A DESIGNERS'
HANDBOOK
SERIES

REVIEW OF THE WEAR AND GALLING CHARACTERISTICS OF STAINLESS STEELS

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Contents

Introduction

For the vast majority of stainless steel applications throughout industry, such as tanks, vessels, piping, structural components, utensils, and general hardware items, material selection is based on four criteria. Listed in order of importance, they are:

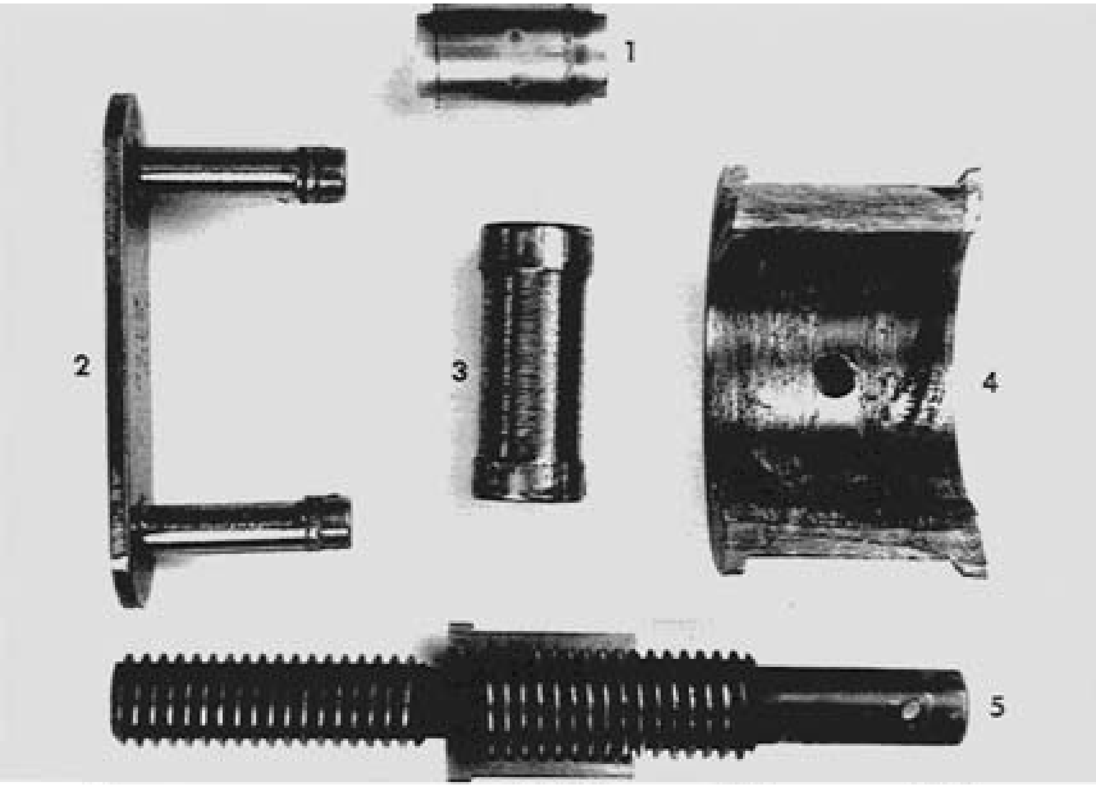
Corrosion Resistance
Mechanical Properties
Fabricability
Cost

For mechanical equipment, however, such as pumps, valves, bearings, seals, conveyors, and fasteners–in which mating metal surfaces rub together–consideration may also be given to wear and galling.

Finding the most effective alloy to withstand wear and galling, while meeting other property requirements, constitutes a worrisome problem for equipment engineers and manufacturers–especially when there is a risk of corrosion or there is need for sanitation as in food or pharmaceutical processing, which precludes the use of lubricants. Not only does wear directly affect equipment life, but galling in a critical part can shut down or endanger an entire plant.

In recent years, many new and improved systems have been introduced to help reduce the deleterious effects of wear. Synergistic coatings, electro-deposited coatings, flame sprayed coatings, non-polluting liquid nitriding, new lubricants, and new alloys all make it more difficult for the designer to arrive at the best solution.

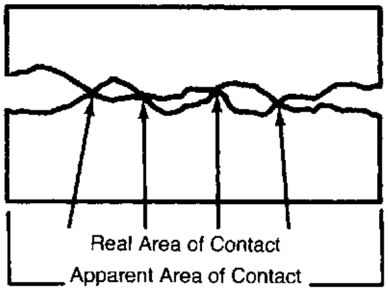
This booklet is intended to be a summary reference on design factors in assemblies where sliding contact exists between wrought stainless steel and another metallic component, not necessarily stainless.



Typical wear and galling problems:
1. Bushing for chain belt.
2. Link for chain belt.
3. Bushing for chain.
4. Rod end bearing.
5. Valve stem.

Definitions of Wear and Galling

The study of wear and galling (1) involves surface phenomena as well as the fundamental properties of materials. This is particularly true when the metals do not benefit by conventional lubrication. The smoothly finished surfaces associated with conventional bearing applications are in reality rough and irregular, as shown in the following sketch



Thus when two smooth metal surfaces are brought into contact, asperities, or high points, and not the nominal areas are in contact. Under static loading, deformation of the asperities occurs until the real contact area increases to support the load.

If relative motion is then introduced, adhesive wear or galling may occur in one or both of the following ways: (1) by shearing of interface oxides protective to the base metals followed by asperity contact and welding under pressure, with the weaker of the two metals yielding; (2) by the formation of a weld junction that is stronger than either of the base metals causing wear to take place in the bulk of both materials in sliding contact.

The ASTM Subcommittee on Wear (G02.30) of the Erosion and Wear Committee (G-2) has encouraged the study of wear testing to assist designers in solving wear problems. ASTM published (2) a number of papers presented at the Symposium on the Selection and Use of Wear Tests for Metals, held November 20, 1975 in New Orleans, LA. A few of the papers review the field of wear and list several references from which many of the following definitions of wear were extracted.

Adhesive Wear

This booklet deals primarily with adhesive wear, which is probably the most common form of wear, especially in mating stainless steel components. It has been defined as "wear by transference of material from one surface to another during relative motion, due to a process of solid-phase welding" (3). In most cases there is an absence of an abrasive.

Adhesive wear results from two metal surfaces rubbing together under sufficient load so that the surface oxide film on the asperities is broken, causing direct contact between the two metals. When the adhesive forces of the two metals exceed the strength of either metal, adhesion and, subsequently, adhesive wear occurs. Under low stress, slight bonds form wherever high points of the two surfaces touch and subsequent motion results in plastic deformation with a loss of ductility and eventual fracture. These wear fragments may transfer back and forth between the surfaces, causing further damage.

Galling

At high stresses, much stronger bonds form over a greater contact area; gross surface damage occurs, and the equipment may even seize or "freeze-up." This latter gross damage is usually referred to as galling, and it may take place after just a few cycles of movement between the mating surfaces.

Some applications where adhesive wear is encountered are roller chain belt pins, woven screening, hanger, end, and spherical bearings, and valve and pump components. Galling is a potential problem in all types of threaded assemblies including fasteners, turnbuckles, check valves, stems, inserts and electrical connectors.

Abrasive Wear

Abrasive wear results when a harder material cuts or plows grooves in a softer surface (4) usually resulting in loose wear fragments. The harder material may be one of the contacting surfaces or it may be a third body introduced between the two surfaces. Abrasive wear is a major concern to the farming industry (plow shares, tine points) (5) and mining industry (ore crushers, shovel teeth, drill bits) (6).

The initial remedy for abrasive wear is to make the mating surfaces as hard as possible and reduce the hardness difference between surfaces. Foreign abrasive particles should also be eliminated with air cleaners, oil filters, dust covers, and seals.

Corrosive Wear

In an aggressive environment wear can be increased by chemical or electrochemical reaction, or corrosion, and is usually more severe under hot, wet conditions.

Fatigue Wear

Cyclic stress variations in machine components can result in the removal of particles by fatigue.

Erosive Wear

Abrasive wear caused by a gas, liquid, or particles contained in a liquid is generally classified as erosive wear, and it can be intensified by chemical action (corrosion).

Thermal Wear

Removal of particles at elevated temperature by softening, melting, or evaporation is thermal wear or high-temperature erosion.

Fretting Wear

Not to be confused with fretting corrosion in which chemical reaction predominates, fretting wear occurs between two surfaces having oscillatory relative motion of small amplitude. (Sometimes applied to adhesive wear depending on amplitude of relative motion.)

Factors Affecting Wear

Numerous factors have been found to affect wear, such as those in the following table (7):

Wear Variables

- Temperature
- Load
- Velocity
- Contact Area
- Shape
- Sliding Distance
- Atmosphere
- Material Properties
- Lubrication
- Finish
- Vibration
- Type of Motion

These can be grouped into material factors, conditions imposed by service, lubrication, and environmental factors.

Material factors known to have an effect on adhesive wear include the following:

Hardness–In general, resistance to wear is increased by increasing hardness, provided other factors remain constant. There is some question, however, whether the controlling hardness is the bulk hardness or simply surface hardness. It has been stated that to increase wear resistance, hardness should be increased by alloying or heat treatment. Further, it is noted that work hardening, prior to placing in service, fails to increase the resistance of materials to wear and that surface hardening treatments, such as nitriding, are not effective in severe wear conditions (8). Elsewhere (9) it has been stated that wear volume is inversely proportional to the hardness of the surface being worn away, and that this hardness is not the bulk hardness measured before the wear process, but rather that attained at the wear interface during sliding. This is why the high-strain-hardening alloys such as the austenitic stainless steels outwear some harder alloys like the precipitation hardening grades (10).

Surface Finish–Generally the rougher the surface the greater the wear. On the other hand, very smooth surfaces, less than about 10 microinches (RMS) lack the ability to store wear debris (and lubricants) due to the absence of valleys between asperities.* In addition, very smooth surfaces increase molecular interaction forces that promote cold welding and increase the strength of welds (8, 10). It has been noted that, when initially formed, welds due to adhesion are small and motion across the surface finish lines, as opposed to paralled motion, minimize the growth of welds (11).

Microstructure–Cold welding and adhesive wear may be lessened by a complex structure (two or more phases). Complex structures include alloys with a single phase matrix having a dispersion of carbides, nitrides, sulfides, or silicides (12, 13).

