tempering

In heat treatment, reheating hardened steel to some temperature below the eutectoid temperature to decrease hardness and/or increase toughness.

TIG

Tungsten inert gas.

TVA

Tennessee Valley Authority.

tetragonal

A crystal that has three mutually perpendicular axes, two that are equal in length but unequal to the third axis.

texture

In a polycrystalline aggregate, the state of distribution of crystal orientations. In the usual sense, it is synonymous with *preferred orientation*, in which the distribution is not random.

TIR

Total indicated run-out.

TMS

The Minerals, Metals & Materials Society.

TMT

Turbine Metal Technology.

toughness

An indication of the ability of a steel to absorb energy and deform plastically before fracturing, particularly in the presence of a notch or crack. Toughness is measured using special fracture toughness testing techniques and is also inferred from the results of notched impact tests such as Charpy and Izod.

transformation ranges

The ranges of temperature within which austenite forms during heating and transforms during cooling. The two ranges are distinct, sometimes overlapping, but never coinciding.

transformation temperature

The temperature at which a change in phase occurs. The term is sometimes used to denote the limiting temperature of a transformation range. The following symbols are used for iron and steels:

 AC_{cm} .

In hypereutectoid steel, the temperature at which the solution of cementite in austenite is complete during heating.

 Ac_1 .

The temperature at which austenite begins to form during heating.

 Ac_3 .

The temperature at which transformation of ferrite to austenite is complete during heating.

 Ac_4 .

The temperature at which austenite transforms to δ -ferrite during heating.

M_s .

The temperature at which the transformation of austenite to martensite begins during cooling.

M_f .

The temperature, during cooling, at which the transformation of austenite to martensite is substantially complete.

transgranular

Within or across crystals or grains.

transmission electron microscope

A microscope in which the image-forming rays pass through (are transmitted by) the specimen being observed.

transverse direction

Literally, across, usually signifying a direction or plane perpendicular to the direction of working. In rolled plate or sheet, the direction across the width is often called long transverse, and the direction through the thickness, short transverse.

TU

Texas Utilities.

twin

Two portions of a crystal with a definite orientation relationship; one may be regarded as the parent, the other as the twin. The orientation of the twin is a mirror image of the orientation of the parent across a twinning plane or an orientation that can be derived by rotating the twin portion about a twinning axis.

twin bands

Bands across a crystal grain, observed on a polished and etched section, where crystallographic orientations have a mirror-image relationship to the orientation of the matrix grain across a composition plane that is usually parallel to the sides of the band.

U

unit cell

A parallelepiped element of crystal structure containing a certain number of atoms, the repetition of which through space will build up the complete crystal.

UNS

Unified Numbering System.

U.S.

United States.

V

vacancy

A structural imperfection in which an individual atom site is temporarily unoccupied.

valve

- (1) Any of the various devices that regulate the flow of gases, liquid, or loss material through piping or apertures by opening, closing, or obstructing ports or passageways.
- (2) The movable control element of such a device.

valve body

The vessel or casing that holds the fluid (steam) going through the inside of the valve.

valve seat

A component in the interior surface of the valve casing that contacts or could contact the disc to form a seal. The seal should be steam leakage tight when the valve is closed.

Vickers hardness number

The numerical value of the microindentation hardness obtained using the Vickers (diamond) indenter. The Vickers hardness test is described in ASTM E 384.

W

wear

The damage to a solid surface involving a progressive loss of material that is due to the relative motion of the surface and the contacting substances.

wear resistance

The resistance to the removal of material by wear processes.

weld structure

The microstructure of a weld deposit and the heat-affected zone material.

work hardening

The increase in resistance to deformation in metals produced by cold working.

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B

SUMMARY OF MATERIAL DATA

This section gathers the data presented in the body of the report and presents the results in tabular form. The material data of interest for the steam turbine valve materials include the tensile properties, mean coefficient of thermal expansion, wear resistance, and oxidation resistance. The tensile properties and mean coefficient of thermal expansion are given as a function of temperature. The data values are given in separate tables based on the three main types of steam turbine valve materials: low alloy, stainless steels, and superalloys. The qualitative rankings of the oxidation and wear resistance for the nitrided steels are also given in tables.

The tensile properties are given in Tables B-1, B-2, and B-3. The values of the mean coefficient of thermal expansion are given in Tables B-4, B-5, and B-6. The tensile strength values are typical of handbook listings and are intended for comparison purposes only. The range of values given indicates expected variations due to material and heat-treatment variations within the specified range, for example, tempering temperatures of 1125°F (607°C) and 1200 °F (649°C) for 410 stainless steel and estimated minimum to mean of ASM values as a function of titanium content for W-545.

