Joining of Advanced and Specialty Materials VII (#05116G)

Recent Developments in Weldability Testing for Advanced Materials

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Abstract

The term "weldability" has been used to describe a wide variety of characteristics when a material is subjected to welding. These include the physical and mechanical properties of the welded structure, the ease with which welding can be accomplished from a practitioner's standpoint, the ability of the material to avoid metallurgical degradation (usually assessed by its susceptibility to cracking during welding or subsequent heat treatment), and the ability of the welded structure to perform in its intended service environment. A number of weldability tests have been developed over the years to evaluate and quantify material weldability. Many of these test techniques have focused on the phenomenon known as "hot cracking". This paper will review the basic concepts associated with hot cracking and other forms of elevated temperature cracking and describe some recent advances in the use of testing approaches to quantify susceptibility to these forms of cracking. This description will include the use of the Varestraint test, the cast pin tear test, and the Gleeble™ thermo-mechanical simulator for quantifying cracking susceptibility and providing comparative measures of weldability among alloys.

Introduction

The cracking of welded construction during fabrication has been a problem since the first welding processes were first widely adopted in the early 20th century. Cracking occurs for two reasons, 1) the presence of tensile stress, and 2) a susceptible microstructure in the weld metal or heat-affected zone. Since the elimination or control of stresses during welding is usually quite difficult, a better approach is often control of the weldment microstructure.

The various forms of cracking are generally grouped by the temperature range over which they occur. "Hot cracking" is associated with the presence of liquid films along grain boundaries or elsewhere in the structure and includes weld solidification cracking, HAZ liquation cracking, and weld metal liquation cracking. "Warm cracking" occurs in the solid state at temperatures between the solidus and approximately half the melting temperature of the material and may occur either during fabrication or subsequent postweld heat treatment. Various forms of warm cracking include ductility-dip cracking, reheat cracking, strain-age cracking, and lamellar cracking. Finally, "cold cracking" occurs at or near room temperature and is usually associated with the presence of hydrogen and hydrogen-assisted cracking mechanisms.

Over the past 50 years, numerous studies of weld cracking have been published and various theories proposed to describe the cracking mechanisms. In addition, a number of test techniques (well over 200) have been developed to study and quantify cracking susceptibility. In this paper, four types of weld cracking are reviewed and test procedures described to quantify susceptibility, namely, 1) weld solidification cracking, 2) HAZ liquation cracking, 3) ductility-dip cracking, and 4) strain-age cracking. All three of these cracking phenomena have been observed in austenitic stainless steels and Ni-base alloys, and often plague the fabrication of these materials.

Weld Solidification Cracking

Weld solidification cracking occurs during the final stages of solidification when tensile shrinkage stress accumulates and liquid films still persist along solidification grain boundaries in the structure. If the imposed shrinkage strain exceeds the inherent ductility of the solidifying weld metal, cracking will occur. The temperature range over which this occurs has been defined by Prokhorov[1], Matsuda[2], and others as the Brittle Temperature Range (BTR). The BTR is represented by a drop in ductility between the liquidus and solidus temperature, where the width (temperature) and depth (ductility) of the BTR can be used to assess susceptibility to weld solidification cracking. As a general rule, the wider and deeper the BTR, the more susceptible the material is to cracking. Thus, the ability to measure the BTR during welding should provide some approximation of a material's susceptibility to weld solidification cracking. Unfortunately, it has proven very difficult in practice to measure the BTR.

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Transverse Varestraint Test. The Varestraint test, in a variety of forms, has been used since the 1960's to quantify susceptibility to "hot cracking", i.e. weld solidification and liquation cracking. A variety of methods have been used for quantification, including total crack length, maximum crack length, total number of cracks, threshold strain for cracking, and others. Recently, Lippold et al.[3] developed a new methodology for evaluating cracking susceptibility using the transverse Varestraint test that provides a measure of the temperature range over which cracking occurs. This has been termed the solidification cracking temperature range (SCTR) and is a subset of the BTR. Samples are tested over a range of augmented strain and the maximum crack distance (MCD) in the fusion zone is measured. A schematic of the transverse Varestraint test is shown in Figure 1.

