Transformation Plasticity in Steel Weld Metals

H. K. D. H. Bhadeshia, J. A. Francis, H. J. Stone, S. Kundu
R. B. Rogge, P. J. Withers and L. Karlsson

Universities of Cambridge and Manchester, U. K. and Chalk River Laboratories, Canada, ESAB AB, Sweden

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1 Introduction

Professor Ulrich Dilthey's passion for the science and technology of joining processes is amply reflected in the enormous archive of published work which will forever serve the community. It is a pleasure therefore to be able to present this small story as a tribute to someone who has been a scholar, a gentleman and a leader in this most difficult of subjects.

The matter of our everyday world is made up of atoms and it is the behaviour of collections of these entities which governs the properties of macroscopic samples. The choreography of atomic motions during transformation is particularly important when dealing with martensite or bainite. These phases evolve by the synchronised movement of atoms, leading to visible displacements which can in principle be exploited to do work, a phenomenon intrinsic to the mechanical behaviour of TRIP–assisted steels. The subject of this paper is somewhat different, *i.e.,* the control of the transformation strains to compensate for the contraction when a constrained welded component cools. We begin with a rigourous description of the deformation caused by the change of austenite into martensite or bainite.

2 Shape Deformation

The conservative glide of a dislocation on a slip plane causes shear in a direction which lies in that plane. The material in the slip plane remains crystalline during the deformation, with nothing more than a momentary change in the relative positions of atoms on that plane, which is said to be *invariant* to the strain. Mechanical twinning is also a conservative mode of deformation and the plane on which the twinning shear occurs is similarly invariant.

If a material which has a Poisson's ratio equal to zero is uniaxially stressed below its elastic limit, then the plane that is normal to the stress axis is unaffected by the deformation since the only non-zero strain is that parallel to the stress axis (beryllium has a Poisson's ratio which is nearly zero).

All these strains belong to a class known as the *invariant–plane strains*, the operation of which leaves a plane undistorted and unrotated. Fig. 1a illustrates an invariant–plane strain (IPS) which is dilatational, and is of the type to be expected when a plate–shaped precipitate grows diffusionally. The change of shape is due to the volume change accompanying transformation. In Fig. 1b, the IPS corresponds to a simple shear at constant volume, as in slip or mechanical twinning.

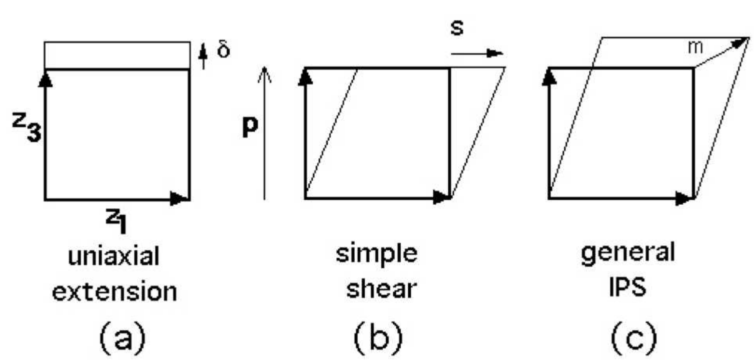

Figure 1: Invariant–plane strains. Squares indicate the shape before deformation. δ, s and m are magnitudes of the dilatational, shear and general displacement respectively. $\mathbf{p}$ is a unit vector.

The most general IPS is a combination of dilatation and shear (Fig. 1c); if $\mathbf{d}$ is a unit vector in the direction of the displacements involved, then $m\mathbf{d}$ represents the displacement vector, where m is a scalar giving the magnitude of the displacements. $m\mathbf{d}$ may be factorised as $m\mathbf{d} = s\mathbf{z}_1 + \delta\mathbf{z}_3$, where s and δ are the shear and dilatational components, respectively, of the invariant–plane strain. Fig.1c is representative of the shape deformation accompanying the formation of martensite or bainite, with $s \simeq 0.22$–0.26 and $\delta \simeq 0.02$–0.03. These deformations are much larger than elastic strains in a tensile test, which are of the order of 10^{-3}. s and δ therefore have profound effects on properties, as described below.

