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THE STRESS RELIEF OF TITANIUM WELDS FOR LOW-TEMPERATURE APPLICATIONS

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Much concern has been shown in recent months about the need for stress relieving welds in titanium alloys, particularly for applications at low temperatures. A typical inquiry from a pressure-vessel fabricator asks, "Is it necessary to stress relieve welds in Ti-6Al-4V?" This Technical Note is a composite of answers furnished by the Defense Metals Information Center to such questions. The comments apply mainly to those alloys used in pressure vessels: Ti-6Al-4V, Ti-5Al-2.5Sn and unalloyed titanium. They are general of necessity because the need for stress relief often depends upon the end use of the product.

Stress-relieving treatments are commonly required when fabricating complex welded assemblies. They reduce residual-welding stresses and promote dimensional stability. The treatment is most often performed on the finished part but may also be done at various stages of assembly if dimensional control is a problem. Stress-relaxation annealing times and temperatures for different alloys are presented in Table 1. The actual temperature and time should be determined for each heat of base metal, base-metal filler-metal combination, base-metal condition, and weld structure because they can vary with any or all of these variables.

Stress-relieving treatments for welds in the Ti-6Al-4V alloy are not absolutely necessary for all applications. However, such treatments may be desirable and necessary for some applications. The need for stress-relieving operations depends on a number of factors, including operating temperatures, design stresses, weld-metal composition, presence of stress raisers, extent of welding in the structure, and weld quality. The decision of whether or not to use stress-relieving treatments generally is based on judgment and previous experience. Some of the factors that influence this decision are discussed below.

One reason for advocating stress-relieving treatments is to increase the dimensional stability of welded structures. Also, stress relieving will act as a hot-sizing operation and can greatly reduce problems in manufacturing parts to close dimensional tolerances. This is especially true for complex weldments that are made up of several subassemblies.

Another reason for recommending stress-relieving treatments is to reduce the possibility of premature failures. Residual welding stresses approaching the yield strength of the weld metal are possible in welded structures. The magnitude of these stresses depend on the rigidity of the structure and the restraint on the weld. With these high residual stresses present in a structure subjected to stress, the weld plastically deforms. If the weld has sufficient ductility and toughness to deform in the presence of defects, the residual stresses do not cause a problem. On the other hand, if the weld has low ductility and low toughness, it may fail. Furthermore, if the structure is subjected to dynamic loading, the possibility of fatigue failures may be increased by the presence of residual stresses in the welds.

TABLE 1. STRESS-RELAXATION ANNEALING TEMPERATURES AND TIMES

Nominal Composition, weight per cent	Stress Relieving Temperature, F	Time at Temperature, hours
Commercially pure titanium	800	8
	900	3/4
	1000	1/2
Ti-5Al-2.5Sn	900	20
	1000	6
	1100	2
	1200	1
Ti-6Al-4V, annealed	900	20
	1000	2
	1100	1
Ti-6Al-4V, solution treated	900	15
	1000	4
Ti-6Al-4V, solution treated and aged	900	15
	1000	5

The ductility and toughness of welds in most metals decrease both as the temperature of the welds is lowered and as strain rate is increased. Therefore, operating temperature is important in deciding whether or not stress-relieving treatments are necessary. Also, the presence of notches or stress raisers in the joint increases the strain rate. Stress-relieving treatments may not be necessary for welded joints in Ti-6Al-4V that are not subjected to severe stress concentration and are in service at room temperature and above. This is based on good-quality welded joints that are properly designed. Poor welds, especially if they are contaminated, can fail in service under almost any condition.

In addition to service temperature, the purity of the base and filler metal and the composition of the filler metal are important. The purity of the titanium alloy affects the toughness of the base and weld metals. This is the reason many fabricators now use the ELI grades, especially for low-temperature service. With good-quality welds, a particular alloy can be used as both base and filler metal at temperatures considerably less than room temperature, but we do not have sufficient data to relate performance of welds at low temperatures with impurity content.

A further consideration is the effect of stress-relieving treatments on the mechanical properties of the welds. Stress-relieving temperatures in the range of 900 to 1100 F are considered necessary to reduce residual stresses in Ti-6Al-4V. At these temperatures, this alloy will age harden if it has been rapidly cooled from welding temperatures. Therefore, if age hardening occurs, it may reduce the beneficial effects of stress relieving. To circumvent these difficulties, some companies have found it convenient to combine the aging and stress-relief anneals in a single heat treatment.