The reader is referred to the literature for discussions on the effects of various service, lubrication and environmental factors on wear (2).

Wear and Galling Tests

It can be seen from the previous discussion and from a review of the literature that many factors can affect wear, and there appear to be no hard and fast guidelines for preventing wear. Consequently, the problem a designer faces in selecting appropriate materials is very complex, and testing of various materials under actual operating conditions may be necessary. However, wear testing under laboratory conditions can reduce the number of candidates for in-service tests and facilitate a solution to the design problem.

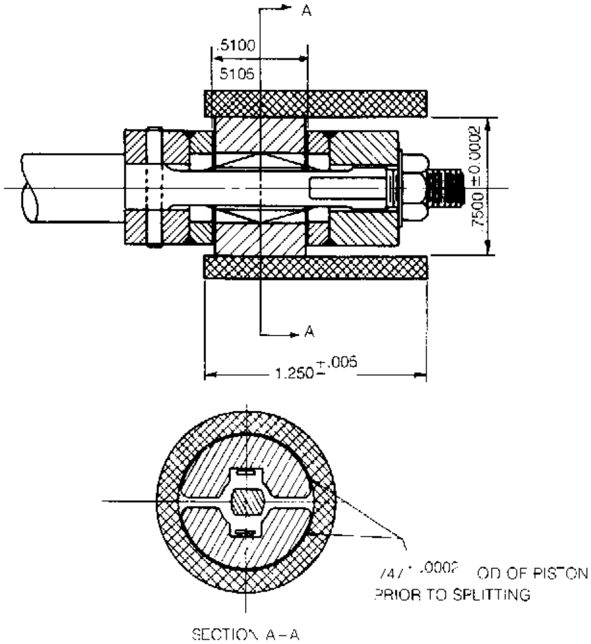
Several laboratory tests have been devised to evaluate the wear and galling properties of stainless steels and other metals, and some of the data are reviewed in this publication. It should be emphasized that any wear data presented in literature should not be used for design purposes. Results obtained from these tests, even under identical laboratory conditions, are not always reproducible.

*Recent work by Schumacher has shown that variations in surface roughness from 70 microinches (AA) to 4-5 microinches (AA) and electropolished surfaces have no significant effect on the wear rate of Nitronic 60, S17400 (17-4 PH), and Type 430F. These wear samples were nonlubricated.
Source: Unpublished report by W. J. Schumacher, October 31, 1977,

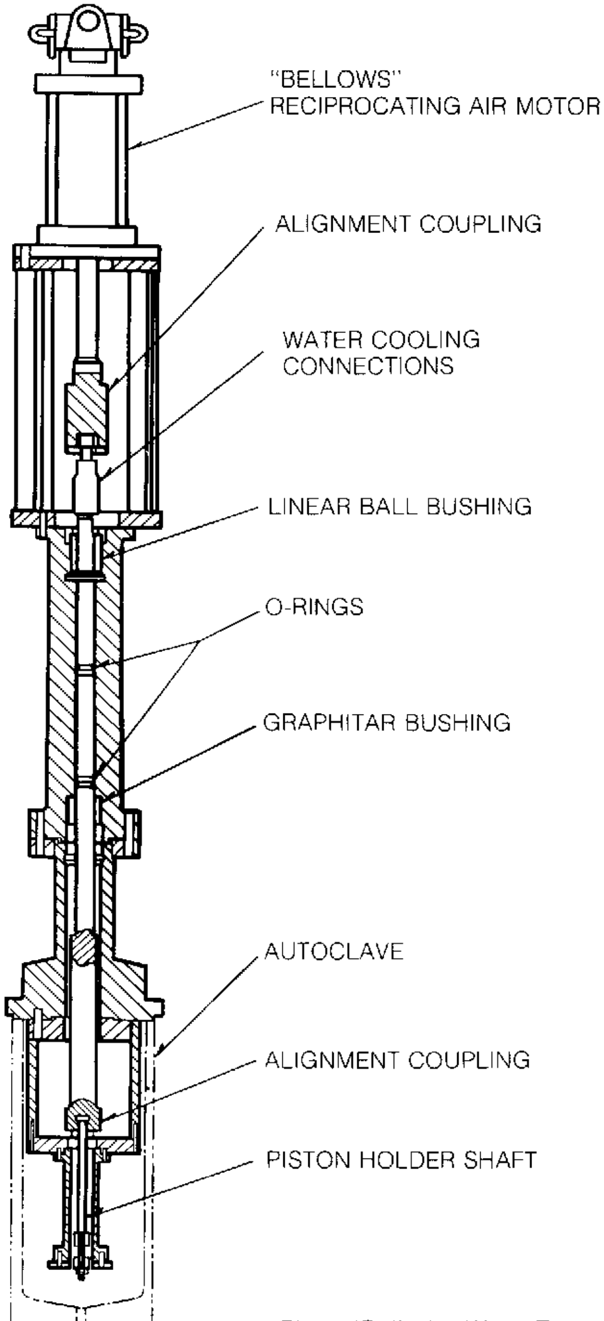
Blaser (1) describes test arrangements used to investigate the wear properties of materials in a high-temperature (500ºF or 260ºC) water environment. These tests utilized components whose shape, relative motion, and load simulate the design and application of components used in water-cooled nuclear reactors. Journals rotating in sleeves, shafts rotating against flat plates, spherical specimens moving against conical slotted pieces, and pistons moving within cylinders were some of the shapes used.

For example, linear motion was observed in piston/cylinder tests in which reciprocating motion was produced by a piston moving within a restraining cylinder. Temperature was maintained by conducting the test in an autoclave.

The specimens consisted of a split piston fitting within a cylinder. Chevron rings located between piston halves loaded the system by forcing the piston halves outward against the cylinder wall.



Piston-cylinder specimen assembly.



Piston/Cylinder Wear Test

To simulate rotating motion, as opposed to linear motion described above, a journal/sleeve test was utilized. The test specimens were designed so the nominal wear area was the same as that encountered in the piston/cylinder tests.

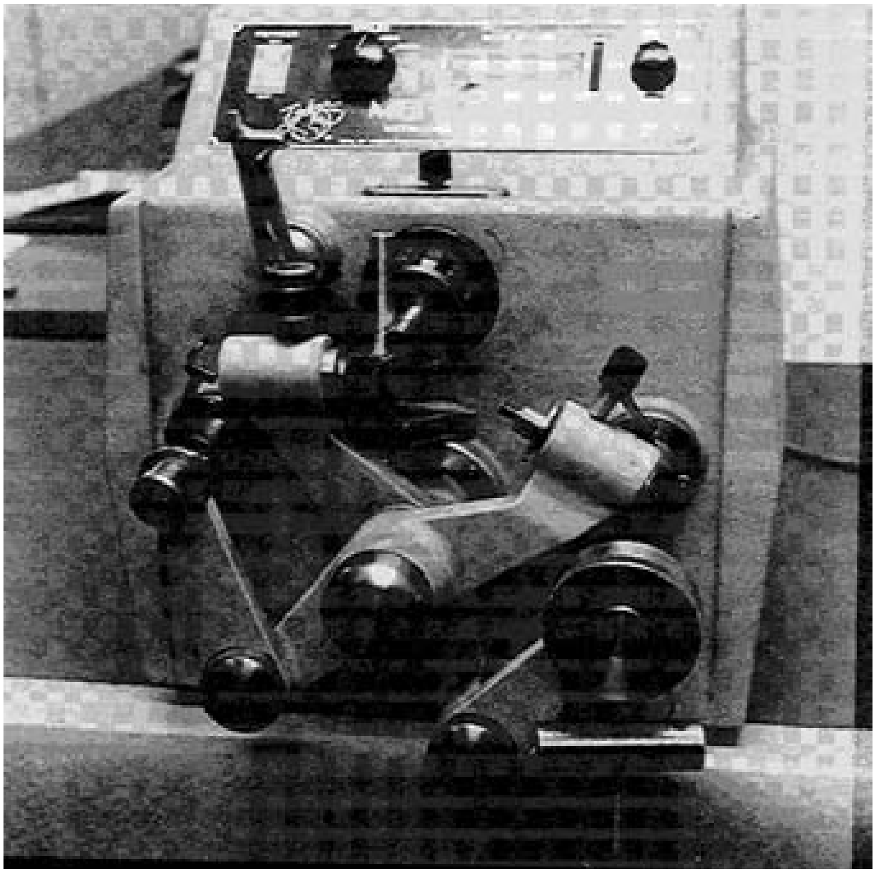
The tests were conducted in oxygenated water containing 10 to 30 cc of oxygen per kilogram of water. The martensitic stainless steels were tested in the hardened condition; the others in the annealed condition– except the precipitation hardening grade Type S17400 (UNS). Type S17400 was tested in both the hardened condition and as solution-annealed. The surface finish of specimens prior to testing ranged from 8 to 16 microinches (RMS).

Wear factors were determined by measuring the weight loss (in milligrams) per pound load per million cycles. Tests were conducted for 500,000 cycles at a loading of eight pounds per square inch (psi), and at a temperature of 500ºF (260ºC).

Schumacher (10) describes a more recent test using a modified commercial wear machine,* which is used to evaluate metal-to-metal sliding wear (nonlubricated). The machine was altered by replacing one grinding wheel with a fixture to hold a ½" diameter specimen vertically which is pressed against a rotating ½" diameter horizontal specimen under a 16-pound load.

For this test, specimens were polished with a 120-grit cloth to about 25 microinch as (arithmetic average) finish, and run at 105 revolutions per minute (rpm) for 10,000 cycles. Replicate tests of dissimilar couples were run in both positions and averaged to cancel out differences arising from greater wear for the moving position.

Tests were run at room temperature, with specimens degreased in acetone immediately before testing. Weight loss (mg/1,000 cycles) was corrected for density differences to put the information on a volume basis, although it is reported as a weight loss.



Taber Met-Abrader, Model 500, modified to evaluate metal-to-metal sliding wear, using ½" diameter specimens.

