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Stress measurements in welds: Problem areas

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Abstract

There have been many stress measurements on welds by neutron diffraction over the past 20 years but there are still a number of serious experimental issues that are often not addressed. The primary fact is that the microstructure generally changes across the weld and accompanying this may be a change in the concentration of strengthening elements in solution. This will lead to a shift in lattice spacing which may be incorrectly interpreted as a strain. Secondly, a gradient of plastic deformation near the weld may be expected. Since plastic deformation by application of a stress always generates intergranular (type-2) strains this may lead to a range of intergranular effects superposed on the conventional weld-related strains. The effects are illustrated by neutron diffraction studies of Zr-4, ferritic and austenitic welds where chemistry, intergranular effects and crystallographic texture can all play a role.

Keywords: Neutron diffraction; Welds; d_0 reference coupons

1. Introduction

Neutron diffraction is an ideal tool for obtaining the stresses at depth in welds since the observable strains are large and easy to measure and the size of the region probed by the neutrons in each measurement is usually a fraction of the width of the weld. However, it is possible that the usual adjective applied, "non-destructive", is a little over-optimistic for welds. There are invariably changes in microstructure in the weld metal and heat-affected zones which can lead to a change in alloy content and hence lattice parameter. Often the welding rod is a different alloy to the parent metal to give superior mechanical properties. In these cases it should be clear, as was first pointed out by Krawitz and Winholtz [1] that reference samples need to be prepared from a companion weld to get the stresses right. This is not yet uniformly practised unfortunately.

There are also more subtle questions that can be addressed by careful choice of the reference samples. It is well-known that mechanical deformation beyond the yield point, which is not uniform across the sample (such as bending), generates both a stress field in the sample and type-2 stresses on the size-scale of the grains. The latter balance among the different grain orientations in a given direction over a small volume. Thus type-2 effects do not affect mechanical strain gauge measurements, because of the finite size of the gauge, but they bias diffraction measurements. In the case of welds, differential cooling is the driving force for plastic deformation so it is of interest to ask whether stress-related type-2 effects should occur in welds. Another difficult question is the effect of texture on residual stress in welds. If one can isolate the strains corresponding to the residual stress field, then one expects that every reflection will indeed give the same stress value at any location with the use of the appropriate diffraction elastic constants. This should be the case even though the texture varies rapidly near the weld. On the other hand it will be seen that texture does influence the underlying type-2 strains.

The purpose of this paper is to underscore the importance of preparing appropriate reference samples for welds, and to investigate any underlying intergranular effects associated with welding. The procedure followed was to wire-cut small samples, of the order 1.5–2.0 mm on a side, as a function of position from the weld centreline in companion welds. The general requirement is that the coupon size be small compared with the extent of the stress field. The cutting process destroys the stress field but leaves the intergranular stresses and strains unaltered because

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they are on the scale of the grain size. Likewise any changes in lattice parameter resulting from chemistry are unaffected by cutting. Note that the former are direction-dependent while the latter are isotropic.

Measurements were made on three welds. The first is a butt-weld between two strongly textured Zr-4 plates of thickness 8.6 mm. The filler metal had the form of a rectangular wire cut from the plate. The crystal structure is hexagonal close-packed. The sample is similar to the welds made in the vessel of the Replacement Research Reactor at Lucas Heights, Australia. The second is a double-V butt-weld between two weakly textured 10 mm plates of the Japanese high-strength steel SNC631 exhibiting the body-centred cubic crystal structure. The third is also a double-V butt-weld between two 10mm plates of hot-rolled 304-type stainless steel exhibiting the face-centred cubic crystal structure. The filler metal was 308-type stainless steel.