3 Residual Stress

It has long been recognised that phase transformations in steels can radically affect the development of residual stresses. Jones and Alberry [1] showed how the transformation temperature influences the evolution of stress as a constrained sample cools from the austenitic state (Fig. 2).

The $2\frac{1}{2}$Cr1Mo sample begins to transform to bainite at about 600°C. When this happens, the transformation strain compensates for the accumulated contraction. However, because the sample continues to cool after transformation is exhausted, there is a further sharp accumulation of stress.

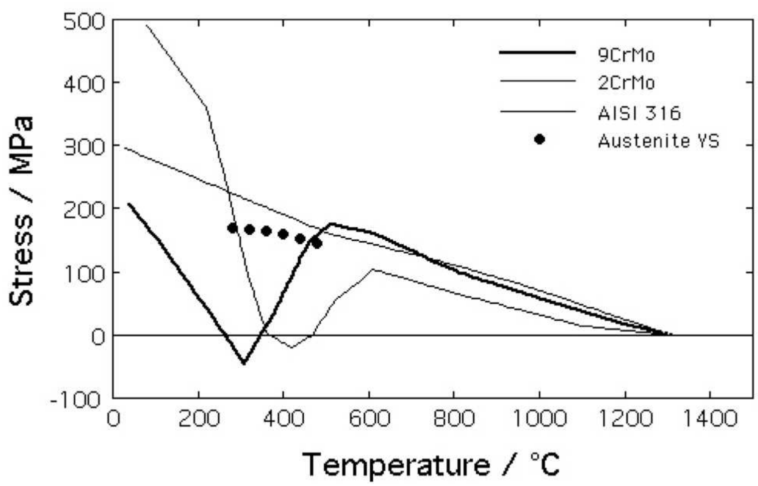

Figure 2: Axial stress in uniaxially constrained samples during cooling of a martensitic (9Cr1Mo), bainitic ($2\frac{1}{2}$Cr1Mo) and austenitic steel (AISI 316) [1]. Also plotted is the yield strength of austenite.

It is significant that the Alberry and Jones' experiments show that the stress remaining at ambient temperature is smaller when the transformation temperature is reduced (*cf.* 9Cr1Mo and $2\frac{1}{2}$Cr1Mo steels). There are three reasons which explain this phenomenon:

(i) Since the expansivity of austenite is greater than that of ferrite ($e_\gamma > e_\alpha$), the volume expansivity $3(e_\gamma - e_\alpha)\,\mathrm{K}^{-1}$ due to transformation is larger at lower temperatures, allowing a greater compensation of the accumulated thermal contraction strain.

(ii) If transformation becomes exhausted much before ambient temperature is reached, then it is the ferrite which contracts on cooling. Ferrite has a high yield strength (at low T) and hence there is a lesser compensation of contraction strain by plastic relaxation. This is why the stress rises sharply in the $2\frac{1}{2}$Cr1Mo steel after transformation is exhausted.

(iii) Transformation in constrained specimens, when it occurs at low temperatures, leads to a greater bias in the microstructure, making the shear strain s more prominent in mitigating thermal contraction. This is because there is a greater accumulation of stress before the low transformation–temperature is reached.

We now proceed to describe the exploitation of these phenomena.

4 Welds

Fatigue depends on many factors, one of the more important being the presence of residual stresses in the context of welded structures. Following Jones and Alberry [1], Ohta *et al.* [3–7] designed a welding alloy with an exceptionally low transformation temperature (M_S), in which martensitic transformation in an unconstrained specimen starts at about 180°C and is just completed at ambient temperature (Table 1). In contrast, normal welding alloys have $M_S \simeq 500 - 400$°C. As illustrated in Fig. 3a, the net strain (ϵ) on cooling between M_S and ambient temperature is a contraction in the case of the high–M_S "conventional" alloy, whereas there is a net expansion for the new welding alloy. This results in a large residual tensile stress for the high–M_S sample and a compressive one for the low–M_S alloy (Fig. 3b).