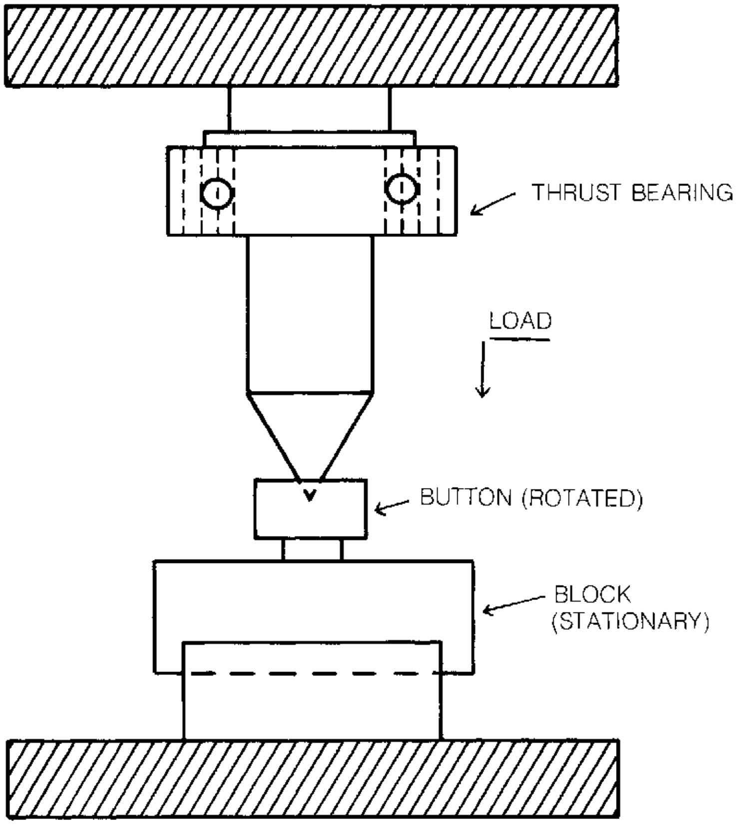
**Taber Met-Abrader, Model 500*

Galling Test

In metal-to-metal wear tests, high stresses can result in catastrophic galling and eventual seizure even after a single cycle, so a simple button-and-block galling test was devised. The test described by Schumacher (10) is modification of a test developed over 20 years ago, which now better simulates in-service conditions.

In this test a small button specimen and a large block specimen were machined to provide parallel contacting surfaces. Polished to a 3/0 grit finish, the specimens were dead-weight loaded in a Brinell hardness tester, and the button was rotated 360 degrees against the block.

Specimens were then examined for galling at 10X magnification, with new specimens tested at progressively higher stress levels until galling just begins. This point is called the *threshold* galling stress. Galling usually appears as a groove, or score mark, terminating in a mound of metal.



Arrangement for galling test shows how test blocks are loaded and rotated on the stationary block. Blocks are examined for galling after each turn.

Solutions to Wear and Galling Problems

Before interpreting the test data, it is important to keep in mind the basic criteria for selecting a stainless steel–as outlined in the introduction to this booklet. The criteria, listed in order of importance, are:

Corrosion Resistance–the primary reason for specifying stainless steels. The designer needs to know the nature of the environment and the degree of corrosion resistance required.

Mechanical Properties–with particular emphasis on general strength properties at room, elevated, or cryogenic temperatures. Generally speaking, the combination of corrosion resistance and strength is the basis for selection.

Fabrication Operations–and how the product is to be made is a third-level consideration. This includes forging, machining, forming, welding, etc.

Cost–to put everything into proper perspective, a total value analysis that will consider not only material and production costs, but the cost-saving benefits of a maintenance-free product having a long life expectancy is appropriate.

Selection procedures are thoroughly covered in technical publications and in product literature available from companies represented on the Committee of Stainless Steel Producers and from the Committee. The companies are listed on the back cover of this publication. An excellent reference is "Design Guidelines for the Selection and Use of Stainless Steel." (Tables I, II, III, and IV list the chemical compositions and mechanical properties of all AISI-numbered stainless steels, and Tables V and VI show, composition and property values of several proprietary stainless steels.)

Wear Resistance

Tables VII and IX show a partial summary of the piston/cylinder wear tests described by Blaser (1), and Tables VIII and X show data developed by Schumacher (10).

In Tables VII and VIII are data on "self-mated" combinations; i.e., identical materials for each of the two wear specimens in a test. As indicated by these data, wear resistance of the austenitic stainless steels ranges from excellent to poor. (The Nitronic stainless steels are proprietary austenitic grades containing chromium, nickel, manganese, and nitrogen.) In Table VII, for example, Type 304 vs. Type 304 shows a very high wear rate, due to lack of strain hardening at 500ºF (260ºC), and in Table VIII, a moderate wear rate. Types 201 and 301 (in Table VIII) do better probably because of their higher work-hardening rates at ambient temperature (below 350ºF or 175ºC).

Except for Type 440C (a high-hardness stainless steel frequently used for bearings), the martensitic stainless steels and precipitation hardening Type S17400 exhibited rather poor resistance in the self-mated evaluations–despite their relatively high hardness. Table VII shows Type S17400 in both the solution annealed and precipitation hardened condition.

In Table VIII, Type 316 is shown to have fair resistance to wear, while Type 303 shows poor resistance. Type 303 is a free-machining grade containing sulfur, and evidently the sulfides foster wear debris before much strain hardening can take place.

On the basis of these data, it appears that Types 416, 420, 303, 304, 316 or S17400 would not provide good wear resistance when mated to themselves in a nonlubricated application; whereas Types 201, 301, and hardened 440C, and the proprietary Nitronic austenitic grades would. Overtempering Type 440C effectively destroys its otherwise good wear resistance.

The high-nickel alloys generally placed intermediate between the austenitic and martensitic stainless steels. Waukesha 88 contains a second phase high in tin and bismuth, which acts as a solid lubricant and serves to reduce the wear rate despite the high nickel content. The cobalt-base alloys also did well.

Tables VII, VIII, IX and X suggest that considerable improvement in wear resistance can be achieved with the proper selection of alloys. For example, Type 304 improved considerably when coupled with other materials, except with Type S17400. Type 440C matched with Nitronic 60 sustained the lowest weight losses of all dissimilar stainless steel couples tested. However, low corrosion resistance, poor weldability and poor cold formability may preclude the use of Type 440C in some applications.

Coupled with silicon bronze or the Stellite alloys, the stainless steels exhibited significant improvement over the self-mated couples. These alloys protect the mating stainless steels well with very little wear to themselves.

Galling Resistance

The data in Tables XI and XI I, developed by Schumacher (10, 14), show the relatively low galling resistance of the austenitic and precipitation hardening stainless steels. The remaining standard alloys exhibit fair to good galling resistance in a few combinations. On the other hand, two austenitic stainless steel alloys in the Nitronic family (32 and 60) exhibit high galling resistance. The latter alloy was developed especially to exhibit antigalling and metal-to-metal wear resistance.

Although few non-stainless steels were tested, Schumacher demonstrated the detrimental effect of high-nickel content on galling resistance. Unless a nickel-base alloy is modified specifically for galling resistance (as is the case with Waukesha 88), poor galling resistance may result. Waukesha 88 exhibited high galling resistance (50+ksi) in combination with several stainless steels.

Wear Coatings

Table XIII (1) shows that further improvement in wear resistance can be achieved by altering the surface characteristics, such as nitriding, or adding a surface coating, such as chrome plating. For example, nitrified Type 347 in the piston/cylinder wear tests shows a zero wear factor, and chrome plated Type S17400 enhances wear resistance when mated to unplated Type 304 or S17400. Also, hardfacing with the nickel-base or cobalt-base alloys can improve wear resistance.

Nitriding

Nitriding is a case hardening process whereby nitrogen is introduced into the surface of stainless steel by holding at a temperature between 925ºF (496ºC) and 1050ºF (566ºC) in a nitrogen atmosphere. Two processes are widely used; one in which the atmosphere is nitrogenous gas, such as ammonia, and the other a liquid nitriding process that uses a salt bath consisting of potassium cyanide (KCN) and potassium cyanate (KCNO). The result of the reaction is the formation of a compound layer reported to consist of iron nitrides and chromium nitride.

While the austenitic stainless steels (300 Series) are difficult to nitride, Types 301, 302, 303, 304, 308, 309, 316, 321 and 347 have been successfully nitrided (15).

Since these alloys cannot be hardened by heat treatment, the core material remains relatively soft, and the nitrided surface is limited as to the loads it can support. On the other hand, the hardenable martensitic stainless steels are capable of providing high core strength to support the nitrided case. Precipitation hardening grades, such as S17400 and A-286, have also been successfully nitrided.

The comparative galling characteristics of seven stainless steels with and without nitriding are shown in Table XIV (16). In this test, two sets of specimens from each stainless steel, one of each of which was nitrided, were tested on a Faville-LeVally Falex machine, which is used to determine comparative galling and seizing characteristics. The test is conducted by clamping test blocks around a test pin (as shown opposite) in the machine, applying a load, and measuring the time required for galling to occur.

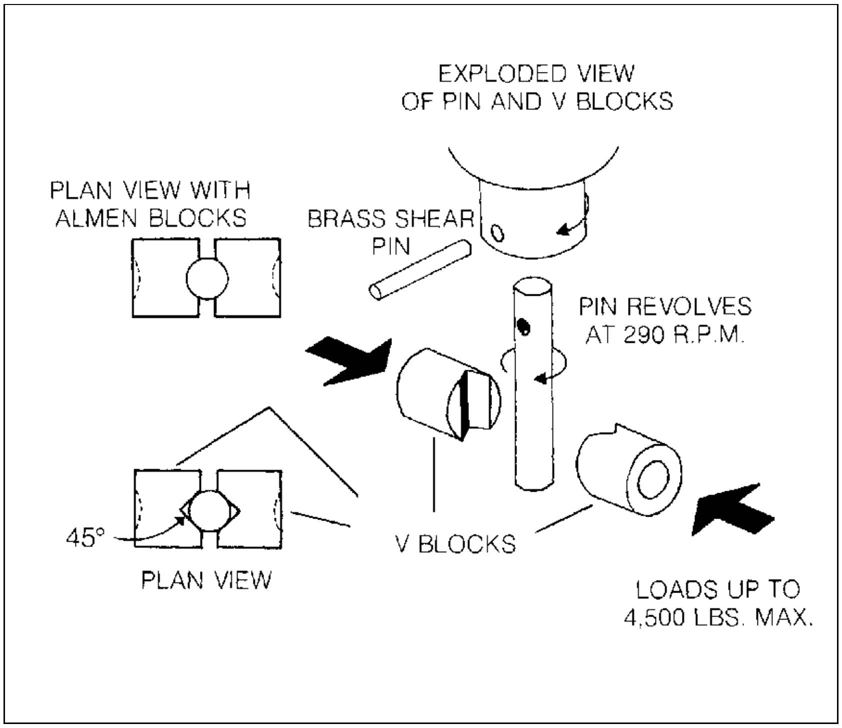
Types 416 and 440C were hardened and tempered (the latter being accomplished in the 1050ºF (566ºC) salt bath). The other stainless steels were annealed.