Some titanium alloys are susceptible to stress-corrosion cracking when subjected to high stress levels at elevated temperatures in the presence of chlorides. Thus, another good reason for stress relieving is to reduce the stress level of parts subjected to elevated temperatures and chloride environments during service. Because of the susceptibility to stress corrosion, certain precautions are necessary during stress relieving. Parts should not be degreased with solvents which may leave chloride residues. Several fabricators have reported cracking in weldments during stress relief when the components or tooling were degreased in trichloroethylene prior to heating.[1] Final solvent cleaning with alcohol, acetone, or draw filing just before welding will avoid the possibility of stress-corrosion cracking during stress relief. This will also minimize weld porosity.

There are other more fundamental aspects which could show an advantage to be gained by stress relieving. A recent study performed by DMIC[2] of a delayed fracture in seam-welded unalloyed titanium indicated that failure was due to high residual stresses in restrained areas as a result of welding. An examination of the fracture surface by means of electron microscopy clearly showed that the titanium failed in a brittle manner. Although the nature of the embrittlement was not positively identified, metallographic examination showed that hydride-phase precipitation was concentrated in the weld and heat-affected zone. On the basis of information discussed below, it is suspected that hydride precipitation on planes oriented normal to the principal axis of residual stresses in the sheet contributed to a significant lowering of the fracture stress for cleavage. This particular material contained only 65-73 ppm of hydrogen which was apparently uniformly distributed in the base and weld metal on a macroscale.

A hydride phase generally can act in two ways to embrittle titanium: (1) as a stress raiser, and (2) through its inherent brittleness which results in the introduction of numerous microcracks. Usually, the hydride phase is randomly located, so that brittleness is observed only when the hydrogen content is excessive, or when conditions are such that the ductile behavior of the matrix is minimized, i.e., at high strain rates or low temperatures.

Recently, however, M. R. Louthan[3] has shown that hydride platelets in titanium can be preferentially oriented by stress. Thus, on cooling a weld-rolled sample of unalloyed titanium from 800 F under an applied tensile stress of 30,000 psi, hydride platelets precipitated nearly perpendicular to the principal stress axis.

Other work by R. P. Marshall and M. R. Louthan[4] showed the orientation of hydrides in Zircaloy was in turn dependent upon the orientation of hydride platelets. Stated in terms of the hydrogen content, as much as 100 ppm of hydrogen present as randomly oriented hydrides did not decrease the ductility of Zircaloy below 10 per cent RA, but when 50 ppm hydrogen was present as hydrides oriented on planes normal to the stress axis, the material was brittle. The ultimate strength was also greatly reduced.

Although data showing the stress dependence of hydride orientation in titanium alloys are not available, hydrides would also be expected to precipitate on planes normal to tensile stress in an alloy. Such orientation of hydride is energetically favorable because the matrix would be expanded in a direction to relieve the applied stress. Titanium alloys such as Ti-6Al-4V and Ti-5Al-2.5Sn have a higher hydrogen tolerance than unalloyed titanium. A hydrogen content of 150 ppm (randomly oriented hydrides) has been shown not to affect the room-temperature tensile ductility of welded joints in Ti-6Al-4V, while hydrogen in excess of 100 ppm (randomly oriented hydrides) embrittles welds in unalloyed titanium.[5]

In the case of the fracture investigated at Battelle, it is expected that a stress-relief treatment, after preliminary welding and before the final welding operation, would minimize hydride embrittlement. The positive effects of such a stress-relief treatment would be threefold: (1) residual stresses (the forces for crack initiation) would be reduced, (2) hydride precipitation on planes normal to residual tensile stresses (the embrittling condition) would be minimized, and (3) redistribution of the hydrogen would lower the amount of hydride phase in the heat-affected zone.

More recently, additional information on the desirability of stress relieving titanium alloy welds intended for low-temperature applications has become available to DMIC.[6] In this instance, tensile properties were determined on a number of Ti-5Al-2.5Sn TIG- and electron-beam-welded samples of the ELI-grade alloy, both with and without an unspecified stress-relief anneal, at temperatures to -423 F. These data are summarized in Table 2. On the basis of the apparently beneficial effect of stress relief on the low-temperature tensile elongation and spread in elongation values, it was concluded that stress-relief annealing is beneficial and desirable. It is of further interest to note that metallographic evaluation of two electron-beam-welded fo ging specimens (which failed prematurely at -300 F and -423 F) showed evidence of what appeared to be a hydride phase on the fracture surface. The suspect precipitates disappeared when the specimen was heated to 1475 F for 30 minutes.

