ATI 332Mo™

Stainless Steel: Austenitic

(UNS S35125)

GENERAL PROPERTIES

ATI's ATI 332Mo™ alloy is an austenitic stainless steel intended primarily as an economical material for automotive flexible connectors. It was designed to provide resistance to both aqueous corrosion and elevated temperature degradation while maintaining both weldability and formability. This alloy is currently available primarily as Precision Rolled Strip® product. Customers interested in other product forms (i.e., sheet, plate) should inquire.

COMPOSITION

ATI 332Mo™ alloy is an austenitic stainless steel with relatively high chromium and nickel levels for strength, corrosion and oxidation resistance. The alloy contains a moderate addition of molybdenum for resistance to aqueous corrosion and manganese for resistance to oxidation in air containing water vapor. A small amount of niobium (columbium) is added for resistance to sensitization and resultant susceptibility to intergranular corrosion.

Chemical Composition (weight percents)

Element	Typical	ASTM A 240 Range
Nickel	34.5	31.0-35.0
Chromium	21.0	20.0-23.0
Manganese	1.1	1.00-1.50
Molybdenum	2.4	2.00-3.00
Silicon	0.40	0.50 max
Carbon	0.04	0.10 max
Nitrogen	0.04	---
Niobium	0.40	0.25-0.60
Iron	Balance	Balance

PHYSICAL PROPERTIES

ATI 332Mo™ alloy is a single phase austenitic (face centered cubic) stainless steel at all temperatures up to the melting point. The alloy can not be hardened by heat treatment. The physical properties of the alloy are similar to other Fe-Ni-Cr-Mo alloys.

Property	Value	Units
Density at 72°F (22°C)	8.13 0.294	g/cm^3 lb/in^3
Elastic Modulus at 72 °F (22°C)	29 200	million psi GPa

Linear Coefficient of Thermal Expansion

Temperature Range		CTE	
(ºC)	(ºF)	10^{-6}/C°	10^{-6}/F°
100	212	14.5	8.1
200	392	15.4	8.5
300	572	15.8	8.8
400	752	16.2	9.0
500	932	16.5	9.2
600	1112	16.9	9.4
700	1292	17.4	9.6
800	1472	17.8	9.9
900	1652	18.1	10.1

MECHANICAL PROPERTIES

The room temperature mechanical property data for ATI 332Mo™ alloy was generated using both sheet material at 0.030" thick and foil material at 0.008" thick. The alloy exhibits excellent ductility, particularly at foil gauges.

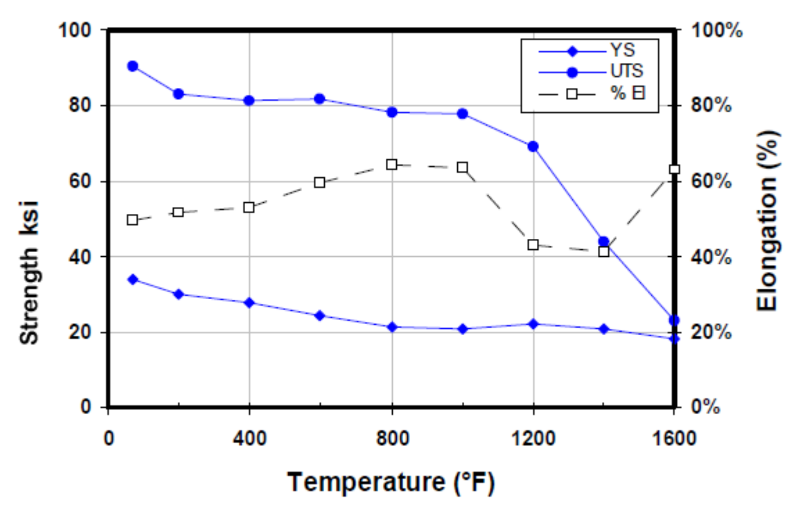
Typical Room Temperature Tensile Properties

Yield Strength (0.2% offset)	35 ksi (240 MPa)
Tensile Strength	85 ksi psi (585 MPa)
Total Elongation (2 in. gage)	40% (0.008" thick foil)

Typical Short–Term Elevated Temperature Tensile Properties

Short-term elevated temperature tensile properties for ATI 332Mo™ alloy were generated using sheet material at 0.030" thick. The alloy retains a significant fraction of its room temperature strength at elevated temperatures.