The superiority of the nitrided pins was observed either with increased load or time to galling–or both. The results in Table XIV also show a variation in behavior among the different alloys, which suggests that composition is a factor. For example, Alloy 303MA (a proprietary stainless steel in which the free-machining characteristics are enhanced by the alloying addition of aluminum instead of sulfur), shows a surprisingly high level of galling resistance in the nitrided condition as compared to Type 303.

It should be pointed out that while nitriding enhances wear resistance, it decreases corrosion resistance by the fact that the surface chromium combines with nitrogen to form chromium nitride. Also, at the temperatures required for nitriding, carbide precipitation does occur in the austenitic stainless steels which can lead to intergranular corrosion. However, nitrided stainless steels have many years of successful application in food and textile processing, petroleum refining, nuclear power generation, alkaline solutions, ammonia, caustics, steam (to 1100ºF or 593ºC), and stack gases–and in cryogenic applications to –320ºF (–195ºC). Service life of nitrided stainless steels is questionable when in contact with mineral acids or salts of these acids.

Chromium Plating (17)

Hard chromium plating differs from decorative chromium plating in several ways: (1) Hard chromium deposits are intended primarily to improve wear resistance rather than to enhance appearance. (2) Hard chromium deposits range in thickness from 0.1 to 20 mils, whereas, decorative plating seldom exceeds 0.1 mil. (3) Hard chromium plating is usually applied directly to the base metal; decorative plating is applied over undercoats of other materials, such as nickel. (4) Hard plating is more likely to be impervious than decorative coatings.



Extensive performance data (including those in Table XIII) indicate the effectiveness of hard chromium plating in enhancing wear resistance in metal-to-metal contact. It also has excellent resistance to galling, seizing, and corrosion, although it is *not* recommended for applications where extreme heat or pressure are generated because the plating may crack and spall. The electro-deposited chromium begins to decrease in hardness when exposed to temperatures above 400ºF (204ºC), and as hardness decreases so do its wear-resistance characteristics.

From the standpoint of processing, hard chromium plate may be applied to stainless steels regardless of their chemical composition and surface hardness. The hardness of the base metal, however, is important because it provides support for the plate. Chromium plating is available through many commercial sources.

Surface Coating With Infused PTFE

A recent article in AMERICAN MACHINIST (18) describes a proprietary process in which a controlled amount of polytetra-fluorethylene (PTFE) is infused into a porous nickel plating to enhance resistance to corrosion and wear.

In the process, hard porous, nickel plating is electro-deposited onto a base-metal surface,* and through a series of proprietary operations the micropores are enlarged. The enlarged pores are then infused with PTFE, which provides lubricity and resistance to a wide variety of organic and inorganic chemicals. This is followed by heat treatment that ensures thorough infusion of the PTFE and increases hardness of the electro-deposited matrix.

Abrasion and wear resistance is provided by a coating hardness of 750 Vickers (about Rc62), and the infusion of PTFE produces a surface with a coefficient of friction of 0.05, eliminating the likelihood of galling or seizing. Service temperatures of the coated parts range from cryogenic to 500ºF (260ºC). Tests conducted on a Taber Met-Abrader, Model 500 (modified to accommodate metal-to-metal wear evaluations) with Types 303 and S17400 coated with infusion PTFE show a significant improvement in wear resistance (19) over uncoated specimens. With S17400, for example, tested at 10,000 cycles, the effectiveness of the coating was calculated to be 91.7%.

Hardfacing

Corrosion and wear-resistant coatings are applied to stainless steels and other metals with a variety of methods that result in coatings that are mechanically or metallurgically bonded to the base metal. Four basic processes are used: weld surfacing, metallizing, plasma spraying, or cold spraying (20).

Weld surfacing, which can be achieved by oxyacetylene or arc welding, flame spraying, or fused paste, produces a metallurgical bond between the coating and base metal. A wide variety of coating materials are available in the form of bare or covered electrodes, and powders. For example, American Welding Society (AWS) Specification A5.13 and American Society for Testing Materials (ASTM) Specification A399 lists 20 types of weld rods and 25 types of covered or bare electrodes, and there are many more unclassified types. Materials include nickel-base, cobalt-base, and iron-base alloys, chromium carbide, and chromium boride.

*General Magnaplate Corporation Nedox Coating Process

Metalized coatings can be applied by two techniques: spraying powder or spraying wire. Where weld surfacing produces a metallurgical bond between coating and base metal, metallizing results in only a mechanical bond. Such a coating may not stand up in service where galling is a problem even though the metallized surface has good wear- and corrosion-resistant characteristics.

Plasma spraying offers a means of depositing virtually any inorganic material that will not decompose when heated to 2500ºF (1400ºC) in a plasma stream. The high temperature of the ionized gas and the fact that the plasma is generated without combustion make it possible to spray reactive materials without changing their composition. The coating produced contains little oxidized material, and it is dense, strong, and well bonded to the base metal.

In **cold spraying**, a powder and binder are applied to a surface by an air-powered spray gun without the aid of heat. Fusion takes place in a subsequent furnace-brazing operation.

Fused Salt Sulfurization (21)

A spectacular improvement in antigalling properties was shown by alloys that had been given a fused salt sulfurization treatment, such as described by Jousset (22). Untreated Type 304 was found to gall excessively at 14,000 psi bearing stress, while sulfurized Type 304 operated self-mated at stresses as high as 22,000 psi without galling. With lubrication, no galling occurred in sulfurized Type 304 at stresses as high as 61,000 psi.

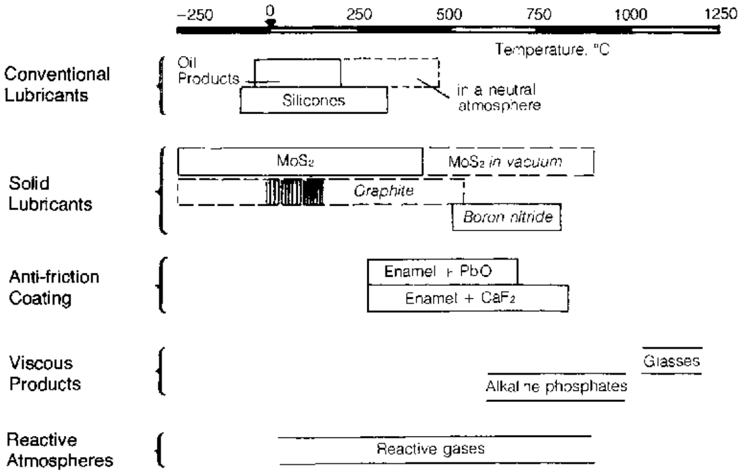
The success or failure of surface coatings to enhance wear or galling resistance depends on the nature of both the coating and application. Obviously the coating must overcome any wear or galling tendencies of the base alloy, and it must be sufficiently adherent to remain intact on the metal surface during use. Also, unless the coating resists corrosion or high temperature oxidation, it will soon deteriorate and become worthless. This aspect needs to be thoroughly investigated before any coating can be considered for use in a specific environment.

Lubrication

Working with nickel-base alloys and an Amsler Wear Test Apparatus, Kozlik 21 demonstrated the extent to which lubrication minimized wear and galling problems in metal-to-metal couples. In his test involving lubrication, an oil reservoir was mounted on the test apparatus to provide constant lubrication to one member of the test couple. The lubricant used was a light turbine oil having a viscosity of 305 Saybolt second at 100ºF (38ºC) and 50.8 Saybolt seconds at 210ºF (99ºC). This particular type oil was selected because of its freedom from additives that might have introduced additional variables to the tests.

From the Kozlik data the conclusion is drawn that materials in a self-mated test, which have a marked tendency to wear or gall, do not benefit greatly from the addition of lubrication. In order to be effective, lubrication should be used with dissimilar metal couples, as discussed in previous sections of this booklet. In other words, metals should be selected first on an evaluation of their wear and galling characteristics *unlubricated,* and then add lubrication to enhance their performance. In addition to the reduction of friction, the lubricant acts as a coolant and to wash away any products of wear.

For a great majority of applications, the standard oil-base lubricants are generally used. However, for service at elevated temperatures, it may be necessary to use a solid-type lubricant. The following figure summarizes the application temperatures for various kinds of lubrication



Service Temperature of Various Lubricants

For example, the temperature range in which conventional lubrication methods can be applied is –22ºF to 392ºF (–30ºC to 200ºC) for hydrocarbons, and –103ºF to 617ºF (–75ºC to 325ºC) for silicones. In a neutral atmosphere, which prevents decomposition, the application range could reach higher temperatures. From tests conducted by NASA, for instance, it was reported that a ball-bearing showed excellent performance lubricated with mineral oil and in service for 20 hours at 851ºF (455ºC) in a nitrogen atmosphere.

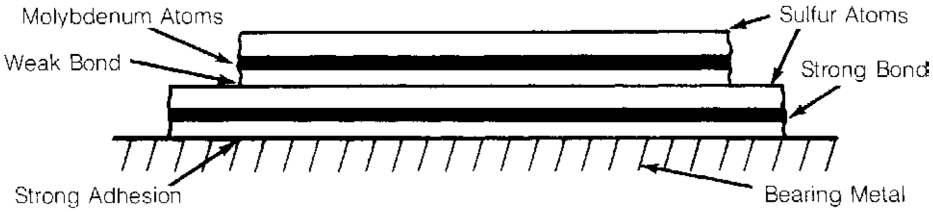
Considerable data are available on conventional oil products from oil companies and their distributors, and from suppliers of lubrication equipment. The practices followed are those normally used for lubricating any machinery components.

High-Temperature Applications

Stainless steels have been used successfully to prevent galling and seizing at temperatures of up to 1500ºF (816ºC). A typical example is the use of stainless steel in an early fuel evaporation (EFE) valve in automotive emission control systems. Exposed to hot exhaust gases, the valve is designed to operate–without lubrication–for 50,000 miles. Function of the valve is to redirect exhaust gases to preheat cold fuel droplets during cold starts. When the engine warms, the valve opens to allow normal exhaust flow.