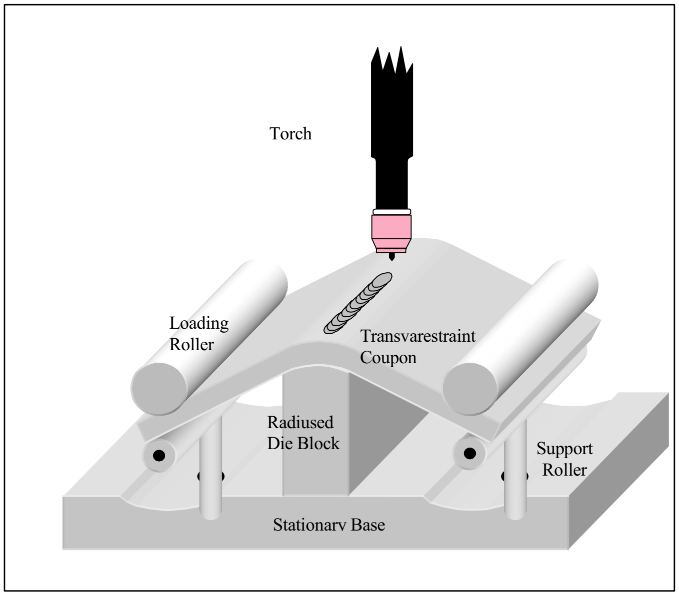

Figure 1. Schematic of the transverse Varestraint test for evaluating weld solidification cracking susceptibility.

Above a critical strain level, designated the saturated strain, the MCD does not increase with increasing strain. This indicates that the solidification crack has propagated the full length of the crack susceptible region. By testing over a range of augmented strain, an MCD versus strain plot such as that shown in Figure 2 can be generated. In this manner, the threshold strain for cracking to occur and the saturated strain above which the MCD does not increase can be identified. The typical strain range over which samples are tested is 0-7%.

Most fully austenitic weld metals stainless steels and Ni-base alloys exhibit saturated strain levels between 5 and 7%. Threshold strain levels are generally in the range from 0.5 to 2.0%. Although, the threshold strain may, in fact, be an important criterion for judging susceptibility to weld solidification cracking, the MCD at or above saturated strain is much easier to determine and provides a measure of the SCTR.

In order to determine SCTR, the cooling rate through the solidification temperature range is determined by plunging a thermocouple into the weld pool. The time over which cracking occurs is approximated by the MCD above saturated strain divided by the solidification velocity. Using this approach, SCTR can be calculated using the following relationship, where V represents the welding velocity.

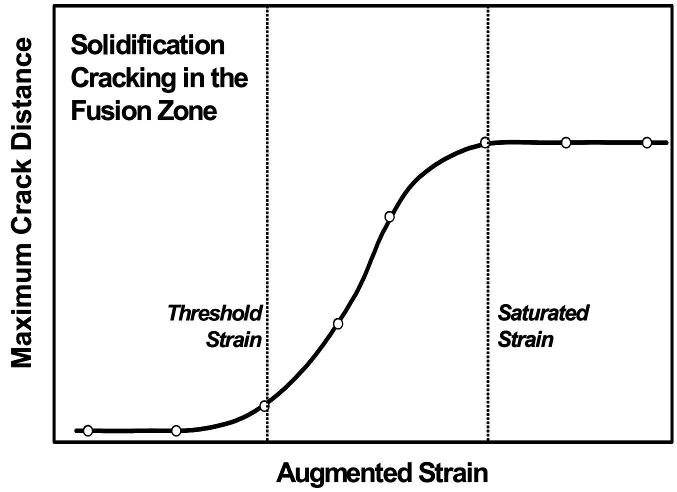

Figure 2. Maximum crack distance in the fusion zone versus applied strain during transverse Varestraint testing.

$$SCTR = [Cooling\ Rate] \times [MCD/V]$$

The concept for determining SCTR using this approach is shown in Figure 3. By using a temperature rather than a crack length as a measure of cracking susceptibility, the influence of welding variables (heat input, travel speed, etc.) can be eliminated. SCTR then represents a metallurgically significant, material-specific measure of weld solidification cracking susceptibility.