It is clear that significant variations in the strength and ductility of as-manufactured valve components can occur depending on material, chemistry, hot-cold work, and heat treatment. For example, the elevated temperature tensile properties for several of the stainless steels shown in the table are relatively low due to the annealed or solution heat treatment condition. For valve stem applications, significantly higher tensile strengths are needed. Although no stainless steel stems were examined in the current study, it is believed that these materials are used in the cold worked condition for steam turbine applications.

For replacement parts, there is a need to have detailed specifications to ensure good service performance. For valve components, reverse engineering is often used to allow the utility to manufacture the part. In the same sense that dimensional analysis is required to determine the part size and shape, metallography and chemical analysis are useful to determine the microstructure, hardness, and chemistry required to develop the specifications. Metallographic examinations have been performed for several of the steam turbine alloys (135M, 422, EME, and 901), and results were discussed in Section 2 of the report.

Table B-1
Tensile properties of low-alloy valve materials

Material	Temp – °F (°C)	Ultimate Tensile Strength – ksi (MPa)	Yield Strength – ksi (MPa)	Elongation - %	Reduction in Area - %
Nitralloy 135M	RT	120-142 (830-980)	93 (640)	14	--
AISI 4140	RT	125 (862)	109 (752)	19	58
AISI 4140	1000 (538)	82 (565)	60 (413)	29	75

Table B-2
Tensile properties of stainless steel valve materials

Material	Temp – °F (°C)	Ultimate Tensile Strength – ksi (MPa)	Yield Strength – ksi (MPa)	Elongation - %	Reduction in Area - %
AISI 410	RT	100-120 (690–825)	80-90 (550–620)	12	40
AISI 410	1000 (538)	62-71 (427-490)	55-65 (379-450)	20	80
AISI 422	RT	150 (1027)	125 (862)	18.5	52
AISI 422	1000 (538)	96 (662)	82 (565)	24.8	67
AISI 422	1100 (593)	76 (524)	72 (496)	29.6	69
AISI 422	1200 (649)	52 (358)	45 (310)	30	83
EME	RT	125-145 (862 – 1000)	85-103 (586-710)	21-28	--
EME	1200 (649)	78-86 (538 – 590)	75-79 (517-545)	14-21	--
ASTM A 453 Gr 651 (19-9 DL)	RT	110 (759)	68 (469)	39	48
ASTM A 453 Gr 651 (19-9 DL)	1000 (538)	89 (614)	42 (290)	43	52
ASTM A 453 Gr 651 (19-9 DL)	1200 (649)	75 (517)	37 (255)	34	34
AMS 5700	RT	110 (758)	48 (331)	40	45
AMS 5700	1202 (650)	75 (517)	34 (234)	35	45

Table B-2 (continued)
Tensile properties of stainless steel valve materials

Material	Temp – °F (°C)	Ultimate Tensile Strength – ksi (MPa)	Yield Strength – ksi (MPa)	Elongation - %	Reduction in Area - %
AISI 316	RT	82 (565)	42 (290)	68	81
AISI 316	1000 (538)	68 (469)	23 (159)	55	70
AISI 316	1200 (649)	51 (352)	23 (159)	24	32
AISI 347	RT	90 (621)	37 (255)	50	65
AISI 347	1000 (538)	59 (407)	21 (145)	34	65
AISI 347	1200 (649)	48 (331)	20 (138)	36	67

Table B-3
Tensile properties of superalloy valve stem materials

Material	Temp – °F (°C)	Ultimate Tensile Strength – ksi (MPa)	Yield Strength – ksi (MPa)	Elongation - %	Reduction in Area - %
Incoloy 901	RT	175 (1205)	130 (895)	14	
Incoloy 901	1000 (538)	149 (1030)	113 (780)	14	
Incoloy 901	1200 (649)	139 (960)	110 (760)	13	
Refractaloy 26	RT	154 (1060)	91 (627)	19	20
Refractaloy 26	1000 (538)	143 (986)	85 (586)	18	
Refractaloy 26	1200 (649)	136 (938)	89 (614)	15	
W-545	RT	150-181 (1030-1248)	105-132 (725-910)	10	12
W-545	1000 (538)	127-154 (877-1062)	96-120 (660-827)	12-15	31-37
W-545	1200 (649)	110-133 (760-917)	91-114 (625-786)	15-21	33-46
Inconel 718	RT	210 (1448)	175 (1207)	22	--
Inconel 718	1000 (538)	185 (1276)	155 (1069)	18	--
Inconel 718	1200 (649)	168 (1158)	149 (1027)	19	--