To reduce wear in moving parts in high-temperature service, in which there is metal-to-metal contact, it is often necessary to apply a lubricant. As far as industrial applications are concerned, solid lubricants, such as molybdenum disulfide, form the most important category of unconventional lubrication methods.

Molybdenum disulfide essentially comprises a layer of molybdenum atoms sandwiched between two layers of sulfur atoms, as shown in the figure below.



Sulfur atoms are strongly attracted to metallic atoms, but the bond between individual sulfur atoms is weak. Friction between two metal surfaces covered by a film of molybdenum disulfide will be low due to the ease with which the sulfur/sulfur bond shears, and the fact that surface asperities have difficulty penetrating the layers of molybdenum.

The lubricating properties of molybdenum disulfide are unaffected by temperatures up to 725ºF (400ºC), since, being solid, viscosity changes with temperature changes do not occur as with normal oils and greases. Where oxygen is excluded, as in atomic reactors or in close engineering fits, the upper temperature limit for molybdenum disulfide is as high as 1913ºF (1045ºC) (23). The unusual characteristics of solid films makes them well suited to extreme-pressure lubrication.

In general, pretreatment of metal surfaces prior to solid film lubricant deposition has been found to increase wear life characteristics. For example, the Falex wear test results shown in Table XV demonstrate the differences in running time, as affected by pretreatment, for a Type 302 pin rotated under load against two steel V-blocks. The solid film lubricant applied to the test pin after pre-treatment consisted of molybdenum disulfide, graphite, and sodium silicate. No pretreatment or lubricant was applied to the V-block specimens.

Seizing of Threaded Couplings

A frequent complaint expressed about stainless steel fasteners and other threaded couplings is the problem of seizing. The problem is frequently not that of the material itself but more than likely caused by mismatched threads, nonuniform threads, and dirt on threaded surfaces. Reasonable care should be exercised in the handling of fasteners to prevent damage and to keep threads clean.

Fasteners made in accordance with nationally recognized standards, such as published by the American National Standards Institute, Inc. (ANSI), will assure that nuts and bolts are uniformly threaded. Torque should also be considered for a properly fastened joint. Suggested maximum torque values for stainless steels are published in the booklet "Stainless Steel Fasteners A Systematic Approach to Their Selection," copies of which are available from the Committee of Stainless Steel Producers. Nevertheless, galling may occur in clean, carefully machined threads, and it may be desirable to use a lubricant if another alloy material either cannot be used or is not available.

If a lubricant is going to be used with threaded fasteners, tests should be conducted to determine torque requirements and to evaluate the compatibility of the lubricant to the environment. Among the popular lubricants are those containing substantial amounts of molybdenum disulfide, graphite, mica, talic, copper or zinc fines, or zinc oxide. Zinc-bearing lubricants are not recommended for use with stainless steels at elevated temperature.

Design Considerations for Reducing Galling and Wear

Design Considerations

1. Lubricate where possible.
2. Keep load, temperature, and speed as low as possible.
3. Start with mated surfaces having a finish between 10 and 70 microinches. (Below 10 increases suscepitibility to galling; above 70 increases susceptibility to wear.)

4. Increase contact area:
    a. to lower stress below threshold galling stress.
    b. to produce less depth of wear (by spreading the wear volume over a greater area).
5. In unlubricated systems or where the lubricant may not always be present, alloy selection is critical. Therefore, it is desirable to:
    a. select alloys with high threshold galling stresses as one mating surface for significant improvement in galling resistance.
    b. use dissimilar alloys and/or those with differential hardnesses on the sliding surfaces to achieve somewhat lesser improvements in galling resistance.
    c. select high work-hardening austenitic stainless steels for improved wear resistance (but not galling resistance) at temperatures below 350ºF (175ºC).
6. Consider the use of wear coatings.

(A)

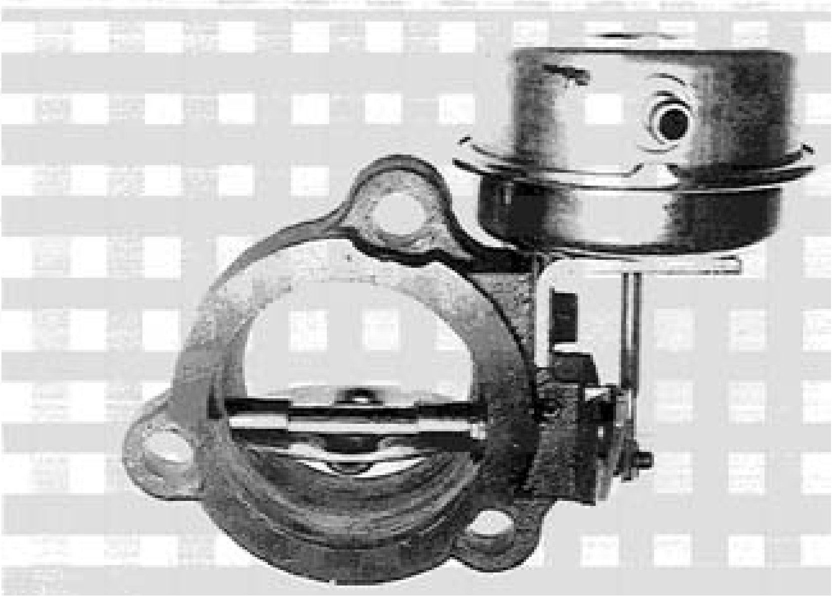
(A) Sailboat Turnbuckles

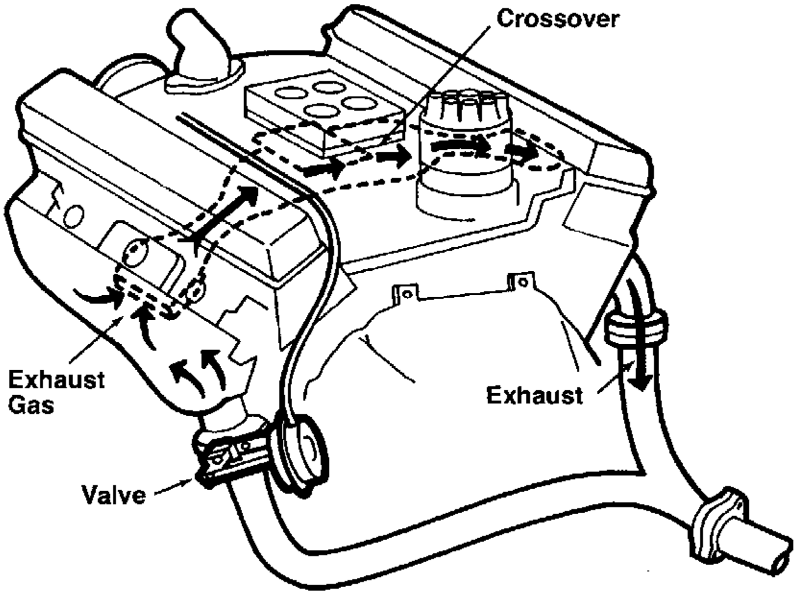
A switch to stainless steel from silicon bronze for yacht turnbuckles has virtually eliminated problems of galling during assembly or "cold welding" under load. Type 304 and a proprietary alloy (22Cr-13Ni-5Mn) were selected for the mating parts because of their resistance to corrosion and galling.

(B) Early Fuel Evaporation Valve

The EFE valve is a butterfly valve located near the exit of an automotive exhaust manifold, and it is used to direct hot exhaust gas to preheat fuel during cold starts. When the engine warms, the valve opens to allow normal exhaust flow. Exposed to 1500°F, the materials must have resistance to corrosion, good high-temperature strength and oxidation resistance, and–because lubrication is not practical–good resistance to wear and galling. A stainless steel was selected for the application because of its desirable anti-galling properties.

(B)





Primary Flow Sensor

The all-stainless flow sensor was experiencing galling problems in the Type 304 nuts and adjusting rods. By switching the rods to a stainless steel with better anti-galling characteristics, the problem was solved at minimum cost and without loss of corrosion resistance.