The SCTR values for a number of austenitic and duplex stainless steels, and Ni-base alloys is shown in Table 1. Alloys that solidify as primary ferrite (duplex stainless steels 2205 and 2507, and Types 304 and 316L) have low SCTR values, typically less than 50°C. Alloys that solidify as austenite exhibit SCTR values above 100°C. Alloy A-286, which is notoriously susceptible to solidification and liquation cracking, has a very high SCTR value.

Table 1. Solidification Cracking Temperature Range (SCTR) values determined using the Transverse Varestraint Test.

Material	**SCTR (ºC)**
Duplex SS Alloy 2205, FN 100	26
Type 304L SS, FN 6	31
Duplex SS Alloy 2507, FN 80	45
Type 316L SS, FN 4	49
Superaustenitic SS, AL6XN	115
Ni-base Alloy 690	121
Type 310 SS	139
Ni-base Alloy 625	200
A-286	418

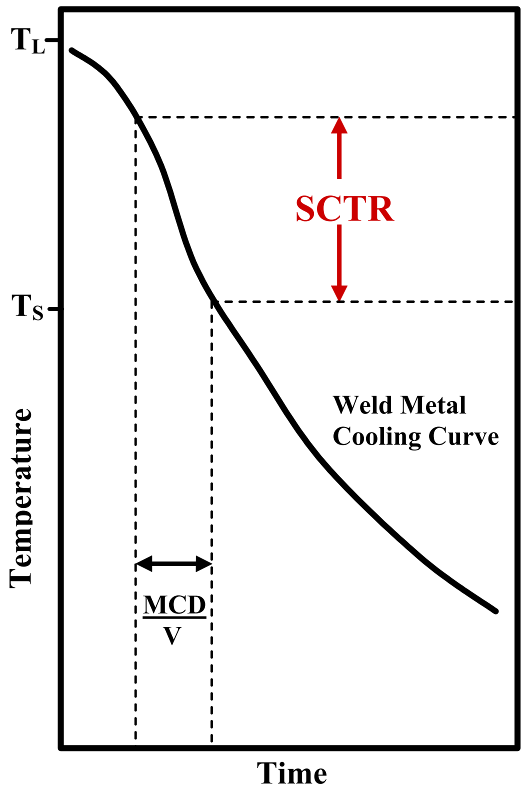

Figure 3. Method for determining the solidification cracking temperature range (SCTR) using the cooling rate through the solidification temperature range and MCD (maximum crack distance) at saturated strain. (3)

The SCTR data allows a straightforward comparison of cracking susceptibility. These values may also allow alloy selection based on restraint conditions. For example, in high restraint situations, SCTR values below 50 °C may be required to prevent cracking, while for low restraint weldments 150 °C may be sufficient.

Recently, Finton and Lippold[4] used a statistical approach to evaluate the variables associated with transverse Varestraint testing. This study used both austenitic stainless steels (Type 304 and 310) and Ni-base alloys (Alloys 625 and 690) to determine the statistical importance of different variables and to establish variable ranges in which testing should be conducted to give reproducible results. Based on this study, they recommended the variable ranges in Table 2 for use with stainless steel and Ni-base alloys.

More research is required to relate the SCTR to the local restraint conditions required for cracking. As a minimum, the overall transverse Varestraint approach described here appears to provide a good relative measure of solidification cracking susceptibility and has been found to work well in predicting the behavior in other systems, including structural steels and aluminum alloys.

Table 2. Variables and variable ranges for transverse Varestraint testing of stainless steels and Ni-base alloys.