Table B-4
Physical properties of low-alloy valve materials

Temperature	Temperature	Coefficient of Thermal Expansion From 70°F (21°C) to Temperature	
°F	°C	10 ⁻⁶ /°F	10 ⁻⁶ /K
135M			
200	93	6.3	11.3
AISI 4140			
212	100	6.8	12.2
392	200	7.0	12.6
752	400	7.6	13.7
1112	600	8.1	14.6
2.25Cr-1Mo			
200	93	6.60	1.88
400	204	7.07	12.73
600	316	7.38	13.28
800	427	7.62	13.72
1000	538	7.82	14.08
1100	593	7.90	14.22

Table B-5
Physical properties of stainless steel valve materials

Temperature	Temperature	Coefficient of Thermal Expansion	
°F	°C	$10^{-6}/^{\circ}\text{F}$	$10^{-6}/\text{K}$
AISI 410 (From 32°F (0°C) to Temperature)			
212	100	5.5	9.9
600	315	6.3	11.4
1000	538	6.4	11.6
AISI 422 (From 32°F (0°C) to Temperature)			
212	100	6.2	11.2
600	315	6.3	11.4
1000	538	6.6	11.9
AISI 316 (From 32°F (0°C) to Temperature)			
212	100	8.8	15.9
600	315	9.0	16.2
1000	538	9.7	17.5
AISI 347 (From 32°F (0°C) to Temperature)			
212	100	9.2	16.6
600	315	9.6	17.2
1000	538	10.3	18.6
ASTM A 453 Gr 651 (19-9 DL) (From 70°F (21°C) to Temperature)			
200	93	8.5	15.3
600	316	9.31	16.6
800	427	9.59	17.3
1000	538	9.78	17.6
1200	649	9.97	17.9
AMS 5700 (From 77°F (25°C) to Temperature)			
200	93	7.9	14.2
600	316	9.5	17.1
1000	538	10.2	18.4
1200	649	10.5	18.9

Table B-5 (continued)
Physical properties of stainless steel valve materials

Temperature	Temperature	Coefficient of Thermal Expansion	
°F	°C	$10^{-6}/^{\circ}\text{F}$	$10^{-6}/\text{K}$
G18B (From 70°F (20°C) to Temperature)			
212	100	8.9	16
572	300	8.9	16
932	500	9.4	17
1292	700	10.0	18

Table B-6
Physical properties of superalloy valve materials

Temperature	Temperature	Coefficient of Thermal Expansion From 70°F (21°C) to Temperature	
°F	°C	$10^{-6}/^{\circ}\text{F}$	$10^{-6}/\text{K}$
Alloy 718			
200	93	7.3	13.1
400	204	7.5	13.5
600	316	7.7	13.9
1000	538	8.1	14.6
1200	649	8.4	15.1
Incoloy 901			
392	200	7.89	14.2
752	400	8.06	14.5
1112	600	8.33	15.0
1292	700	8.50	15.3
Refractaloy 26			
392	200	7.89	14.2
752	400	8.39	15.1
1022	550	8.72	15.7
1112	600	8.89	16.0

Table B-6 (continued)
Physical properties of superalloy valve materials

Temperature	Temperature	Coefficient of Thermal Expansion From 70°F (21°C) to Temperature	
°F	°C	10 ⁻⁶ /°F	10 ⁻⁶ /K
W-545			
300	149	9.32	16.8
600	316	9.67	17.4
900	482	9.88	17.8
1200	649	10.1	18.2
Stellite 6B			
392	200	7.8	14.1
572	300	8.0	14.5
752	400	8.2	14.7
932	500	8.3	15.0
1112	600	8.5	15.3
Stellite 6			
200	93	7.70	13.86
400	204	7.83	14.09
600	316	8.11	14.60
800	427	8.17	14.71
1000	593	8.36	15.05
1200	649	8.62	15.52

A qualitative ranking of the oxidation and wear resistance for the steam turbine materials is given in Table B-7. The rankings are given for the three classes of material: low alloy, stainless steel, and superalloy. They are based on an engineering evaluation of overall service performance found in the current study and limited test data found in the open literature.

Table B-7
Qualitative ranking of wear and oxidation resistance of valve materials

Class of Material	Wear Resistance and Antigalling of Nitrided Material	Oxidation Resistance of Nitrided Material
Low Alloy	Good	Poor to Fair
Stainless Steel	Good	Fair to Good
Superalloy	Good	Good to Excellent

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