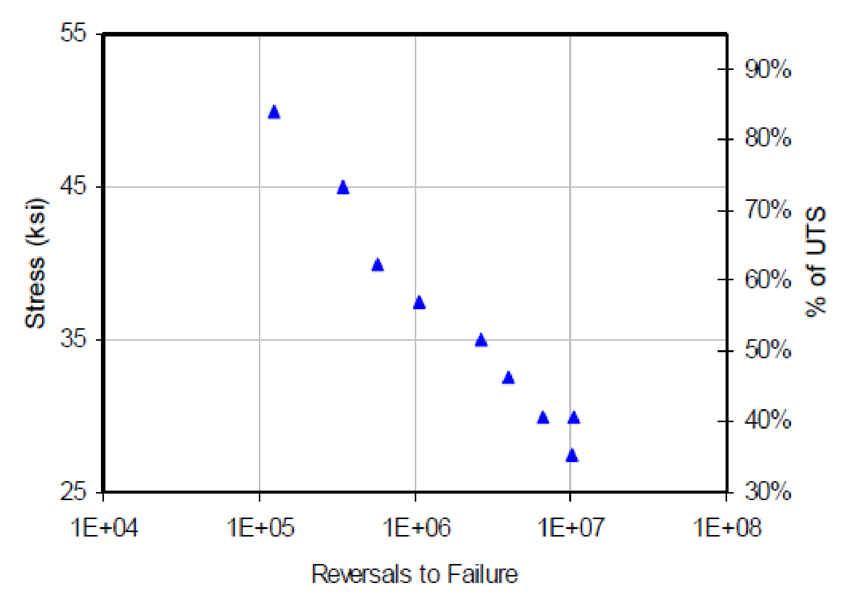
Tensile properties as a function of temperature



Room Temperature High Cycle Fatigue

Fatigue resistance is critical for applications such as exhaust bellows, which are subjected to a high-vibration environment. The fatigue limit at room temperature under reverse bending conditions was determined to be approximately 35% of the ultimate strength, which is considered nominal performance for an austenitic stainless steel.

S/N curve (reverse bending) for 0.030" thick strip



CORROSION RESISTANCE

Extensive corrosion testing has been carried out on ATI 332Mo™ alloy. The results are presented in the following section, along with comparative data for other common flexible connector alloys.

General Corrosion in Dilute Reducing Acids

	Corrosion Rate, mils per year (mm/y)[1]		
Boiling Solution	**ATI 332Mo™**	**625 Alloy**	**Type 316**
10% Sulfuric Acid (base metal)	13 (0.033)	25.3 (0.64)	636 (16.2)
10% Sulfuric Acid (weld metal)	1.2 (0.031)	__	658 (16.7)
1% Hydrochloric Acid (base metal)	5.9 (0.15)	36.3 (0.92)	226 (5.74)
1% Hydrochloric Acid (weld metal)	7.2 (0.18)	__	300 (7.62)

(1) Results are the average of five 48-hour test periods.

Sensitization Resistance (ASTM A262 Testing)

Test Practice	Pre-test Heat Treatment	Result	Rate
A (oxalic acid etch)	base metal, one hour at 1200°F	passed - step structure	
B (Ferric sulfate- sulfuric acid)	as-welded	passed	0.33 mpy (0.008 mm/y)
C (nitric acid)	as-welded	passed	0.25 mpy (0.006 mm/y)
E (copper-cupric sulfate-sulfuric acid)	as-welded	passed - no cracking after 180° bend	0.15 mpy (0.004 mm/y)

Pitting and crevice corrosion are commonly encountered modes of attack. A simple means to compare the pitting and crevice corrosion resistance of different alloys is the pitting resistance equivalent number value (PRE_N), which is calculated using the composition of a given alloy. A higher PRE_N value signifies that an alloy is likely to be more resistant to localized corrosion.

Alloy	PRE_N for Nominal Alloy Composition
ATI 332Mo™	30
Alloy 625	51
Type 316Ti	25