Arc Length Range:	0.05-0.15 in.
Maximum Voltage Changes:	± 1-1.5 volts
Minimum Specimen Length:	3.5 in.
Minimum Specimen Width (parallel to welding direction)	3.0 in.
Current Range:	160-190 amps
Travel Speed Range:	4-6 in./min
Augmented Strain Range:	3-7%
Ram Travel Speed Range:	6-10 in./sec

Cast Pin Tear Test. Although the Varestraint test has great utility for assessing the solidification cracking susceptibility of most structural alloys, the test may be too severe for evaluating some of the highly-alloyed Ni-and Co-base alloys used for repair of turbine engine components, since these alloys may crack at very low strain levels. For these materials, a modified version of the cast pin tear (CPT) test, originally introduced by Hull[5], can be used. With this test, small charges of the material of interest are melted in a copper crucible using a gas tungsten arc welding (GTAW) torch under argon shielding. This charge is then dropped through the bottom of the crucible into a copper mold. A range of mold diameters and lengths are used to control the restraint in the solidifying pin. This procedure and apparatus design is described in detail elsewhere.[6]

Using the CPT test, a plot of percent cracking versus mold size is developed, as shown in Figure 4. 100% cracking represents the situation where cracking occurs completely around the diameter of the pin or there is complete separation of the pin. Less than 100% cracking indicates that cracking does not occur a full 360 degrees around the pin circumference. Note that for Alloys 3 and 5 only small increases in mold length result in large changes in cracking susceptibility, while Alloy 1 and Alloy 625 are resistant to cracking until relatively long mold lengths are used.

Other distinct advantages of this test are that virtually no sample preparation is required and very little material is used. Entire curves, such as those shown in Fig. 4, can be generated with about 200 grams of material. Additionally, testing is not time intensive. For a given material, testing and analysis can be completed in just a few hours. The cooling rates achieved, based on evaluation of solidification substructure size, are equivalent to those in arc welds.

The test is under further development and refinement at Ohio State University. An improved molten metal delivery system has recently been developed that greatly facilitates mold filling and allows a wider range of mold geometries to be used. This allows alloys with only moderate solidification cracking susceptibility to be tested.

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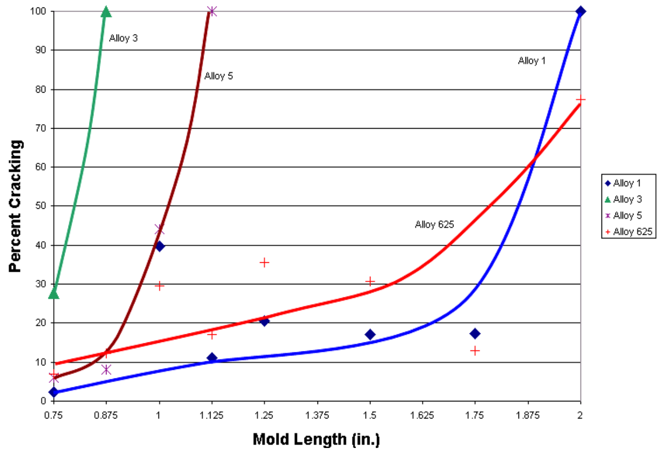

Figure 4. Cast pin tear test data for Ni- and Co-base alloys. Alloy 1 is Co-20Cr-10Ni-9W-4Al, Alloy 3 is Ni-10Co-8Cr-10W-5Al, and Alloy 5 is Ni-12Co-7Cr-5W-6Al.

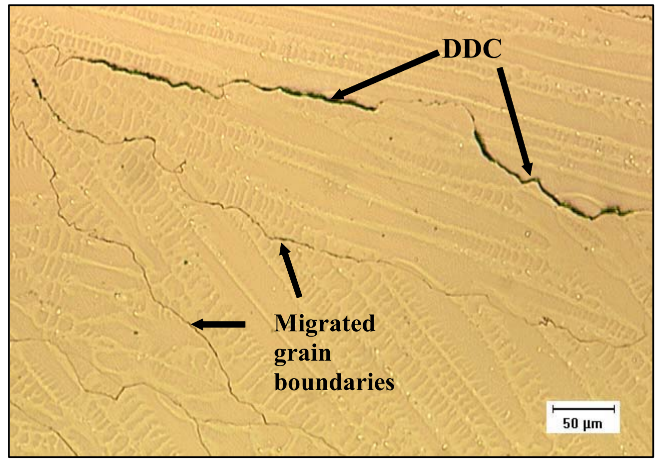

Figure 5. Ductility-dip cracking along migrated grain boundaries in fully austenitic weld metal.