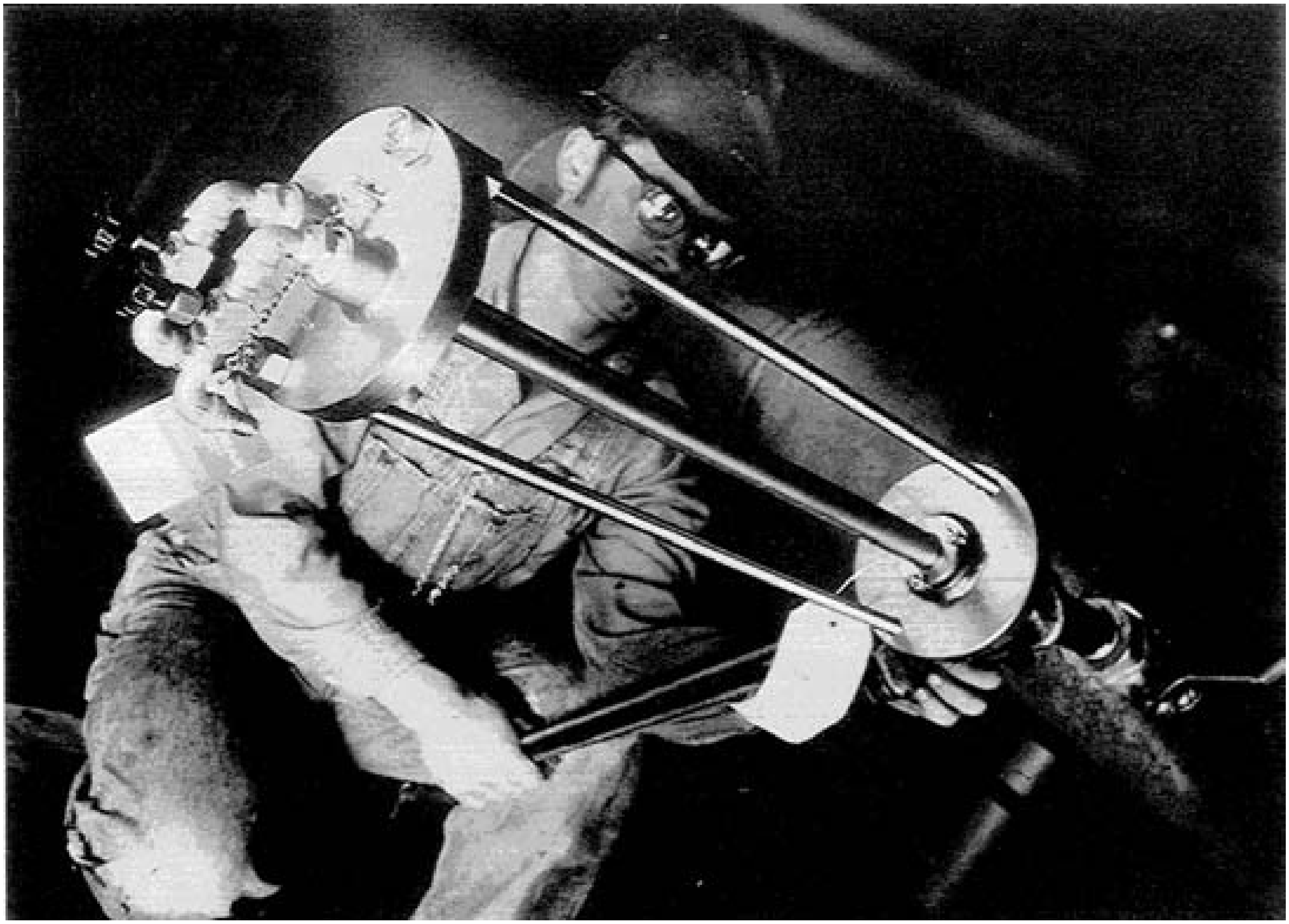


TABLE I

AUSTENITIC STAINLESS STEELS

AISI Type (UNS)	Chemical Analysis % (Max. unless noted otherwise)									Nominal Mechanical Properties (Annealed sheet unless noted otherwise)						
	C	Mn	P	S	Si	Cr	Ni	Mo	Other	Tensile Strength		Yield Strength (0.2 % offset)		Elongation in 2" (50.80 mm)	Hardness (Rockwell)	Product Form
										ksi	MPa	ksi	MPa	%		
201 (S20100)	0.15	5.50/7.50	0.060	0.030	1.00	16.00/18.00	3.50/5.50		0.25N	95	655	45	310	40	B90	
202 (S20200)	0.15	7.50/10.00	0.060	0.030	1.00	17.00/19.00	4.00/6.00		0.25N	90	612	45	310	40	B90	
205 (S20500)	0.12/0.25	14.00/15.50	0.030	0.030	0.50	16.50/18.00	1.00/1.75		0.32/0.40N	120.5	831	69	476	58	B98	(Plate)
301 (S30100)	0.15	2.00	0.045	0.030	1.00	16.00/18.00	6.00/8.00			110	758	40	276	60	B85	
302 (S30200)	0.15	2.00	0.045	0.030	1.00	17.00/19.00	8.00/10.00			90	612	40	276	50	B85	
302B (S30215)	0.15	2.00	0.045	0.030	2.00/3.00	17.00/19.00	8.00/10.00			95	655	40	276	55	B85	
303 (S30300)	0.15	2.00	0.20	0.15(min.)	1.00	17.00/19.00	8.00/10.00	0.60*		90	621	35	241	50		(Bar)
303Se (S30323)	0.15	2.00	0.20	0.060	1.00	17.00/19.00	8.00/10.00		0.15Se (min)	90	621	35	241	50		(Bar)
304 (S30400)	0.08	2.00	0.045	0.030	1.00	18.00/20.00	8.00/10.50			84	579	42	290	55	B80	
304L (S30403)	0.030	2.00	0.045	0.030	1.00	18.00/20.00	8.00/12.00			81	558	39	269	55	B79	
S30430	0.08	2.00	0.045	0.030	1.00	17.00/19.00	8.00/10.00		3.00/4.00Cu	73	503	31	214	70	B70	(Wire)
304N (S30451)	0.08	2.00	0.045	0.030	1.00	18.00/20.00	8.00/10.50		0.10/0.16N	90	621	48	331	50	B85	
305 (S30500)	0.12	2.00	0.045	0.030	1.00	17.00/19.00	10.50/13.00			85	586	38	262	50	B80	
308 (S30800)	0.08	2.00	0.045	0.030	1.00	19.00/21.00	10.00/12.00			115	793	80	552	40		(Wire)
309 (S30900)	0.20	2.00	0.045	0.030	1.00	22.00/24.00	12.00/15.00			90	621	45	310	45	B85	
309S (S30908)	0.08	2.00	0.045	0.030	1.00	22.00/24.00	12.00/15.00			90	621	45	310	45	B85	
310 (S31000)	0.25	2.00	0.045	0.030	1.50	24.00/26.00	19.00/22.00			95	655	45	310	45	B85	
310S (S31008)	0.08	2.00	0.045	0.030	1.50	24.00/26.00	19.00/22.00			95	655	45	310	45	B85	
314 (S31400)	0.25	2.00	0.045	0.030	1.50/3.00	23.00/26.00	19.00/22.00			100	689	50	345	40	B85	
316 (S31600)	0.08	2.00	0.045	0.030	1.00	16.00/18.00	10.00/14.00	2.00/3.00		84	579	42	290	50	B79	
316F (S31620)	0.08	2.00	0.20	0.10min	1.00	16.00/18.00	10.00/14.00	1.75/2.50		85	586	38	262	60	B85	
316L (S31603)	0.030	2.00	0.045	0.030	1.00	16.00/18.00	10.00/14.00	2.00/3.00		81	558	42	290	50	B79	
316N (S31651)	0.08	2.00	0.045	0.030	1.00	16.00/18.00	10.00/14.00	2.00/3.00	0.10/0.16N	90	621	48	331	48	B85	
317 (S31700)	0.08	2.00	0.045	0.030	1.00	18.00/20.00	11.00/15.00	3.00/4.00		90	621	40	276	45	B85	
317L (S31703)	0.030	2.00	0.045	0.030	1.00	18.00/20.00	11.00/15.00	3.00/4.00		86	593	38	262	55	B85	
321 (S32100)	0.08	2.00	0.045	0.030	1.00	17.00/19.00	9.00/12.00		5xC Ti (min.)	90	621	35	241	45	B80	
329 (S32900)	0.10	2.00	0.040	0.030	1.00	25.00/30.00	3.00/6.00	1.00/2.00		105	724	80	552	25	230 (Brinell)	(Strip)
330 (N08330)	0.08	2.00	0.040	0.030	0.75/1.50	17.00/20.00	34.00/37.00		0.10Ta 0.20Cb	80	552	38	262	40	B80	
347 (S34700)	0.08	2.00	0.045	0.030	1.00	17.00/19.00	9.00/13.00		10XC Cb-Ta (min)	95	655	40	276	45	B85	
348 (S34800)	0.08	2.00	0.045	0.030	1.00	17.00/19.00	9.00/13.00		10XC Cb+Ta (min) 0.2 Cu	95	655	40	276	45	B85	
384 (S38400)	0.08	2.00	0.045	0.030	1.00	15.00/17.00	17.00/19.00			75	517	35	241	55	B70	(Wire)

*May be added at manufacturer's option

Note: Mechanical properties of AISI-numbered stainless steels are typical values as shown in the “Steel Producers Manual, Stainless and Heat-Resisting Steels,” American Iron and Steel Institute, December 1974. For additional engineering data, refer to pertinent ASTM Standard Specifications, including:

A666	“Austenitic Stainless Steel Sheet, Strip, Plate, and Flat Bar for Structural Applications.”
A240	“Heat Resisting Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Fusion-Welded Unfired Pressure Vessels.”

TABLE II

FERRITIC STAINLESS STEELS

AISI Type (UNS)	C	Mn	P	S	Si	Cr	Ni	Mo	Other	Tensile Strength ksi	Tensile Strength MPa	Yield Strength (0.2 % offset) ksi	Yield Strength (0.2 % offset) MPa	Elongation in 2" (50.80 mm) %	Hardness (Rockwell)	Product Form
Chemical Analysis % (Max. unless noted otherwise)										**Nominal Mechanical Properties (Annealed sheet unless noted otherwise)**						
405 (S40500)	0.08	1.00	0.040	0.030	1.00	11.50/14.50			0.10/0.30 Al	65	448	40	276	25	B75	
409 (S40900)	0.08	1.00	0.045	0.045	1.00	10.50/11.75			6xC/0.75 Ti	65	448	35	241	25	B75	
429 (S42900)	0.12	1.00	0.040	0.030	1.00	14.00/16.00				70	483	40	276	30	B80	(Plate)
430 (S43000)	0.12	1.00	0.040	0.030	1.00	16.00/18.00				75	517	50	345	25	B85	
430F (S43020)	0.12	1.25	0.060	0.15(min.)	1.00	16.00/18.00		0.60*		95	655	85	586	10	B92	(Wire)
430FSe (S43023)	0.12	1.25	0.060	0.060	1.00	16.00/18.00			0.15 Se (min.)	95	655	85	586	10	B92	(Wire)
434 (S43400)	0.12	1.00	0.040	0.030	1.00	16.00/18.00		0.75/1.25		77	531	53	365	23	B83	
436 (S43600)	0.12	1.00	0.040	0.030	1.00	16.00/18.00		0.75/1.25	5xC/0.70 Cb +Ta	77	531	53	365	23	B83	
442 (S44200)	0.20	1.00	0.040	0.030	1.00	18.00/23.00				80	552	45	310	20	B90	(Bar)
446 (S44600)	0.20	1.50	0.040	0.030	1.00	23.00/27.00			0.25N	80	552	50	345	20	B83	

