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Phase Transformations in Constrained Weld and Parent Metals During Cooling

1 Background

Engineering failures are often attributed to fatigue, exacerbated by residual stresses introduced during welding. The conventional way of coping with this is to reduce the design stress. In some cases the component can be heat–treated to relieve the built–in stress prior to service. This project had the aim of using the plasticity due to phase–transformations to eliminate the development of residual stresses in welded structures.

In a classic set of experiments, Alberry and Jones showed that the stress which accumulates during the cooling of a rigidly constrained tensile test specimen of austenite can be mitigated when the austenite decomposes into bainite or martensite [1]. As illustrated in Fig. 1, the stress due to thermal contraction begins to accumulate once again when the transformation is exhausted, so it is important to stabilise the austenite so that it continues to transform until ambient temperature is reached.

Simple experiments subsequently demonstrated that the distortion associated with welding could be reduced by selecting welding alloys with low transformation temperatures [2]. In Japan, weld metals were designed following similar principles, to counter the problem of residual stresses [3–7]. Although this led to a remarkable improvement in fatigue properties [4], the methodology did not lead to tough weld metals and was not based on understanding. We intended in this project to develop and verify the theory needed to create such alloys as a means for mitigating residual stress in welded components.

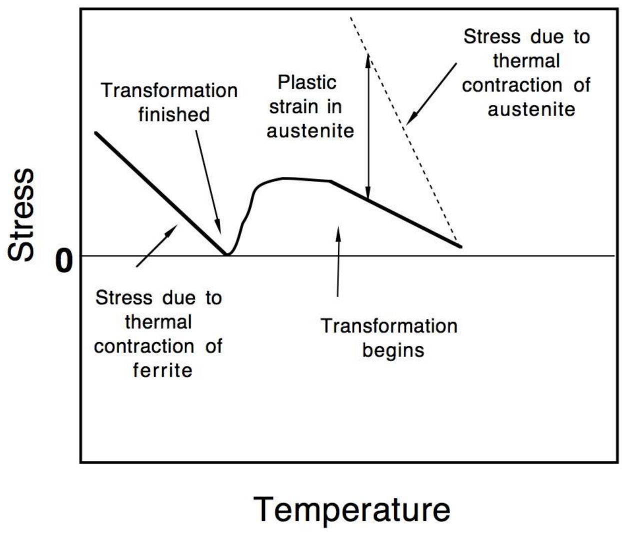

Figure 1: Interpretation of the Alberry and Jones experiments [2]. The curve shows the state of stress as a rigidly constrained tensile specimen is allowed to cool from its austenitic state. To reach a zero stress at ambient temperature it is necessary for the transformation to finish at that temperature.

2 Key Advances and Supporting Methdology

We have experience in modelling the microstructure and mechanical properties of weld metals, spanning some 20 years of research, and based on the most advanced phase transformation theory combined with structure–property relationships. The details are not described here but methodology and recent developments been reviewed [8–10]. One outcome from previous work is that the long–standing perception that nickel additions enhance toughness is not correct [11]. There are circumstances where this leads to the formation of a coarse phase known as *coalesced bainite* which is detrimental [12–14].

Using all this theory and models, we designed in the first year of the project, low–carbon welding alloys in which the austenite transforms to martensite at a sufficiently low temperature to mitigate residual stresses, and yet has the required strength and toughness [15]. The expected level of chemical segregation and the solidification state were two further design variables which were optimised. These alloys were manufactured by our project partners, ESAB AB of Sweden.

In parallel with this alloy design, we began at an early stage to develop theory for predicting the response of the metal to transformation under stress. This is because all of the previous work on welds [3–5, 7] does not in fact go into the mechanism of stress cancellation, but assumes incorrectly that the volume change of transformation is the key factor. The shear strain is in fact much larger than the volume change. However, in a random microstructure the shear components cancel on average, but transformation under stress leads to variant selection in which case the shear strain becomes dominant [2]. Variant selection in turn leads to crystallographic texture because the microstructure becomes biased. There has of course been a huge amount of work published in the field of texture prediction, but we identified critical difficulties in existing knowledge which prevented its application to the essential problem. The difficulties can be summarised as follows and arise primarily because of arbitrary assumptions made in the crystallography of the problem.