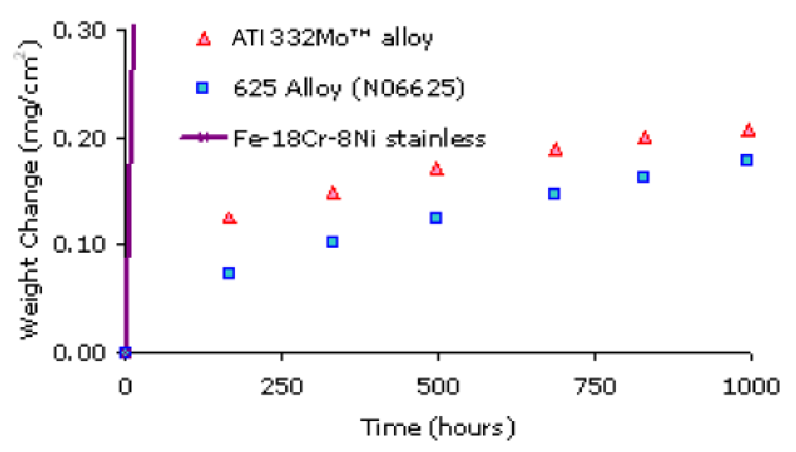
Test results for pitting corrosion are presented below. The results apply to both base metal and weld metal samples. The welded samples were prepared by making partial thickness autogenous bead-on-plate welds. The ATI 332Mo™ alloy samples performed significantly better than the baseline Type ATI 316Ti™ material. Welding did not have a significant effect on crevice corrosion resistance.

Alloy	ASTM G48 Practice D Critical Crevice Temperature
ATI 332Mo™	41°F (5°C)
Alloy 625	110°F (43°C)
Type 316Ti	<32°F (<0°C)

OXIDATION RESISTANCE

ATI 332Mo™ alloy is resistant to oxidation at elevated temperatures (i.e., scaling) due primarily to its high chromium and nickel contents. Exposure to high temperature air results in a slow-growing protective chromium oxide scale. Water vapor is present in many environments and has been noted to result in accelerated attack on lower alloyed stainless steels (e.g., 18Cr-8Ni alloys such as Types 304, 347, and 316). Oxidation testing in humidified air has shown that water vapor has essentially no detrimental effect on ATI 332Mo alloy due to its high chromium and nickel contents, along with a deliberate addition of manganese, which reduces the likelihood of oxide scale evaporation. The underlying figure shows rapid attack of a common 18-8 stainless steel in humidified air, manifested by extremely large weight gains due to the growth of an extremely thick oxide scale. ATI 332Mo™ alloy shows resistance to this form of attack comparable to the nickel-base superalloy 625.

Oxidation Weight Change As A Function Of Time In Air Containing 7% Water Vapor By Volume At 1400ºF (760ºC)



RESISTANCE TO HIGH TEMPERATURE SALT ATTACK

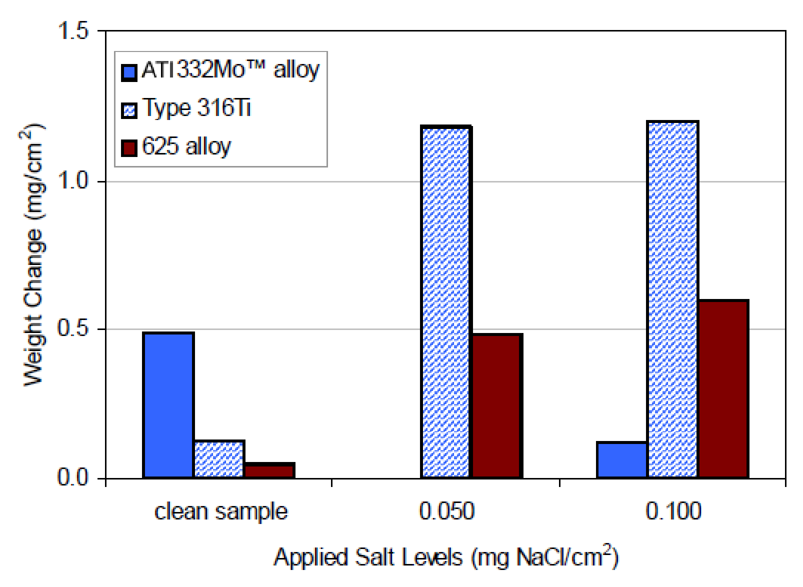
Automotive flexible connectors operate under difficult conditions. Elevated temperature oxidation is exacerbated by the presence of surface contaminants such as chloride salts, which can strip the protective oxide off the surface, leaving the underlying metal open to attack. Two tests were developed to evaluate an alloy's susceptibility to this type of attack.

Flat Sample Testing

Flat sample testing involves the application of a controlled, repeatable amount of salt (measured in milligrams of NaCl dry weight per square centimeter of sample area) on both sides of a square alloy coupon, followed by a 72 hour isothermal exposure. Samples were held in crucibles to collect loose corrosion products.