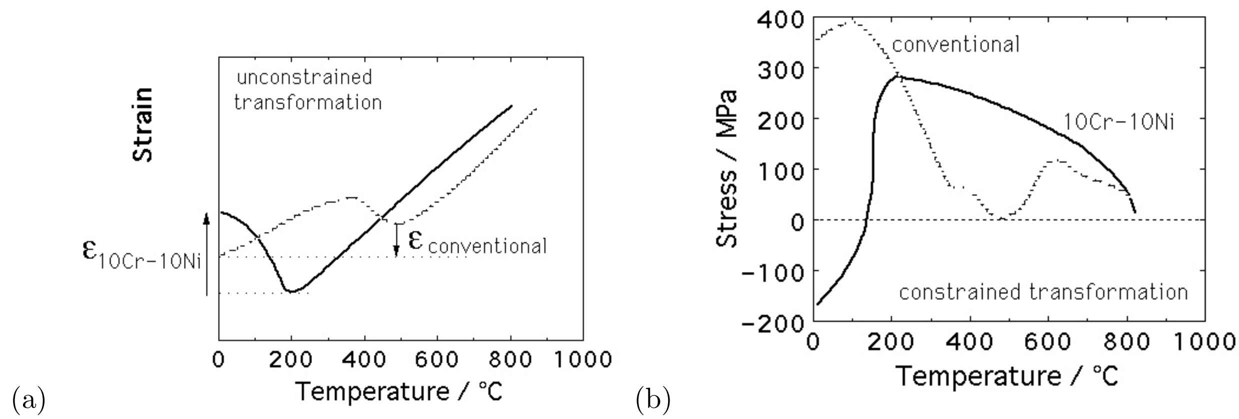

Figure 3: (a) Transformation of weld metal during unconstrained cooling; (b) development of stress during constrained cooling. The chemical compositions of the alloys are given in Table 1. The low–M_S alloy is designated 10Cr10Ni in Table 1. After Ohta and co-workers.

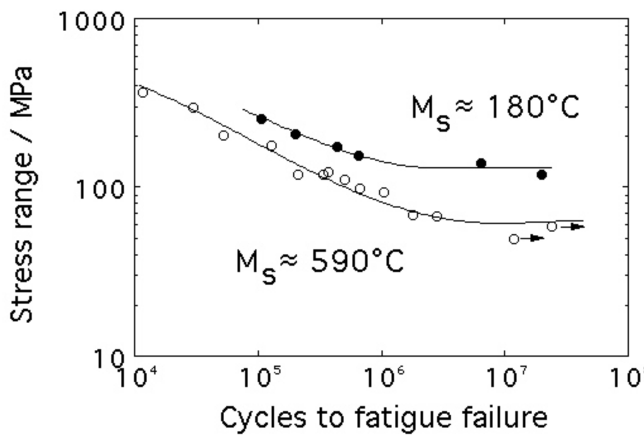

Figure 4: Improvement in the fatigue performance of welded structure using a low transformation temperature welding alloy. After Ohta *et al.*

When tests were done on welded sections, the structures joined using the low–M_S weld metal gave a much higher fatigue strength (Fig. 4). This improvement is attributed to the compressive residual stress which reduces the effective stress–range that the structure experiences during fatigue testing. The results are spectacular for engineering; benefits of the order illustrated in Fig. 4 will lead to radical changes in design and lifing philosophies for structural components. The achievement

Table 1: The chemical compositions (wt.%), and measured M_S temperature of conventional and novel welding alloys. B_S is the bainite–start temperature. The first two alloys originate in studies by [4, 7] whereas the remainder are our work [8]; *Weldox 960* is the base plate used to make the joints.

Alloy	C / wt.%	Si	Mn	Ni	Mo	Cr	Cu	M_S / °C	B_S / °C
Conventional	0.10	0.39	0.90	–	–	–	–	590	
10Cr10Ni	0.025	0.32	0.70	10.0	0.13	10.0	–	180	
Weldox 960	0.20	0.50	1.6	2.0	0.7	0.7	0.3		
OK 75.78	0.05	0.19	2.0	3.1	0.6	0.4	–		421
LTTE	0.07	0.2	1.3	8.5	–	9.1	–	200	
Series B	0.03	0.65	0.5	12.0	0.5	1.0	–	275	

is based entirely on the fact that the reduction of the transformation temperature allows the shape deformation to compensate for the accumulated thermal contraction strains. The work done in Japan has recently been confirmed by Eckerlid *et al.* [9] and Lixing *et al.* [10].