It is often assumed in texture analysis that the orientation relationship between the austenite and martensite is that due to Kurdjumov–Sachs or Nishiyama–Wasserman [16–19], but it has been known for some time that the true relation must be irrational [20–23]. Although the difference between this irrational and assumed orientation may seem less than a few degrees, it is seminal because the assumed orientations do not in general lead to an invariant–line between the parent and product lattices. The existence of an invariant line is an essential requirement for martensitic transformation to occur. It is not surprising therefore, that Nolze [24] in his experimental study of several hundred thousand γ/α orientation relations, found detailed deviations from assumed Kurdjumov–Sachs *etc.* orientations.

When considering martensitic transformation, the crystallographic set includes the habit plane and shape deformation apart from the orientation relation. This set is mathematically linked and should be considered as a whole in texture analysis [20–22]. It is not appropriate to independently assume orientations, habits *etc.* as is widely apparent in the published literature on crystallographic texture.

To prove this, in our first paper on the subject [25] we used published experimental data [26] and a self–consistent mathematical set to describe all the features of the transformation, to successfully predict detailed transformation texture in strained polycrystalline austenite [25]. The theory is the first to conduct the calculations in a self–consistent manner. Others have attempted a similar calculation [27] but their calculations are wrong because they neglect components of the total deformation.

Given that we used a complete crystallographic set (habit plane, orientation relationship, shape deformation) for the successful calculations, it also becomes possible to predict the transformation strains in all directions, as a natural outcome of the theory. Indeed, instead of using diffraction, the anisotropic strains themselves could be used to characterised the development of transformation texture using our theory.

The work published in [25] based on data from [26] simply involves a validation of overall crystallographic texture. A much more convincing proof, including the measurement of transformation strains was published later [28]. In this, stress–affected transformation theory was developed further to deal with generalised states of stress (tensors), microtexture and transformation strains. All of these detailed predictions were verified using our own microtexture data.

All previous transformation texture theories have failed to predict diffracted intensities, addressing only variant selection. We have for the first time [28] showed a way forward to the problem of intensities, by demonstrating that the extent of variant selection depends on the ratio of the mechanical driving force to chemical driving force for transformation. Applied stress becomes unimportant in variant selection when the ratio is small, because the chemical driving force (which depends on the relative stabilities of the parent and product phases) does not favour particular variants.

The experimental work referred to above dealt with uniaxial stresses. To investigate whether the alloys we designed should lead to residual stress cancellation in welds, special half–penetration welds were fabricated at ESAB AB to simulate complex constraint. The states of residual stress were then characterised at the Chalk River neutron diffraction facility in Canada supplemented with data using the ESRF synchroton in Grenoble [29]. This showed vividly the profound influence of transformation plasticity as illustrated in Fig. 2. It was found that a lower transformation temperature leads to a potentially less harmful stress distribution in and near the fusion zone. Fig. 3 shows the enormous difference in the stresses for the two alloys, the Series B sample showing compressive stress within the weld and reduced stresses in the heat–affected zone. In contrast, OK 75.78 has slight tension in the weld metal and much larger stresses in the heat–affected zone. The detailed interpretation is presented elsewhere [29].

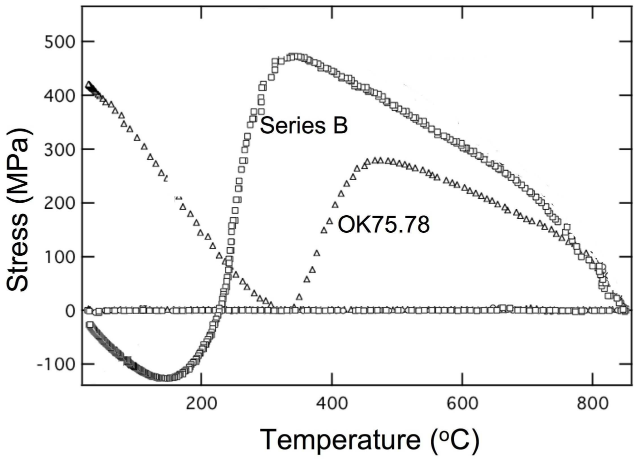

Figure 2: Evolution of measured longitudinal stress in constrained tensile test samples of weld metal "Series B" and a commercially available alloy which is not designed for the purpose of reducing residual stress (OK 75.78). Notice that the stress at ambient temperature is virtually zero for Series B weld metal. More detail in [29].