2. Theory

The measurement of residual strains by neutron diffraction makes use of Bragg's law

$$\lambda = 2d_{hkl}\sin\theta_{hkl} \tag{1}$$

where λ is the wavelength of the neutron, d_{hkl} is the lattice spacing of atomic planes characterised by Miller indices $\{h\,k\,l\}$ and $2\theta_{hkl}$ is the scattering angle of the peak being measured. For monochromatic beam diffraction, the wavelength is fixed and its magnitude known and the measurement of $2\theta_{hkl}$ then gives the lattice spacing. For time-of-flight diffraction, the diffraction angle is fixed and known and the time of arrival of the neutron in the counter gives λ and hence d_{hkl} may be found from Eq. (1). For cubic materials the lattice spacings for the different reflections can be placed on a common scale by writing:

$$a_{hkl} = \sqrt{(h^2+k^2+l^2)}d_{hkl} \tag{2}$$

The strain in a particular sample direction, say xx, corresponding to the macroscopic stress field is given by

$$\varepsilon^{xx}_{\mathrm{hkl}} = \frac{d_{hkl}-d^{\mathrm{ref}}_{hkl}}{d^{\mathrm{ref}}_{hkl}} \tag{3}$$

where d^{ref}_{hkl} is the lattice spacing of the small reference coupon for the xx direction. The reference coupon will have no strain associated with the stress field but may have type-2 strains or effects due to chemistry. Finally the elements of the strain tensor are given in terms of the macroscopic stress field by analogy with Hooke's law:

$$\varepsilon^{xx}_{hkl} = \frac{\sigma^{xx}-\nu_{hkl}\sigma^{yy}-\nu_{hkl}\sigma^{xy}}{E_{hkl}} \tag{4}$$

and

$$\varepsilon^{xy}_{hkl} = \frac{(1+\nu_{hkl})\sigma^{xy}}{E_{\mathrm{hkl}}} \tag{5}$$

In Eqs. (4) and (5) E_{hkl} and ν_{hkl} are diffraction elastic constants which are $\{h\,k\,l\}$ specific. For linear welds it is likely that the principal axes will be the longitudinal direction in the weld (LD), the transverse direction (TD) and the plate normal direction (ND). Since the plates are 10mm or less in thickness, it is anticipated that the normal stress will be close to zero even at mid-thickness. It was assumed that the LD, TD and ND were the principal directions and measurements of strain were only made in these directions.

3. Experiments

The experiment [2] on the welded Zr-4 plate was performed on the SMARTS engineering diffractometer [3] at Los Alamos National Laboratory by time-of flight diffraction to get full information on all $\{h\,k\,i\,l\}$ reflections permitted by the texture. Details of the weld preparation and the texture of the plates and the variation in texture across the weld are given in Ref. [2]. The experiments on the two cubic welds were made on the RESA engineering diffractometer [4] at the JRR3 reactor of the Japan Atomic Energy Research Institute in Tokai, Japan. In these two cases measurements were made with a monochromatic beam of neutrons on the $\{1\,1\,0\}$, $\{0\,0\,2\}$ and $\{1\,1\,2\}$ reflections of the bcc structure and the $\{1\,1\,1\}$, $\{0\,0\,2\}$ and $\{2\,2\,0\}$ reflections of the fcc structure, respectively. Details of the experiment on the bcc weld have been given in Ref. [5] and complete results for the fcc weld will be reported elsewhere. The measurements were all made at the mid-thickness of the plates.

In each case 2 mm wide through-thickness slices were cut parallel to the weld at various distances from the weld centre-line. A 2 mm rods of square section were cut from these slices at the mid-thickness and a line was scribed on the top of the rod to identify the LD. These rods in turn were cut into cubes of length 2 mm. The individual cubes were then re-assembled and glued into larger reference samples, 6 mm × 6 mm × 6 mm in size, taking care to preserve the directions correctly. Our preference was for cutting coupons from the welds rather than cutting thin plates or combs to provide references. This was motivated by the desire to measure the type-2 intergranular strains directly in the LD, TD and ND directions. There is no assurance, for example, that the intergranular strain in the ND is zero even when the macroscopic stress in the ND is zero or small. In a flat plate or comb, the macroscopic stress is relieved in two directions though not necessarily completely in the third direction In the Zr-4 weld the gauge volume was determined by a 2 mm wide slit before the sample and 2 mm wide radial collimators in front of the detectors [2]. In the experiments on the cubic welds 3 mm slits were used before and after the sample to define the gauge volume. A single collimated counter was scanned through the angular range of each peak for these experiments.