*May be added at manufacturer's option

TABLE III

MARTENSITIC STAINLESS STEELS

AISI TYPE (UNS)	C	Mn	P	S	Si	Cr	Ni	Mo	Other	Tensile Strength ksi	Tensile Strength MPa	Yield Strength (0.2 % offset) ksi	Yield Strength (0.2 % offset) MPa	Elongation in 2" (50.80 mm) %	Hardness (Rockwell)	Product Form
Chemical Analysis % (Max. unless noted otherwise)										**Nominal Mechanical Properties (Annealed sheet unless noted otherwise)**						
403 (S40300)	0.15	1.00	0.040	0.030	0.50	11.50/13.00				70	483	45	310	25	B80	
410 (S41000)	0.15	1.00	0.040	0.030	1.00	11.50/13.50				70	483	45	310	25	B80	
414 (S41400)	0.15	1.00	0.040	0.030	1.00	11.50/13.50	1.25/2.50			120	827	105	724	15	B98	
416 (S41600)	0.15	1.25	0.060	0.15 (Min.)	1.00	12.00/14.00		0.60*		75	517	40	276	30	B82	(Bar)
416 Se (S41623)	0.15	1.25	0.060	0.060	1.00	12.00/14.00			0.15 Se (Min.)	75	517	40	276	30	B82	(Bar)
420 (S42000)	0.15 (Min.)	1.00	0.040	0.030	1.00	12.00/14.00				95	655	50	345	25	B92	(Bar)
420 F (S42020)	0.15 (Min.)	1.25	0.060	0.15 (Min.)	1.00	12.00/14.00		0.60*		95	655	55	379	22	220 (Brinell)	(Bar)
422** (S42200)	0.20/0.25	1.00	0.025	0.025	0.75	11.00/13.00	0.50/1.00	0.75/1.25	0.15/0.30 V 0.75/1.25 W	145	1000	125	862	18	320 (Brinell)	(Bar)
431 (S43100)	0.20	1.00	0.040	0.030	1.00	15.00/17.00	1.25/2.50			125	862	95	655	20	C24	(Bar)
440 A (S44002)	0.60/0.75	1.00	0.040	0.030	1.00	16.00/18.00		0.75		105	724	60	414	20	B95	(Bar)
440 B (S44003)	0.75/0.95	1.00	0.040	0.030	1.00	16.00/18.00		0.75		107	738	62	427	18	B96	(Bar)
440 C (S44004)	0.95/1.20	1.00	0.040	0.030	1.00	16.00/18.00		0.75		110	758	65	448	14	B97	(Bar)

*May be added at manufacturer's option **Hardened and Tempered

TABLE IV

PRECIPITATION HARDENING STAINLESS STEELS

AISI Type UNS	C	Mn	P	S	Si	Cr	Ni	Mo	Other	Tensile Strength ksi	Tensile Strength MPa	Yield Strength (0.2 % offset) ksi	Yield Strength (0.2 % offset) MPa	Elongation in 2" (50.80 mm) %	Hardness (Rockwell)	Product Form
	Chemical Analysis % (Max. unless noted otherwise)									**Nominal Mechanical Properties (Solution Treated Bar)**						
S13800	0.05	0.10	0.010	0.008	0.10	12.25/13.25	7.50/8.50	2.00/2.50	0.90/1.35 Al 0.010 N	160	1103	120	827	17	C33	
S15500	0.07	1.00	0.04	0.03	1.00	14.00/15.50	3.50/5.50		2.50/4.50 Cu 0.15/0.45 Cb+Ta	160	1103	145	1000	15	C35	
S17400	0.07	1.00	0.040	0.030	1.00	15.50/17.50	3.00/5.00		3.00/5.00 Cu 0.15/0.45 Cb+Ta	160	1103	145	1000	15	C35	
S17700	0.09	1.00	0.040	0.040	0.040	16.00/18.00	6.50/7.75		0.75/1.50 Al	130	896	40	276	10	B90	

TABLE V

PROPRIETARY STAINLESS STEELS

Chemical Composition, %
(Maximum unless noted otherwise)

Alloy No.	C	Mn	P	S	Si	Cr	Ni	Mo	Other
303 MA	0.15	2.00	0.040	0.11/0.16	1.00	17.00/19.00	8.00/10.00	0.40/0.60*	0.60/1.00 Al
Nitronic® 32(1)	0.15	11.00/14.00	0.060	0.030	1.00	16.50/19.00	0.50/2.50	-	0.20/0.45 N
Nitronic® 50(1)	0.03/0.06	4.00/6.00	0.040	0.030	1.00	20.50/23.50	11.50/13.50	1.50/3.00	0.20/0.40 N 0.10/0.30 Cb 0.10/0.30 V
Nitronic® 60(1)	0.10	7.00/9.00	-	-	3.50/4.50	16.00/18.00	8.00/9.00	-	0.08/0.18 N
Carpenter Stainless 18-18 Plus®(2)	0.15	17.00/19.00	0.04	0.04	1.00	17.00/19.00	-	0.75/1.25	0.75/1.25 Cu 0.4/0.6 N
Carpenter Stainless 22Cr-13Ni-5MnA®(2)	0.06	4.0/6.0	0.040	0.030	1.0	20.5/23.5	11.5/13.5	1.5/3.0	0.10/0.30 V 0.10/0.30 Cb 0.20/0.40 N
Carpenter Stainless 18Cr-2Ni-12Mn V®(2)	0.15	11.0/14.0	0.06	0.03	1.0	16.5/19.0	0.5/2.5	-	0.20/0.45 N
Carpenter 303Al Modified®(2)	0.15	2.00	0.05	0.11/0.16	1.00	17.0/19.0	8.0/10,0	0.40/0.60*	0.60/1.00 Al
USS Tenelon	0.12	14.50/16.00	0.045	0.030	0.30/1.00	17.00/18.50	0.75	-	0.35 N (Min.)
205	0.15/0.25	14/16	0.045	0.03	0.50	16/18	1 /1.75	-	0.32/0.40 N
216	0.08	7.5/9	0.045	0.03	0.5	17.5/22	5/7	2/3	0.25/0.5 N

* Producers' option.
Source: Industry Data

(1)® Registered Trademark of Armco Steel Corporation.
(2)® Registered Trademark of Carpenter Technology Corporation.

TABLE VI

PROPRIETARY STAINLESS STEELS
Nominal Mechanical Properties
(Annealed Sheet unless noted otherwise)

Alloy No.	Tensile Strength ksi	Tensile Strength MPa	Yield Strength (0.2% offset) ksi	Yield Strength (0.2% offset) MPa	Elongation in 2" (50.80mm) %	Hardness Rockwell
303 MA**	100	690	60	414	40	BHN 212
Nitronic® 32*(1)	128	882	65	448	55	B96
Nitronic® 50*(1)	120	827	60	414	50	B98
Nitronic® 60*(1)	103	710	60	414	64	B95
Carpenter Stainless 18-18 Plus® (2)	120	827	69	476	65	B95
Carpenter Stainless 22Cr-13Ni-5Mn® (2)	120	827	65	448	45	B96
Carpenter Stainless 18Cr-2Ni-12Mn® (2)	120	827	65	448	65	B96
Carpenter 303AI Modified® (2)	90	621	40	276	50	B85
USS Tenelon	120	827	65	448	40	B95
205	125	862	70	483	45	B98
216	100	690	55	379	45	B92

Source: Industry Data

* – Bar (Annealed)
** – Bar (Cold Drawn)
(1) ® Registered Trademark of Armco Steel Corporation.
(2) ® Registered Trademark of Carpenter Technology Corporation.

TABLE VII

Partial Summary of Piston/Cylinder Wear Tests (1)
In Water Environment at 500ºF (260ºC)
(Self-Mated)

Material: Piston	Material: Cylinder	Wear Factor*
Type 440C	Type 440C	15
Type 420	Type 420	130
Type 416	Type 416	165
Type S17400	Type S17400(PH)	440
Type S17400 (PH)	Type S17400 (PH)	460
Type 304	Type 304	3200
Type S17400	Type S17400	10^6

PH – Precipitation Hardened

CW – Cold Worked

*Wear Factor – mg/lb load/10^6 cycles

The martensitc stainless steels were tested in the hardened condition; all others in the solution annealed condition unless noted otherwise.

Load – 8 psi.

TABLE VIII

WEAR COMPATIBILITY OF CORROSION-RESISTANT ALLOY COUPLES: SELF-MATED SERIES (10)

All weight loss rates in mg/1,000 cycles

Austenitic stainless steels			Martensitic stainless steels			High-nickel alloys		
Alloy	**Rockwell hardness**	**Rate**	**Alloy**	**Rockwell hardness**	**Rate**	**Alloy**	**Rockwell hardness**	**Rate**
Nitronic 60	(B 95)	2.79	Type 440C	(C 57)	3.81	Waukesha 88	(B 81)	7.09
Type 201	(B 90)	4.95	S13800	(C 47)	38.11	Inconel 718	(C 38)	9.44
Type 301	(B 90)	5.47	S17400	(C 43)	52.80	Waspaloy	(C 36)	11.25
Nitronic 32	(B 95)	7.39	Type 416	(C 39)	58.14	Hastalloy C	(B 95.5)	13.88
Nitronic 40	(B 93)	8.94	S13800	(C 32.5)	60.15	A-286	(C 33)	17.07
Nitronic 50	(B 99)	9.95	S17400	(C 31.5)	79.42	Inconel X750	(C 36)	18.70
Type 316	(B 91)	12.50	S17400	(C 37)	81.40	S Inconel	(C 25)	19.67
Type 304	(B 99)	12.77	Type 420	(C 46)	169.74	Monel K-500	(C 34)	30.65
Type 303	(B 98)	386.10	Type 431	(C 42)	181.48	20Cr-80Ni	(B 87)	44.91

Miscellaneous alloys

Alloy	Rockwell hardness	Rate	Alloy	Rockwell hardness	Rate
Tufftrided PH (nitride)	(C 75)	0.33	Haynes 25 (cobalt base)	(C 28)	1.75
D2 Tool steel	(C 61)	0.46	Silicon bronze	(B 93)	5.57
AISI 4337 (low alloy steel)	(C 52)	0.73	AISI 4130 (low alloy steel)	(C 47)	9.44
Stellite 6B (cobalt base)	(C 48)	1.00	Leaded brass	(B 72)	127.91
Hard chrome plate	-	1.66	AISI 1034 (mild steel)	(B 95)	134.05

Test conditions: 1/2-in.-dia. crossed (90°) cylinders; no lubricant; 16-lb load; 105 rpm; room temperature; 120 grit finish; 10,000 cycles; specimen degreased in acetone; duplicate tests; weight loss corrected for density differences.