Ductility-Dip Cracking

Ductility-dip cracking (DDC) refers to elevated temperature, solid-state cracking that results from a sharp drop in ductility at temperatures above approximately half the melting temperature of the material.[7,8] It can occur in wrought alloys, castings, and in the HAZ and fusion zone of highly restrained weldments. Characteristically, it is associated with single phase austenitic alloys with large grain size, and is intergranular in nature.

Considerable work has been conducted over the last few years to understand the nature of DDC in welded austenitic stainless steels and Ni-base alloys.[9,10,11,12,13,14] This work has included investigation of austenitic stainless steels (Types 304 and 310, and AL6XN), Ni-base alloy 690, and Ni-base filler metals 82 and 52.

A typical ductility-dip crack in a Ni-base weld metal is shown in Fig. 5. In weld metals, DDC always occurs along migrated grain boundaries (MGBs). These are crystallographic, high-angle boundaries that have migrated away from their parent solidification grain boundaries during cooling below the solidification temperature range and/or during reheating in multipass welds. A detailed description of these boundaries can be found elsewhere.[15]

Weld metal DDC in stainless steels and Ni-base alloys has been found to be a strong function of grain size, grain boundary character, and precipitation behavior.[13,14] Weld metals exhibiting large grains with straight MGBs and few grain boundary precipitates tend to be the most susceptible. An increase in grain boundary tortuosity resulting from local pinning by precipitates or second phases that form at elevated temperature will decrease susceptibility to DDC. This occurs by a grain boundary locking effect that resists grain boundary sliding, as shown in Figure 6. While not directly linked to DDC, impurity segregation to the MGBs tends to further increase susceptibility to this form of cracking. In Ni-base filler metals, the addition of hydrogen to the shielding gas increases susceptibility to DDC.[16]

In order to quantify susceptibility to DDC, the strain-to-fracture (STF) test was recently developed by Nissley at Ohio State University.[17] The STF test employs a "dogbone" tensile sample with a GTA spot weld applied in the center of the gage section. The spot weld is made under controlled solidification conditions using current downslope control. This results in an essentially radial array of migrated grain boundaries within the spot weld. Samples are then tested in a Gleeble™ thermo-mechanical simulator at different temperatures and strains. Temperature and strain ranges are typically 650-1200°C and 0-20%, respectively. After testing at a specific temperature-strain combination, the sample is examined under a binocular microscope at 50X to determine if cracking has occurred. The number of cracks present on the surface is counted.

Using this data, a temperature vs. strain envelope is developed that defines the regime within which DDC may occur. Both a threshold strain for cracking (ε_{min}) and ductility-dip temperature range (DTR) can be extracted from these curves. Temperature-strain curves are shown in Figure 7 for Type 310, Type 304, and the super-austenitic alloy AL6XN. Based on these curves, Type 310 would be expected to have the highest susceptibility to DDC since the DTR at 15% strain is 400°C and ε_{min} is approximately 5%.

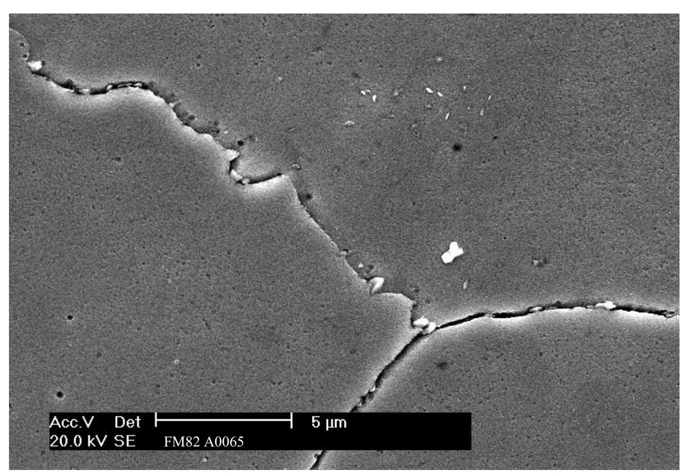

Figure 6. Grain boundary pinning and resulting "tortuosity" in Ni-base filler metal 82. (16)