4. Results and discussion

4.1. Zr-4 weld

The variation of the $\{1\,0\,\bar{1}\,1\}$ lattice spacing of the reference coupons as a function of distance from the centre of the weld is shown in Fig. 1 for the longitudinal direction, LD .The lattice spacing is expressed relative to the value at the edge of the plate and results are presented both for as-welded and as-

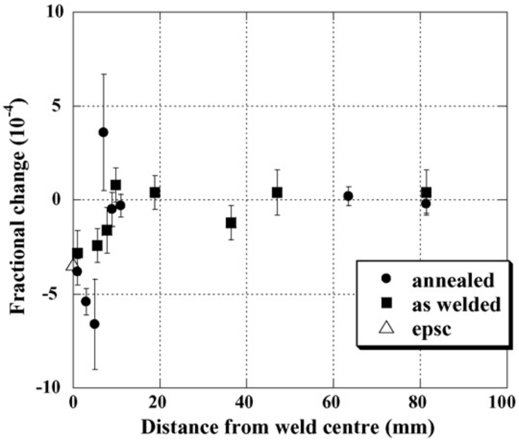

Fig. 1. Variation of the $\{1\,0\,\bar{1}\,1\}$ lattice spacing in the longitudinal direction for coupons cut from a Zr-4 weld as a function of distance from the centre of the weld. The change is expressed relative to the value at the edge of the plate. Results are shown for the as-welded and as-annealed states.

annealed coupons. All the other lattice spacings $\{h\,k\,i\,l\}$ in the LD, though not shown in Fig. 1, show the same relative changes and indicate no variation outside but a *decrease* within the weld metal. The analogous result for the ND shows no change outside but an *increase* within the weld. The TD result shows very little change outside or inside the weld. This variation was initially hard to explain. However, an elasto-plastic self-consistent (EPSC) calculation [6] of the thermal intergranular strains in the textured plate and the weakly textured weld [2] provided a quantitative explanation. The difference between coupons taken from the weld and the plate is positive for the ND, negative for the LD and near zero for the TD. The EPSC result for the LD is shown by an open triangle in Fig. 1. It is interesting to note that the measured changes across the weld are independent of whether the references are as-welded or as-annealed to within the measurement uncertainty (Fig. 2).

To obtain the strains corresponding to the stress field, the lattice spacing for each reflection $\{h\,k\,i\,l\}$ in each direction in the intact weld was referred to the coupon result at the same position and in the same direction. It was found that all the strains for a given sample direction showed the same form of variation for each $\{h\,k\,i\,l\}$. This contrasts, for example, with the transverse strains in a beryllium weld [7] where the $\{1\,1\,\bar{2}\,0\}$ strain was tensile and the $\{10\bar{1}1\}$ strain was compressive. This was interpreted [7] to mean that both strains were predominantly intergranular in character. The stresses in the LD, TD and ND directions in the Zr-4 weld at each position were fitted by the least squares method to a total of 35 measurements of strain in the three sample directions for the various $\{h\,k\,i\,l\}$ permitted by the texture using equation [4]. The appropriate diffraction elastic constants were calculated with the plate texture [2] and the single crystal elastic constants for Zr [8] with the aid of the EPSC model. In the case of Zr the diffraction elastic constants are rather isotropic and do not depend strongly on texture.

The longitudinal stress is tensile (220 ± 40 MPa) in the weld and falls rapidly towards zero around ± 35 mm and is compressive at the edge of the plate as is required for stress balance. The transverse stress (60 ± 40 MPa) is lower in the weld, because the