Welding alloys used in civil constructions have to meet a range of requirements other than fatigue. We have therefore created new alloys based on the simultaneous optimisation of transformation temperature and toughness, as described elsewhere [8]. One of our welding alloys is listed as *Series B* in Table 1. LTTE is similar to the alloy studied by Lixing *et al.* [10], and OK 75.78 is a control sample which transforms at a high temperature.

To assess the ability of the filler metals to compensate for the development of stress, unconstrained tensile samples were austenitised at 850°C, fixed rigidly and then allowed to cool at 10°C s^{-1}. These are the so–called Satoh tests, the results of which are presented in Fig. 5. It is clear that both the Series B and LTTE alloys have the ability to completely compensate for thermal contraction strains by virtue of their low transformation temperatures. On the other hand, the control sample (OK 75.78) exhausts its ability to transform at a temperature which is well above ambient, resulting in the characterisitic accumulation of tensile stress during cooling below about 360°C.

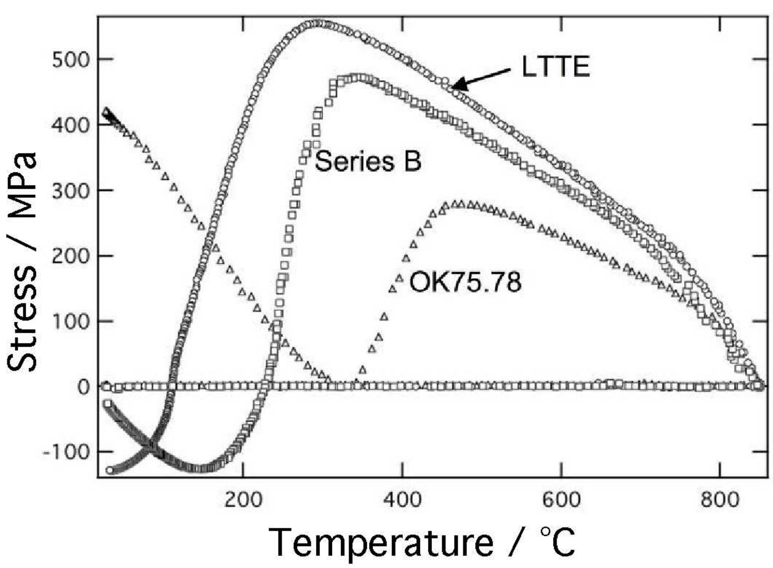

Figure 5: Satoh tests on each of our filler metals, conducted using a thermomechanical simulator attached to a synchrotron X-ray source [8].

To further assess the efficacy of the alloys, actual welds were prepared in a manner designed to enhance constraint effects. Three rectilinear plates (375×200×12 mm) were prepared using Weldox 960. Along the center of each plate, a 5 mm deep Vee-groove was machined with an included angle of

60°, into which a single weld bead was deposited using manual-metal arc welding. The welding was undertaken in the down-hand position with a heat input between 1.1 and 1.4 kJ mm^{-1}. A preheat temperature of 125°C was used and the plates were restrained by clamping during welding.

The state of residual stress was then characterised using neutron diffraction at the National Research Council of Canada facility at the NRU reactor, Chalk River. The results are illustrated in Fig. 6.

With OK 75.78, both the weld nugget and the underlying reaustenitized heat–affected zone (HAZ) transform at high temperatures. Consequently, the stress contours in the HAZ are almost vertical, as if a full-penetration weld has been deposited. The level of stress both in the weld nugget and underlying region is low but the tensile stress increases with distance along the horizontal axis, peaking at about 800 MPa located at about half the depth and in the HAZ. The domain in which the stress is greater than 600 MPa is large, with a width of just under 5 mm parallel to the horizontal axis.