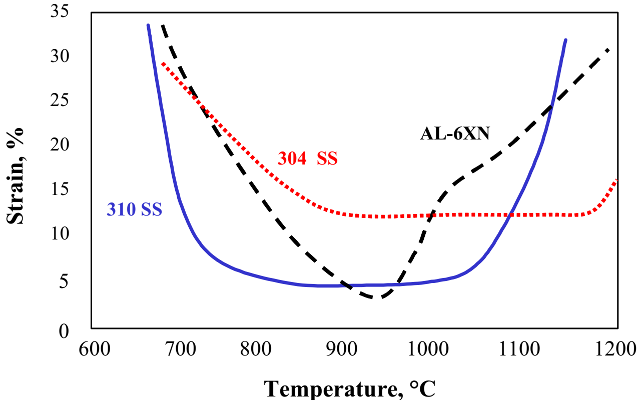

Figure 7. Strain-to-fracture test results for three austenitic stainless steels. [10]

This test has been shown to be remarkably sensitive to the onset of grain boundary cracking in the DDC range and should prove to be a valuable tool for studying elevated temperature embrittlement in the weld metal and HAZ. Work is ongoing at The Ohio State University to further optimize the test. This test is also being using the study the composition and metallurgical variables that affect susceptibility to ductility-dip cracking. The nature of grain boundary precipitates and their effect on the pinning of migrated grain boundaries is the key factor in controlling susceptibility to DDC

Strain-age Cracking

Strain-age cracking (SAC) is a form of postweld heat treatment cracking that is associated with Ni-base superalloys. The term "strain-age" is derived from the fact that cracking occurs in the temperature range were extrinsic and intrinsic strain accumulation overlaps the onset of precipitation hardening, or aging. In most Ni-base superalloys, this form of cracking is closely related to the precipitation of gamma-prime, $Ni_3(Ti,Al)$. Alloys with higher Ti + Al contents tend to be more susceptible to SAC.[18] Grain size and impurity content also influence susceptibility. Materials with much finer HAZ grain size or those with low levels of sulfur, phosphorus, and boron are more resistant to SAC. A relationship between SAC susceptibility and grain boundary liquation has also been reported.[19]

SAC is usually associated with the HAZ of either wrought alloys or castings and occurs along grain boundaries in close proximity to the fusion boundary. A strain-age crack in Waspaloy and the corresponding fracture surface are shown in Figure 8. From a mechanistic standpoint, cracking occurs along the grain boundary due to intragranular strengthening by precipitation and the corresponding formation of a precipitate-free zone (PFZ) at or near the grain boundary. Upon the application of sufficient strain, cracking occurs through this weakened region. There is an ongoing debate about the validity of this mechanism and further research is required to resolve whether the presence of a PFZ near the grain boundary is a prerequisite for SAC.

As with other forms of cracking, numerous tests have been developed to determine susceptibility to SAC. To date however, there is no standardized test for quantifying the susceptibility of an alloy to SAC. Many of the test techniques that have been developed use a Gleeble™ thermo-mechanical simulator. The problem with these tests is that they do not