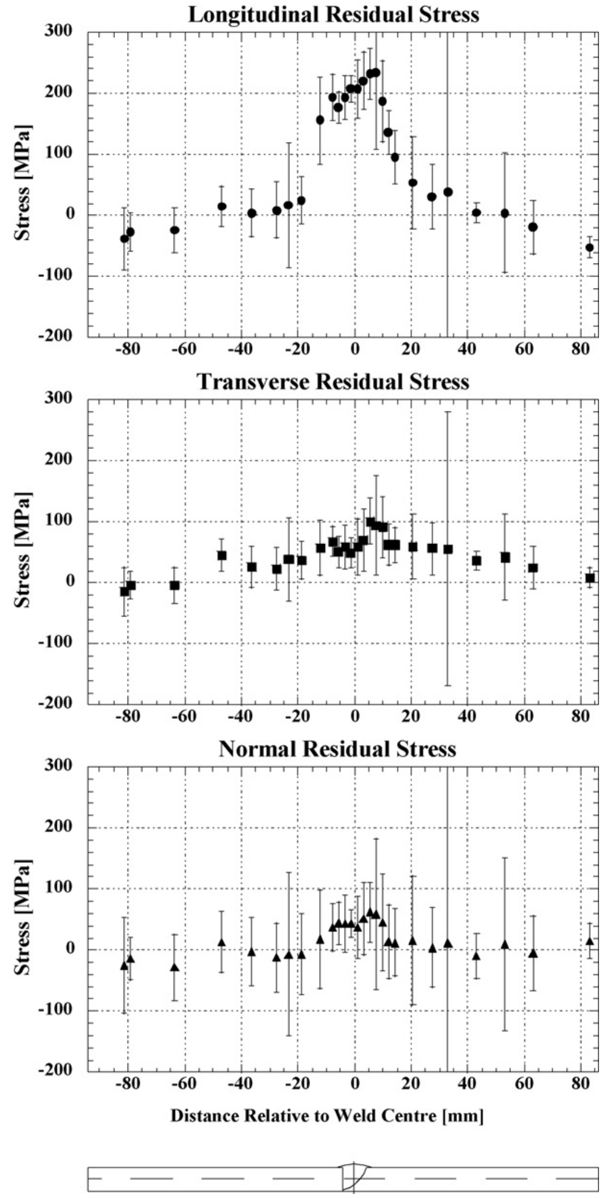

Fig. 2. Longitudinal, transverse and normal stresses measured in a Zr-4 weld as a function of position through the weld.

transverse shrinkage is less than the longitudinal shrinkage, and it falls to zero at the edge of the plate as required. The average normal stress is close to zero. Upon annealing the weld at 748 K to simulate a stress relieving procedure, the longitudinal stress had the same form but was reduced by 100 MPa. The transverse and normal stresses were close to zero.

In summary for the Zr-4 weld, the strains for all $\{h\,k\,i\,l\}$ in a given sample direction had the same form and magnitude in spite of the strong texture variation. The stresses calculated from the measured strains were well-behaved in the sense of fulfilling the equilibrium and boundary conditions. The macroscopic strains were superposed on intergranular strains that were consistent with cooling the weld and plate. The feature which was anticipated, namely that there might be intergranular strains related to mechanical deformation, was not borne out.

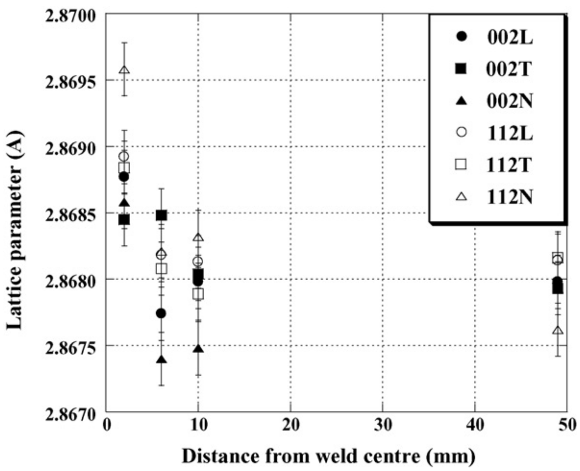

Fig. 3. Variation of the lattice parameter of coupons cut from a bcc weld as a function of distance from the weld centre. The results were derived from the {0 0 2} and {1 1 2} reflections.

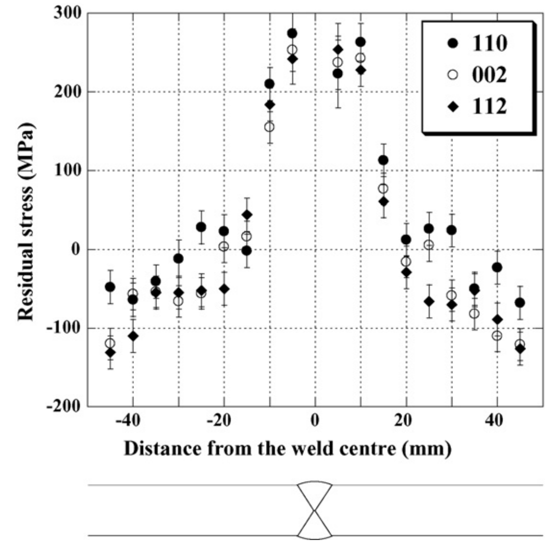

Fig. 4. Longitudinal stress derived from measurements of {1 1 0}, {0 0 2} and {1 1 2} reflections in the high strength steel SNC631 as a function of position through the weld.