In summary, all aspects of welded structure are important in deciding whether stress-relieving treatments are necessary. It is not necessary to stress relieve all welds, but such treatments may be desirable when the structures are:

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TABLE 2. LOW-TEMPERATURE TENSILE DATA ON TIG- AND ELECTRON-BEAM-WELDED Ti-5Al-2.5Sn ALLOY

Material	Test Temperature, F	Ultimate Strength,[a] ksi: As-Received or As-Welded	Ultimate Strength,[a] ksi: Welded and Stress-Relieved	Elongation in 2 Inches,[a] per cent: As-Received or As-Welded	Elongation in 2 Inches,[a] per cent: Welded and Stress-Relieved
Forged material:					
Parent metal	-423	234-253	-	6-10	-
TIG welded	RT	124-12[illegible]	120-127.5	14-15.5	14-15.5
	-300	-	177-183	-	9-10.5
	-423	214-240.5	230.5-240	0.5-3.5	4.5-7.5
EB welded	RT	122-125	-	2-9	-
	-300	185-192	-	1-1.5	-
	-423	204-225	-	1-2.5	-
0.047-inch sheet:					
Parent metal	-423	204-247	-	6-12	-
TIG welded	RT	-	121-125	-	16-20
	-423	227-229.5	228-238	1.5-4	3-3.5
0.063-inch sheet:					
TIG welded	RT	116-117	112-115	15-17	15.5-17
	-423	228-229	-	7-8.5	-
EB welded	RT	115-116	-	7-13	-
	-300	174.5-179	-	1.5-6.8	-
	-423	206-227	-	1-4.5	-

(a) Values given represent the maximum and minimum from at least three tests.

(1) Manufactured to close dimensional tolerances

(2) Complex and contain many stress raisers

(3) Subjected to dynamic loading

(4) Subjected to low-temperature service

(5) Subjected to service conditions that might promote stress corrosion.

Other questions received at the Defense Metals Information Center have been concerned with the type of test program required for establishing the need for stress-relieving treatments. One objective of such a program would be to establish residual stress levels after varying stress-relieving treatments. Variables that should be studied include stress-relieving temperature and time at temperature. A number of procedures can be followed in measuring residual stresses after these treatments.

A second objective should be to establish the effects of stress-relieving treatments on the mechanical properties of the welded joints. Normally, most stress-relieving operations do not affect the mechanical properties of the joint. In the case of the Ti-6Al-4V alloy, however, there is a chance that age hardening will occur in the welds during stress-relieving operations. Hardening can be evaluated on the basis of hardness measurements in the weld zone plus bend, tensile, and V-notch Charpy impact tests.

The final objective of the program should be to determine the effects of stress-relieving operations on the performance of the weldments. Probably, the best performance measurement would be the capacity of the weld to undergo plastic flow under the desired operating conditions. There are a number of tests which could be used to evaluate this capacity. These include bulge tests on specimens with center welds, burst tests on small tanks, or burst tests on cylinders in which a weld is made in an area of stress concentration, such as a dent in the specimen. As-welded and stress-relieved specimens could be compared.

REFERENCES

(1) Brown, H., "Stress-Corrosion Cracking of Ti-5Al-2.5Sn", DMIC Memorandum 60 (August 4, 1960).

(2) Ernst, R. H., Williams, D. N., and Ogden, H. R., "Observations on Delayed Cracking in Welded Structures of Unalloyed Titanium Sheet", DMIC Memorandum 191 (April 29, 1964).

(3) Louthan, M. R., "Stress Orientation of Titanium Hydride in Titanium", Trans. AIME, 227 (5), 1166-1170 (October, 1963).

(4) Marshall, R. P., and Louthan, M. R., "Tensile Properties of Zircaloy With Oriented Hydrides", Trans. ASM, 56 (3), 693-700 (September, 1963).

(5) Williams, D. N., "Hydrogen in Titanium and Titanium Alloys", TML Report 100 (May 16, 1958).

(6) Cawthorne, E. W., "Stress Relief of Titanium Welds", Memorandum to DMIC (data from North American Aviation, Inc., Space & Information Systems Division, Downey, California) (May 12, 1964).

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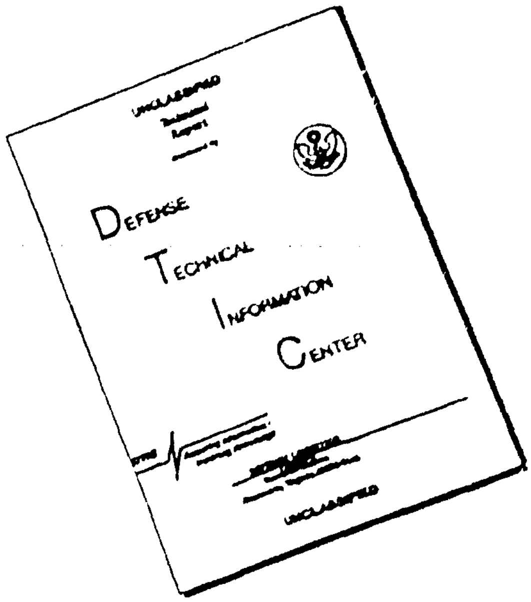

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