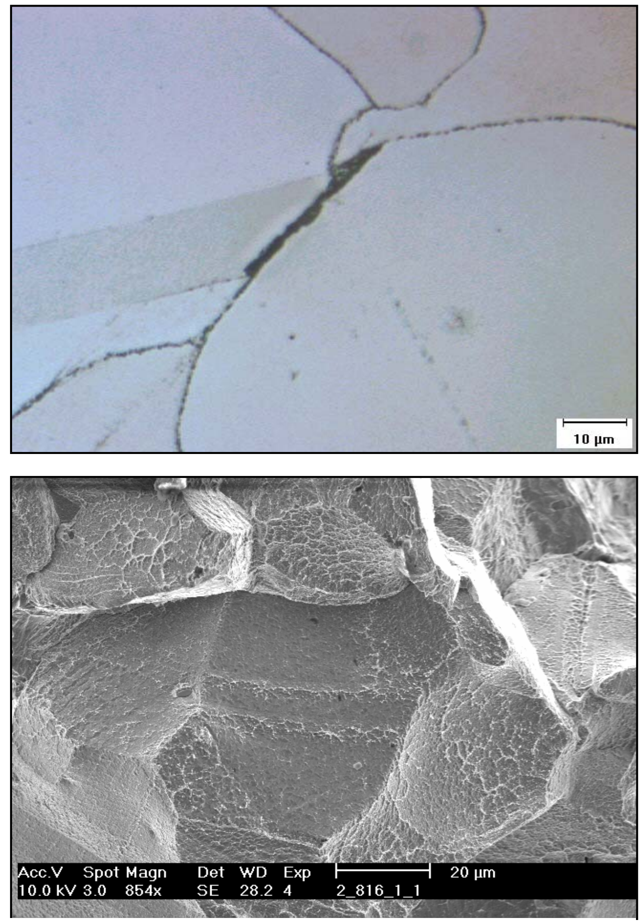

Figure 8. Strain-age crack in Waspaloy, Top) optical micrograph, Bottom) SEM fractograph.

accurately simulate the thermo-mechanical history of a weld. Most tests do not adequately simulate the development of residual stresses in a weldment as it cools after the weld metal is deposited. Those tests that impose stresses on cooling from the peak temperature to simulate weld residual stress do not allow relaxation of the stresses in subsequent PWHT simulations.

The approach used by Norton[20] at The Ohio State University attempted to more closely simulate the actual conditions experienced by the HAZ during welding. The Gleeble was used to impose a simulated thermal cycle on the specimen. After reaching the peak temperature, the sample was restrained in the Gleeble jaws and allowed to cool to room temperature with the application of additional tensile strain. This resulted in the buildup of considerable stress in the sample due to both thermal contraction and mechanical strain. The sample was then heated to an appropriate PWHT temperature and held at temperature for a predetermined time (0 to 4 hours).

Upon reheating to the PWHT temperature, considerable stress relaxation occurs and then stress begins to build in the sample as aging occurs, as shown in Figure 9. The starting stress for both alloys has been subtracted so that that the stress buildup relative to each other can be shown. Note that the increase in stress is more rapid in Waspaloy due to the more

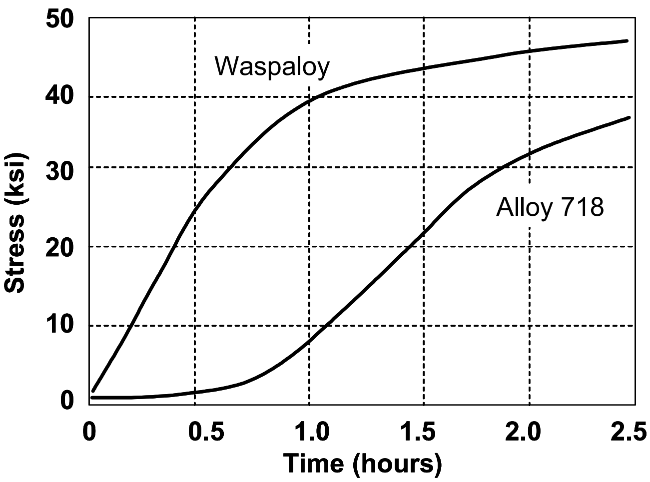

Figure 9. Increase in stress versus hold time at PWHT temperature for two Ni-base superalloys. (20)

rapid aging response associate with gamma-prime precipitates relative to gamma double-prime in Alloy 718.