4.2. Body-centred cubic weld

The variation of the lattice parameter derived from the {0 0 2} and {1 1 2} reflections in the reference coupons as a function of distance from the weld centre is shown in Fig. 3. There is no variation outside the weld metal larger than the experimental uncertainty. Within the weld, there is an increase in lattice parameter for all three reflections and all three principal directions. The result is similar to the results of Krawitz and Winholtz [1] and indicates a change of alloy concentration in the weld, rather than a strain-related phenomena. If intergranular effects had been present, one would expect that the {0 0 2} lattice parameter would be relatively tensile and that {1 1 0} would be slightly compressive to achieve stress balance between grains. Here all reflections show the same behaviour.

The longitudinal stress calculated from the measured strains for the three reflections is shown in Fig. 4. All three reflections give the same result to within the experimental uncertainty of about ±25 MPa. The appropriate diffraction elastic constants were calculated from the single crystal elastic constants for iron [9] with the Kröner model [10] and were $E_{110,112} = 212$ GPa, $\nu_{110,112} = 0.276$, $E_{002} = 165$ GPa and $\nu_{002} = 0.326$. The maximum longitudinal stress (250 ± 50 MPa) is about half the yield stress of the material. The longitudinal stress shows stress balance across the plate to +41 MPa which is 2 standard deviations. The transverse stress has a maximum value of 140 ± 50 MPa and decreases to zero at the edge of the plate. The average normal stress at the mid-thickness is −7 MPa.

Two further points are of interest. There is a 1.5–2.0 times increase of diffraction peak width inside the weld that might have been taken as an indication of plasticity and lead one to expect intergranular effects. However, micrographs show the presence of martensite inside the weld, at a level around 24%, and this is considered to be the source of the observed line-widths. Intensity changes were noted in the weld. In the LD direction at the weld centre the peak was sufficiently weak to prohibit a measurement of lattice spacing. Where measurements were possible in the weld, at ±2.5 and ±5.0 mm from the weld centre, the lattice spacing showed strong scatter from point-to-point and there was little confidence in being able to derive weld stresses accurately. The presence of martensite may be responsible for this scatter.

In summary, the macroscopic stresses agree in magnitude from the three reflections and appear to be balanced and to satisfy the boundary conditions. There is an increase in lattice parameter in the weld consistent with solute concentration changes. There are no evident intergranular effects.

4.3. Face-centred cubic weld

The variation of the lattice parameter derived from the {1 1 1}, {0 0 2} and {2 2 0} reflections as a function of distance from the weld centre is shown in Fig. 5. While there is a fair amount of scatter in the measurements, inside the weld only the lattice parameter for the LD and {0 0 2} reflection appears to increase systematically. The grain size, as determined from

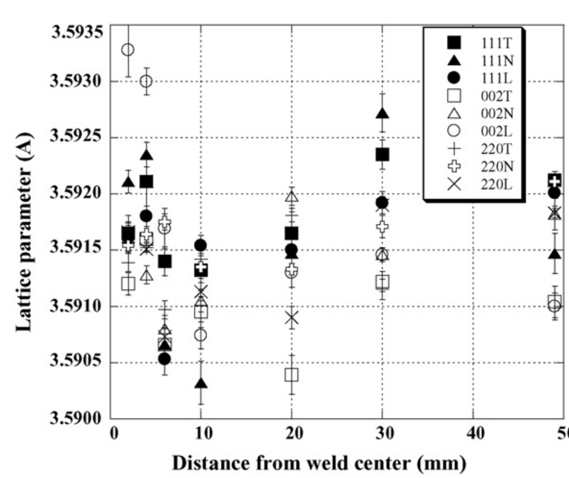

Fig. 5. Variation of the lattice parameter of coupons cut from an fcc weld as a function of distance from the weld centre. The results were derived from the {1 1 1}, {0 0 2} and {2 2 0} reflections.