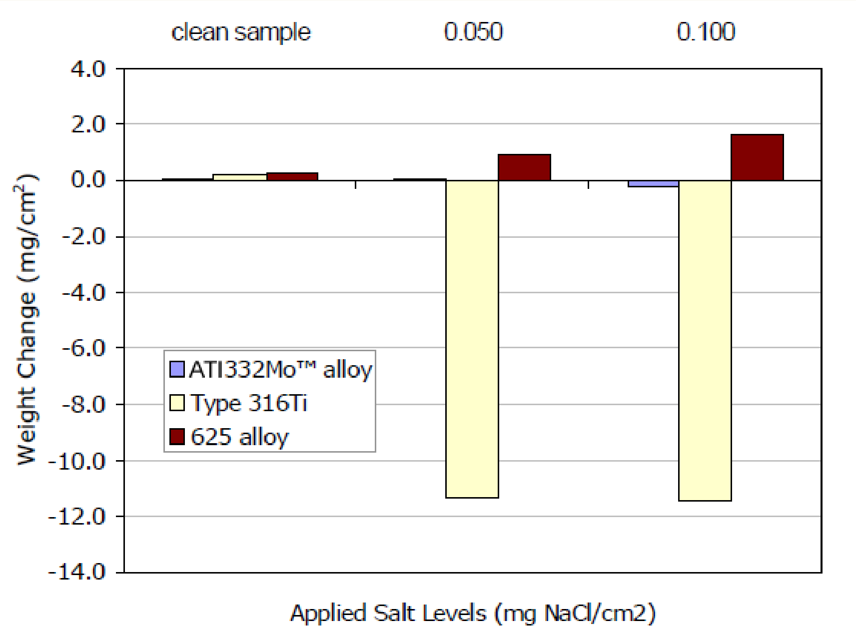
Testing done at 1200ºF resulted in significant attack of the Type 316Ti samples, as measured by higher weight gains due to the formation of corrosion products. The ATI 332Mo™ and 625 alloy samples exhibited superior performance. Exfoliation of corrosion products was not a factor for any of the alloys at this temperature.

Measured Weight Change After 72 Hours At 1200ºF (649ºC) In Air As A Function Of Applied Surface NaCl



Testing at 1500ºF resulted in severe attack for the Type 316Ti samples, with massive loss of corrosion products. The ATI 332Mo and 625 alloy samples exhibited similar resistance to attack.

Measured Weight Change After 72 Hours At 1500ºF (815ºC) In Air As A Function Of Applied Surface NaCl

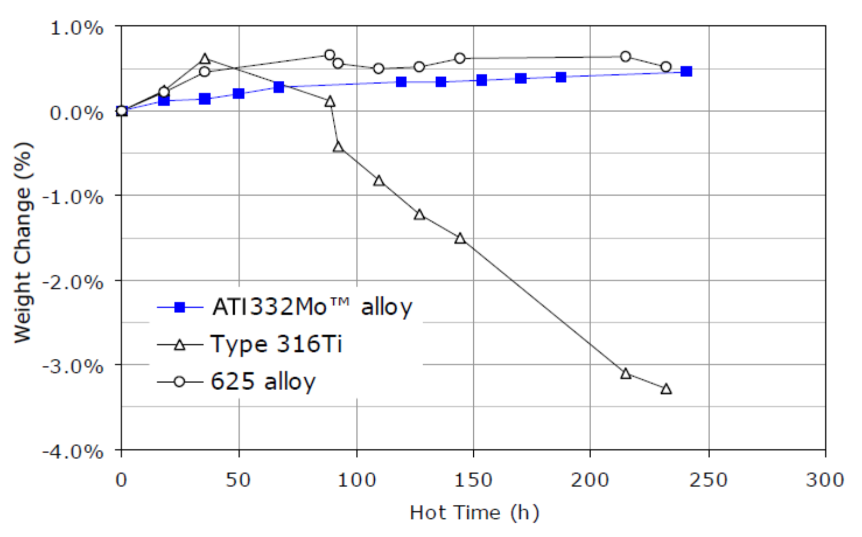


Teardrop Sample Testing

A more complex test was developed to take into account factors such as thermal cycling, residual stress, and the presence of autogenous weldments. Sheet samples were bent around a mandrel into a teardrop shape and welded shut. These samples were sprayed with a coating of NaCl and $CaCl_2$ salts and then exposed to high temperature air. The samples were thermally cycled to room temperature once per hour and were sprayed with a fresh coating of salt every 72 cycles. The samples were weighed prior to salt reapplication to monitor the extent of attack.