After the prescribed hold time the sample is pulled to failure at the PWHT temperature and the ductility measured. The hot ductility following PWHT was used to develop a multivariate polynomial for calculating the ductility as a function of PWHT temperature and time. The collected data appeared to have a parabolic curve, so the model was chosen to be a second order polynomial. A spreadsheet for both alloys was created with factors of time, temperature, and the interactions between the two in a second order equation. A line was fit to the ductility (reduction in area) measurements. The resulting output gave the intercept and coefficient for each of the five variables as well as the coefficient of determination for the fit.

An example of ductility versus temperature curves for Waspaloy and Alloy 718 determined using this method is shown in Fig. 10. The coefficients of determination (R^2) for the Waspaloy and Alloy 718 surface plot polynomials are 0.92 and 0.91, respectively. The regression models show good fit to the measured data over the range of tested times and temperatures both by their high coefficients of determination and the ability to predict the ductility of samples. The curves in Fig. 10 are consistent with actual experience in welding these alloys. Alloy 718 is generally quite resistant to SAC, while Waspaloy is considered moderately susceptible.

Additional details of this test and its potential importance for determining susceptibility to PWHT cracking can be found elsewhere.[20] It should be noted that this test is not limited to the evaluation of Ni-base superalloys, but can also be applied to other materials that are susceptible to PWHT cracking, such as Cr-Mo-V steels and stainless steels (Type 347).

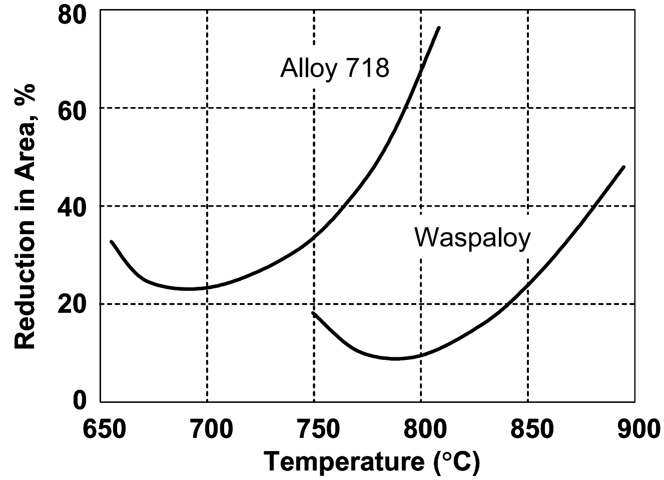

Figure 10. Comparison of elevated temperature ductility of Waspaloy and Alloy 718 regression models for 3 hours of PWHT. (20)

Summary

A number of weldability test techniques currently exist for quantifying elevated temperature cracking susceptibility in advanced materials. Unfortunately, few of these are standardized and considerable variation in test results can occur among laboratories using nominally the same technique. The transverse Varestraint test can be used to evaluate the weld solidification cracking susceptibility of a wide range of alloys. Using this test, a technique has been developed for quantifying the solidification cracking temperature range (SCTR) that can be used to rank alloys and provide insight into alloy selection. For materials that are extremely sensitive to weld solidification cracking, a modified cast pin tear test can be used to provide a qualitative order ranking.

Elevated temperature solid-state cracking in the form of ductility-dip cracking and strain-age cracking also occurs in many advanced materials. A new Strain-to-Fracture test has recently been developed to determine the strain-temperature envelope within which DDC occurs and to study the fundamental mechanisms of DDC. A new test has also been introduced to quantify susceptibility to strain-age cracking and postweld heat treatment cracking. This test measures the degradation in ductility as a function of temperature and time in the postweld heat treatment temperature range.

While these tests provide improved quantification of weld cracking susceptibility, efforts must continue to optimize and eventually standardize weldability test techniques. True quantification of material weldability will not be possible until standardization of these and other tests is achieved.

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Acknowledgements

The author wishes to thank Edison Welding Institute, BWXT, Inc. and the American Welding Society Foundation for financial support. The following former and current students were instrumental in the development of the weldability tests described here: Wangen Lin (SCTR technique), Daniel Ryan (cast pin tear test), Nathan Nissley and Matt Collins (strain-to-fracture test), and Seth Norton (strain-age cracking test).

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