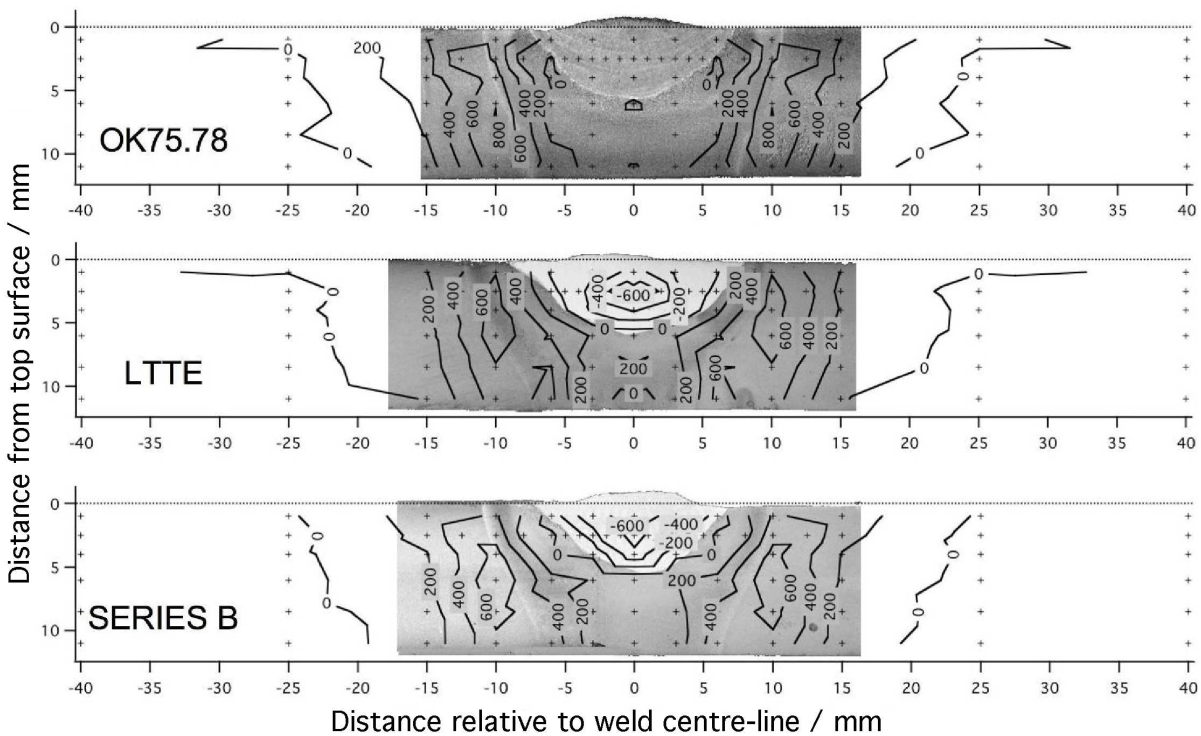

Figure 6: Longitudinal residual stresses estimated using neutron diffraction measurements at locations marked by plus signs. The data have been superimposed on the weld macrographs [8].

The scenario is quite different for the LTTE and Series B samples, both of whose transformation temperatures are suppressed relative to the plate material. There are major compressive stresses within the weld nuggets. To a depth of 5 mm, the stress contours within the HAZ closely follow the shape of the nugget, *i.e.,* steeply inclined stress contours. This is in stark contrast to those in OK 75.78. The phase change within the nugget has resulted in a large reduction of the tensile stresses within the adjacent HAZ up to the depth of 5 mm. The peak tensile stresses are much smaller than in OK 75.78 and the regions within which they occur are also smaller.

In the regions under the nuggets of LTTE and Series B, the phase change occurs at a higher temperature than for the nugget itself. It is therefore possible for tensile stresses to arise in these regions. This would not of course be the case in a full penetration weld.

Detailed interpretation has been published elsewhere [8], but it is evident from these results that there is a clear benefit in using welding consumables which transform at temperatures which are sufficiently low for the compensating effect of transformation–induced plasticity to sustained to ambient temperatures.

5 Conclusions

There are clear benefits in the use of weld filler metals which compensate contraction strains and beneficially modify the system of residual stresses that develop in welded joints.

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