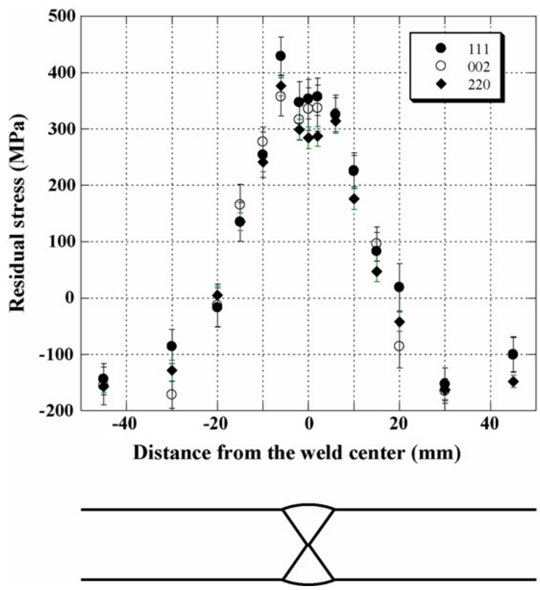

Fig. 6. Longitudinal stress derived from measurements of {1 1 1}, {0 0 2} and {2 2 0} reflections in 304-type stainless steel as a function of position through the weld.

micrographs, averages about 75 μm and this may be the source of the scatter. The lattice parameter derived from the {0 0 2} reflection at the edge of the plate also appears to be low compared with that derived from the {1 1 1} and {2 2 0} reflections. Since the plate was hot-rolled, it was natural to enquire whether this result at the edge of the plate indicated the presence of intergranular effects associate with rolling. An EPSC calculation for rolling 304-type stainless steel was carried. This indicated that all the strains were small. The {0 0 2} intergranular strain in the ND was found to be compressive, the strain in the LD was less compressive and that in the TD was tensile. These systematics were not observed and so the EPSC calculation does not provide a ready explanation of the coupon result. However, repeat measurements on the coupons showed the same experimental effects and independent measurements on a hot-rolled plate from the same batch showed that the {0 0 2} lattice parameter was also systematically low. There appear, therefore, to be qualitative indications that there are stresses in the plate material prior to welding.

The calculated longitudinal residual stresses derived from the {1 1 1}, {0 0 2} and {2 2 0} reflections are shown in Fig. 6 with an experimental uncertainty in each measurement of about ±25 MPa. The residual strains were determined from the lattice parameters in the intact weld and the lattice parameters in the coupons at the same location. In some cases the coupon lattice parameters were linearly interpolated between actual measurement locations. The diffraction elastic constants were derived from the singe crystal elastic constants for 304 stainless steel [11] and the Kröner model [10]. The values were $E_{111} = 242$ GPa and $\nu_{111} = 0.23$, $E_{002} = 152$ GPa and $\nu_{002} = 0.33$. $E_{220} = 211$ GPa and $\nu_{220} = 0.265$. The maximum observed longitudinal stress is 350 ± 50 MPa which exceeds the 0.2% yield point (264 MPa) and is more than 50% of the ultimate tensile strength (615 MPa). Thus there must have been some hardening for a weld stress of this magnitude to be supported. The transverse stress has a maximum value of 200 ± 50 MPa and decreases to zero at the edge of the plate. The average normal stress is 2 MPa. The longitudinal stress balances to 40 MPa which is about two standard deviations.

In summary, there is consistent evidence for an intergranular effect within the weld as evidenced by the increasing {0 0 2} lattice parameter. The estimates of the stresses from the different reflections are in good agreement. It is thought that the {0 0 2} reference lattice parameters at the edge of the plate were influenced by a prior manufacturing operation.

5. Conclusions

We have presented evidence to make the point that measurements in welds should always be accompanied with reference measurements taken from a companion weld. For the Zr-4 weld it has been shown that all reflections give a single stress field in spite of strong texture variations. Type-2 strains associated with cooling the weld metal and plate underlie the macroscopic strains. The stresses in the cubic welds show good agreement between the different reflections when the strain is computed with respect to coupons cut from the welds. Stress balance and the boundary conditions are satisfactorily fulfilled. The coupon data in each case shows a fair amount of scatter. For the bcc weld there is no lattice parameter variation outside the weld metal, but an increase within consistent with solute effects. There is consistent evidence for type-2 effects in the longitudinal direction in the weld metal.

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