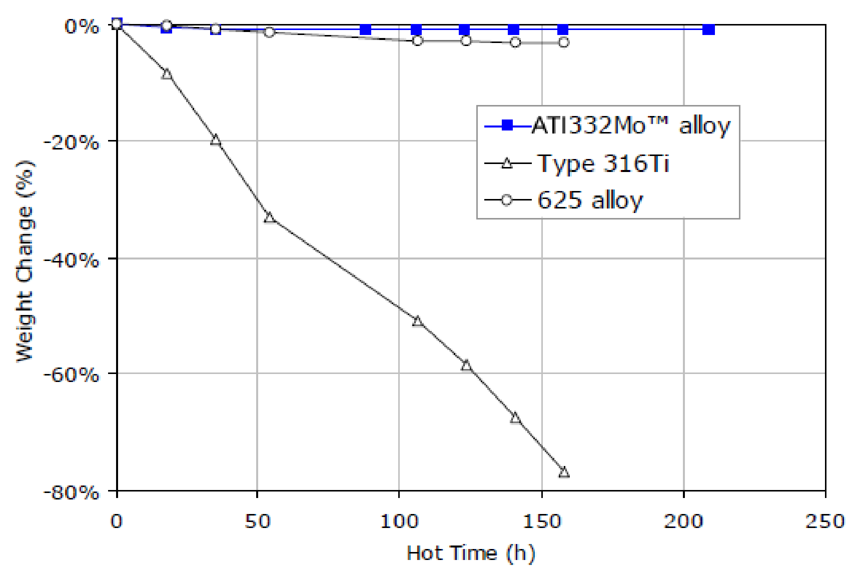
Testing at 1200ºF resulted in minimal attack for both the ATI 332Mo™ and 625 alloy samples. The weight gain was small and positive, indicating that the corrosion products were adherent and relatively protective. The Type 316Ti sample exhibited significant attack manifested as a net weight loss, indicating that the corrosion products were loose and non-protective.

Measured Weight Change Of Salt-Coated Welded Teardrop Samples Exposed At 1200ºF (649ºC) In Air Under Conditions Of Thermal Cycling



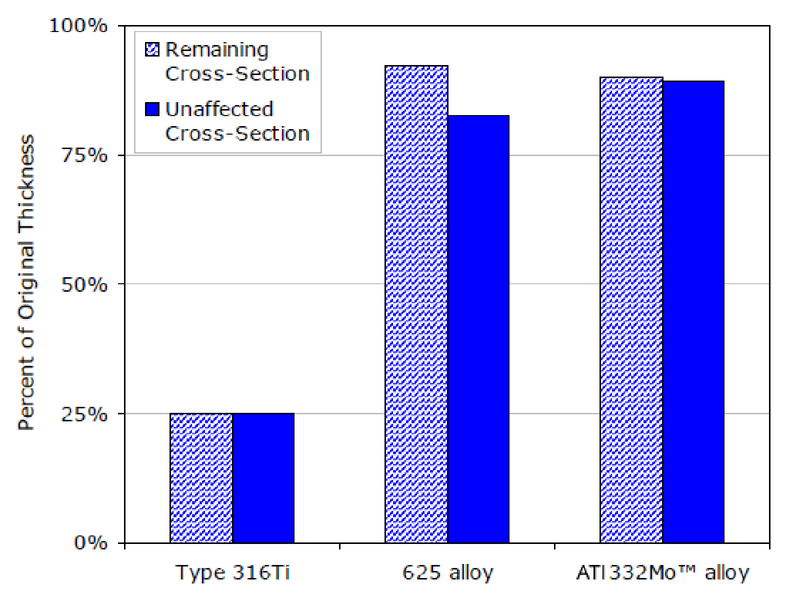
A similar trend was observed for exposures at 1500ºF. It is notable that the Type 316Ti sample exhibited a massive weight loss (approximately 75% of the original weight) and was nearly completely consumed.

Measured Weight Change Of Salt-Coated Welded Teardrop Samples Exposed At 1500ºF (815ºC) In Air Under Conditions Of Thermal Cycling



Post-exposure teardrop samples were examined using metallographic techniques to evaluate the physical extent of attack. Such information is complementary to the weight gain measurements and permit the evaluation of critical items such as remaining section thickness and unaffected section thickness as per ASTM G54 Standard Practice for Simple Static Oxidation. Attack was relatively uniform for both the 625 and ATI 332Mo™ alloys, with slightly greater internal attack for the nickel-base superalloy. The Type 316Ti sample suffered almost complete metal wastage, which supports the weight change data. In addition, the Type 316Ti weldments were completely consumed.