TABLE IX

Partial Summary of Piston/Cylinder Wear Tests (1)
In Water Environment at 500ºF (260ºC)

Material		
Piston	**Cylinder**	**Wear Factor***
Wall Colmonoy No. 6	Type S17400 (PH)	99
Stellite No. 3	Type S17400 (PH)	113
Type 304	Stellite No. 6	170
Stellite No. 6	Type S17400 (PH)	185
Type 304	Haynes 25(CW)	210
Stellite No. 3	Type 304	250
Wall Colmonoy No. 6	Type 440C	270
Type S17400(PH)	Stellite No. 21	340
Type 304	S-Monel	400
Silicon Bronze	Type 304	450
Type S17400(PH)	Haynes 25(CW)	470
Type S17400(PH)	Type 304	475
Haynes 25(CW)	Type 304	810
Type 304	Type S17400	10^5

PH – Precipitation Hardened

CW – Cold Worked

*–Wear Factor – mg/lb load/10^6 cycles

The martensitc stainless steels were tested in the hardened condition; all others in the solution annealed condition unless noted otherwise.

Load – 8 psi.

TABLE X

WEAR COMPATIBILITY OF DISSIMILAR CORROSION-RESISTANT ALLOY COUPLES(10)

Stainless steel couples – weight loss, mg/1,000 cycles

Alloy (Rockwell hardness)	Type 304 (B 99)	Type 316 (B 91)	S17400 (C 43)	Nitronic 32 (B 95)	Nitronic 50 (B 99)	Nitronic 60 (B 95)	Type 440C (C 57)
Type 304	12.8						
Type 316	10.5	12.5					
S17400	24.7	18.5	52.8				
Nitronic 32	8.4	9.4	17.2	7.4			
Nitronic 50	9.0	9.5	15.7	8.3	10.0		
Nitronic 60	6.0	4.3	5.4	3.2	3.5	2.8	
Type 440C	4.1	3.9	11.4	3.1	4.3	2.4	3.8

Other dissimilar corrosion-resistant couples–weight loss, mg/1,000 cycles

Alloy (Rockwell hardness)		Silicon bronze (B 93)	Chrome plate –	Stellite 6 B (C 48)	Monel K-500 (C 34)	Waukesha 88 (B 81)
Type 304	(B 99)	2.1	2.3	3.1		8.1
S17400	(C 43)	2.0	3.3	3.8	34.1	9.1
Nitronic 32	(B 95)	2.3	2.5	2.0		7.6
Nitronic 60	(B 95)	2.2	2.1	1.9	22.9	8.4
Type 316	(B 91)				33.8	9.6
Monel K-500	(C 34)				30.7	9.3

Test conditions: ½-in.-dia. crossed (90°) cylinders; no lubricant; 16-Ib load; 105 rpm; room temperature; 120-grit finish, 10,000 cycles; specimen degreased in acetone, duplicate tests; weight loss corrected for density differences. Hardnesses given apply to both axes.

TABLE XI

GALLING RESISTANCE OF STAINLESS STEELS(10)

Block Material	Condition & Nominal Hardness (Brinell)	Button Material									
		410	416	430	440C	303	304	316	S17400	Nitronic 32	Nitronic 60
Type 410	Hardened & Stress Relieved (352)	3	4	3	3	4	2	2	3	46	50+
Type 416	Hardened & Stress Relieved (342)	4	13	3	21	9	24	42	2	45	50+
Type 430	Annealed (159)	3	3	2	2	2	2	2	3	3	36
Type 440C	Hardened & Stress Relieved (560)	3	21	2	11	5	3	37	3	50+	50+
Type 303	Annealed (153)	4	9	2	5	2	2	3	3	50+	50+
Type 304	Annealed (140)	2	24	2	3	2	2	2	2	30	50+
Type 316	Annealed (150)	2	42	2	37	3	2	2	2	3	38
S17400	H 950 (415)	3	2	3	3	2	2	2	2	50+	50+
Nitronic 32	Annealed (235)	46	45	8	50+	50+	30	3	50+	30	50+
Nitronic 60	Annealed (205)	50+	50+	36	50+	50+	50+	38	50+	50+	50

Values shown are unlubricated threshold galling stress (10^6 psi) for the "button and block" galling test. Condition and hardness apply to both the button and the blank material. Tests were terminated at 50 x 10^6 psi, so values given as 50+ indicate the samples did not gall.

TABLE XII

GALLING RESISTANCE OF ALLOYS(14)

Metals in Contact			Threshold Galling Stress (KSI)
Silicon Bronze	(200) vs. Silicon Bronze	(200)	4
Silicon Bronze	(200) vs. Type 304	(140)	44
A286	(270) vs. A286	(270)	3
AISI 4337	(484) vs. AISI 4337	(415)	2
AISI 1034	(415) vs. AISI 1034	(415)	2
Waukesha 88	(141) vs. Type 303	(180)	50+
Waukesha 88	(141) vs. Type 201	(202)	50+
Waukesha 88	(141) vs. Type 316	(200)	50+
Waukesha 88	(141) vs. S17400	(405)	50+
Waukesha 88	(141) vs. 20Cr-80Ni	(180)	50+
Type 201	(202) vs. Type 201	(202)	15
Type 201	(202) vs. Type 304	(140)	2
Type 201	(202) vs. S17400	(382)	2
Type 201	(202) vs. Nitronic 32	(231)	36
Type 301	(169) vs. Type 416	(342)	3
Type 301	(169) vs. Type 440C	(560)	3
Type 410	(322) vs. Type 420	(472)	3
Type 416	(342) vs. Type 416	(372)	13
Type 416	(372) vs. Type 410	(322)	4
Type 416	(342) vs. Type 430	(190)	3
Type 416	(342) vs. 20Cr-80Ni	(180)	7
Type 440C	(560) vs. Type 440C	(604)	11
S17400	(311) vs. Type 304	(140)	2
S17400	(380) vs. Nitronic 32	(401)	13
S17400	(435) vs. Type 304	(140)	2
S17400	(400) vs. S17700	(400)	3
S17400	(435) vs. S17700	(435)	2
Nitronic 32	(235) vs. S17400	(380)	11
Nitronic 32	(401) vs. Nitronic 32	(401)	34
Nitronic 32	(235) vs. Nitronic 32	(401)	34
Nitronic 32	(235) vs. Type 304	(140)	7
Nitronic 32	(401) vs. Type 304	(140)	13
Nitronic 32	(205) vs. AISI 1034	(205)	2
Nitronic 50	(205) vs. Nitronic 50	(205)	2
Nitronic 50	(321) vs. Nitronic 50	(321)	2
Nitronic 50	(205) vs. Nitronic 32	(401)	13
Nitronic 50	(321) vs. Nitronic 32	(235)	8
Nitronic 50	(205) vs. Type 304	(140)	4
Nitronic 60	(205) vs. Type 301	(169)	50+
Nitronic 60	(205) vs. Type 420	(472)	50+
Nitronic 60	(213) vs. S17400	(313)	50+
Nitronic 60	(205) vs. S17400	(332)	50+
Nitronic 60	(205) vs. Nitronic 50	(205)	50+
Nitronic 60	(205) vs. S13800	(297)	50+
Nitronic 60	(205) vs. S13800	(437)	50+
Nitronic 60	(205) vs. AISI 4337	(448)	50+
Nitronic 60	(205) vs. Stellite 6B	(415)	50+
Nitronic 60	(205) vs. A286	(270)	49+
Nitronic 60	(205) vs. 20Cr-80Ni	(180)	36
Nitronic 60	(205) vs. Ti-6Al-4V	(332)	50+

Values shown are unlubricated threshold galling stress (ksi) for the button and block galling test. Values given as 50+ indicate the samples did not gall. Numbers in parentheses following alloy designations are nominal hardness (Brinell).

TABLE XIII

PARTIAL SUMMARY OF PISTON/CYLINDER WEAR TESTS(1) IN WATER ENVIRONMENT AT 500ºF (260ºC)

Material Piston	 Cylinder	Wear Factor*
Type 347 Nitrided	Type 347 Nitrided	0
Honed Chromium Plate**	Type S17400(PH)	20
Honed Chromium Plate**	Type S17400 (PH-Nitrided)	22
Type S17400(PH)	Honed Chromium Plate**	35
Honed Chromium Plate**	Type S17400	48
Honed Chromium Plate**	Type 304	65
Honed Chromium Plate**	Honed Chromium Plate**	135
As-Plated Chromium	Type 440C	150
Type S17400	Honed Chromium Plate**	195
Silicon Bronze	Honed Chromium Plate**	830

PH – Precipitation Hardened
*Wear Factor – mg/lb load/10^6 cycles
**Honed chromium plate applied to Type S17400 stainless steel.
The martensitic stainless steels were tested in the hardened condition; all others in the solution annealed condition unless noted otherwise.
Load – 8 psi.

TABLE XIV

COMPARATIVE GALLING CHARACTERISTICS FOR SEVEN STAINLESS STEELS(16)

Type	Condition	Initial Hardness	Surface Treatment	Load (lbs)	Time for Galling to Occur (Seconds)
416	Heat Treated	43 Rc	None	400	12
416	Heat Treated	43 Rc	Tufftrided*	1000	37
440C	Heat Treated	59 Rc	None	800	17
440C	Heat Treated	59 Rc	Tufftrided*	1100	41
440A	Annealed	96 Rb	None	650	15
440A	Annealed	96 Rb	Tufftrided*	1000	47
303	Annealed	85 Rb	None	(Only Preload)	3
303	Annealed	85 Rb	Tufftrided*	750	25
303MA	Annealed	88 Rb	None	300	2
303MA	Annealed	88 Rb	Tufftrided*	1350	58
317	Annealed	85 Rb	None	500	7
317	Annealed	85 Rb	Tufftrided*	750	27
347	Annealed	89 Rb	None	600	8
347	Annealed	89 Rb	Tufftrided*	500	22

*Tufftriding is a liquid nitriding process by Kolene Corporation using potassium cyanide and potassium cyanate

TABLE XV

EFFECT OF PRETREATMENT ON WEAR LIFE* (24)

Apparatus: Falex Lubricant Tester

Specimens: V-Blocks – C1137 Steel
Pin – Type 302 Stainless Steel

Speed: 290 rpm

Load: 1000 lb.

Test Pin Pretreatment	Running Time (Minutes)
None	28
HF Etch	33
Sand Blast	31
Vapor Blast	188
H_3PO_4 Etch	126

*Solid film lubricant of molybdenum disulfide, graphite and sodium silicate applied after the pretreatment.

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