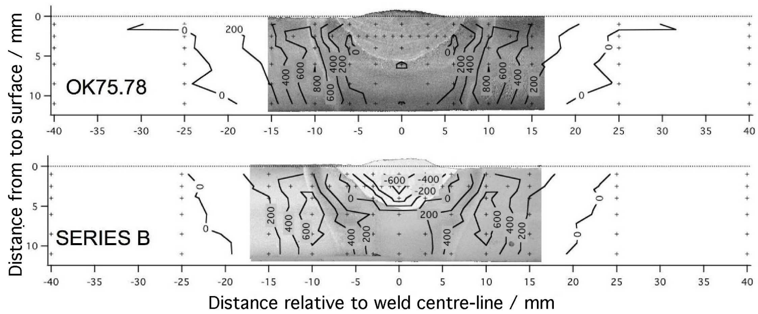

Figure 3: Longitudinal residual stresses estimated using neutron diffraction measurements at locations marked by plus signs. The data have been superimposed on the weld macrographs [29]. Compressive stress is evident in t

Finally, a recent paper [30] claimed that the calculation of texture when austenite (γ) transforms to body–centred cubic martensite (α') should be conducted in two stages, $\gamma \rightarrow \epsilon$ and $\epsilon \rightarrow \alpha'$ where ϵ is hexagonal close–packed. We have demonstrated that this is not necessary, and that the texture can be calculated directly ($\gamma \rightarrow \alpha'$) without the need for intervening transformations, with better accuracy and fewer fitting parameters [31].

3 Project Plan Review

No significant project–plan changes.

4 Research Impact and Benefits to Society

We have developed a rigourous method for the calculation of transformation texture and have demonstrated how this can be used to design weld metals which when used, can help reduced detrimental residual stresses in welded components. The theory developed is generic and applies to any material or system undergoing stress–induced transformation texture.

One Ph.D. student has qualified through the work sponsored at Cambridge University. He now is a senior scientist with TATA–CORUS steel company. Other benefits are listed under further research which has resulted directly for the work funded by the EPSRC.

The work has resulted in 8 publications [8–10, 15, 25, 28, 29, 31] and 6 fully documented computer programs and source code, all of which are in the public domain.

5 Explanation of Expenditure

The candidate for the Ph.D. project, S. Kundu, came from India so the substantial overseas fees component necessary, was fully paid for by TATA Steel as a supplement to the EPSRC project. Kundu turned out to be an outstanding candidate and is now developing the work to apply it within TATA–CORUS.

Many presentations were made at conferences (THREMEC, Canada; Mathematical Modelling of Weld Phenomena, Austria; Martensite and Bainite, Japan) , but because the research assistant had health problems, he preferred not to travel. All of the presentations were by Professor Bhadeshia who through invitations did not need to use the entire travel budget. As a consequence we used the small excess available from the travel budget for consumables.

ESAB AB made major contributions in kind through the manufacture of specially designed welding consumables (electrodes) and indeed the joints used in the neutron diffraction experiments. Dr L. Karlsson advised us throughout of the practicalities of alloys we were designing, leading to a shakedown towards alloys that can readily be manufactured.

6 Further Research or Dissemination Activities

As a direct consequence of the work sponsored by the EPSRC, the MOD has sponsored Professor Bhadeshia with a four year project worth approximately 600,000 GBP to design residual stress–mitigating weld metals for austenitic stainless steels. Another short project worth about 30,000 GBP will probably begin in October 2007, also sponsored by the MOD, which will involve the application of the Series B welding electrode.

An independent Masters project supervised by Professor Bhadeshia, based on the concepts developed here, has been completed at POSTECH on the crystallographic texture in twinning–induced plasticity steels. A Ph.D. project has commenced under the supervision of Professor Bhadeshia, at POSTECH on applying the concepts to diffusional transformations where the textures are diffuse.

All of the work described in this report, including papers, archives, computer programs (source code, documentation) have been made freely available from

www.msm.cam.ac.uk/phase-trans

www.msm.cam.ac.uk/map/mapmain.html

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