Sample Measurements After Cyclic Oxidation Testing Of Welded Teardrop Samples 1500ºF (815ºC) In Air With An Applied Salt Coating



FABRICATION

Mild carbon steel is generally treated as the standard for performance in most metal forming operations. With respect to carbon steel, the austenitic stainless steels exhibit a significant difference — they are tougher and tend to work harden rapidly. While this does not alter the general methods used for cutting, machining, forming, and other fabrication techniques it does affect the specifics of those methods.

Welding/Joining

The austenitic grades are generally considered to be the most weldable of the stainless steels, and can be joined using all of the common processes. The austenitic alloys exhibit a relatively high coefficient of thermal expansion, low thermal conductivity, and form low levels of ferrite in the solidifying weld metal. These factors can lead to hot cracking. The problem can be more severe for restrained and/or wide joints.

ATI 332Mo™ Precision Rolled Strip® product at light gauge (less than 0.010" thick) has been extensively evaluated by end users and has been found to be readily welded using automated GTAW equipment.

Most austenitic stainless steels are amenable to other forms of joining, including cladding, brazing, mechanical fastening, and explosive bonding. Specific processes will require testing and qualification.

Forming

A relatively narrow range of temperatures can be used for effective hot working of most austenitic stainless steels due to environmental and metallurgical factors. Forging should start in the temperature range 1800–2200ºF (980–1200ºC) and finish no cooler than 1600ºF (870ºC). Following forging, the workpiece should be cooled rapidly to a black heat.

The austenitic stainless steels are readily cold formable by standard methods such as bending, stretch forming, roll forming, hammer forming, flaring/flanging, spinning, and drawing. They work harden, which is manifested by steadily increasing amounts of force needed to continue deformation. This results in the need to use stronger forming machines and eventually limits the amount of deformation possible without cracking.

ATI 332Mo™ Precision Rolled Strip® product at light gauge (less than 0.010" thick) exhibits excellent ductility and formability. It has performed well in manufacturing trials and has been found to be readily formed into complex shapes using hydroforming.

Cutting

Cutting and machining the austenitic stainless steels is readily accomplished using standard techniques typically employed for common mild steel, with some modifications. Their cutting behavior can be quite different — they are tougher and tend to harden rapidly during working. The chips produced are stringy and tough and retain considerable ductility. Tooling should be kept sharp and be rigidly held. Deeper cuts and slower speeds are generally used to cut below work hardened zones. Due to the low thermal conductivity and high coefficient of thermal expansion inherent to the austenitic stainless steels, heat removal and dimensional tolerances must be considered during cutting and machining operations.

Annealing

The primary reasons for annealing are to produce a recrystallized microstructure with a uniform grain size and for dissolving detrimental precipitates. To ensure complete annealing, pieces should be held in the range 2000-2150ºF (1093-1179°C) for approximately 30 minutes (time at temperature) per inch of section thickness. This is a general recommendation only— specific cases may require further investigation. When properly annealed, this alloy is primarily austenitic at room temperature, with finely dispersed niobium carbides and possibly a small amount of retained delta ferrite.

Oxide scale formation is inevitable during air annealing of this alloy. The annealing scale generally must be removed prior to further processing or service. There are two typical methods for removing scale-mechanical and chemical. A combination of surface blasting prior to chemical scale removal is generally effective at removing all but the most tightly adherent scale. Silica sand or glass beads are a good choice for the blasting media. Iron or steel shot can also be used, but will lead to embedded free iron in the surface which may then result in surface rusting or discoloration unless the surface is subsequently pickled. Alternatively, the alloy can be annealed in an inert atmosphere, which results in a bright surface typically referred to as a “2BA” finish.

Chemical removal of scale is generally performed with mixed nitric–hydrofluoric acids. The proper bath makeup and process temperature combination depends on the situation. A typical pickling bath used consists of 5-25% HNO_3 (65% initial strength) and 0.5-3% HF (60% initial strength) in aqueous solution. Higher concentrations of hydrofluoric acid leads to more aggressive scale removal. Bath temperatures generally range from ambient to about 140ºF. Higher temperatures result in faster descaling, but may attack grain boundaries aggressively, resulting in surface grooving. Acid pickling must be followed with a thorough water wash to remove all traces of pickling acids. Drying should then be used to avoid spotting and staining.