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INTERNATIONAL JOURNAL OF
Pressure Vessels and Piping

International Journal of Pressure Vessels and Piping 80 (2003) 705–713

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Residual stress relief in MAG welded joints of dissimilar steels

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Received 29 April 2002; revised 15 August 2003; accepted 15 August 2003

Abstract

This paper addresses the relief of residual stress in welded joints between austenitic and non-alloyed ferritic–pearlitic steels. A series of similar and dissimilar steel joints based on the 18G2A (ferritic–pearlitic) and 1H18N10T (austenitic) steels were produced, some of which were stress relieved by annealing and some by mechanical prestressing. For the as-welded and stress relieved test joints the residual stresses were measured by trepanning. To aid the interpretation of these results, 2D plane stress finite element analysis has been performed to simulate the residual stress relieving methods. Analysis of the results has shown that thermal stress relieving of welded joints between dissimilar steels is not effective and may even increase residual stresses, due to the considerable difference in thermal expansion of the joined steels. It was found that, for the loads imposed, the effectiveness of the mechanical stress relieving of dissimilar steel welded joints was much lower than that of similar steel joints.

Keywords: Dissimilar steel welds; Residual stress; Stress relieving; Stress measurement; Finite element modeling

1. Introduction

In many industrial applications, for example for chemical and petrochemical installations, power generation, and in the pulp and paper industry, it is necessary to weld ferritic steels to austenitic ones. Firstly the joints must meet the strength requirements, while the anticorrosive properties are also of importance. In some cases weld residual stresses can have a deleterious effect on the mechanical properties of the joints (e.g. brittle fracture resistance and fatigue performance) and a reduction of these stresses is considered necessary. Decisions are usually taken on the basis of intuition, due to the lack of information regarding the effectiveness of stress relief procedures for these kinds of joints.

Residual stresses in welded joints are most commonly reduced by heat treatment, or by mechanical stress relieving (e.g. pre-stretching). However, because of the difference in the thermal expansion coefficients between ferritic and austenitic steels, residual stresses in welded joints of dissimilar steels cannot be reduced by heat treatment to the same extent as in joints made of single steel. Another problem with heat treatment is the potential for the reactive diffusion of carbon to areas with a higher concentration of carbide forming elements (such as chromium), leading to martensite formation and an increase in hardness close to the fusion boundary [7]. The application of thermal stress relief procedures to welded joints of dissimilar steels is therefore of questionable merit.

The process of mechanical stress relief involves pre-stretching the joint in order to eliminate the residual stress causing misfits by plastic straining [2,3,4]. Since mechanical pre-stretching is not a thermal process it would appear to be more attractive for application to welded joints of dissimilar steels than a conventional stress relief heat treatment. This avoids the diffusion of carbon and the difference in thermal expansion properties of the two steels is unimportant. Two questions arise: firstly, what external load should be applied and whether it should correspond to the yield stress of the ferritic or austenitic steel; secondly, does the difference in mechanical properties introduce new residual stress upon unloading? To our knowledge little work has been carried out previously on the mechanical stress relief of dissimilar steel welded joints.

The work described in this paper has been carried out to clarify these issues.

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doi:10.1016/j.ijpvp.2003.08.004

Table 1
Chemical composition of steels used (wt%)

Steel	C	Mn	Si	P	S	Ni	Cr	Cu	Ti	Al
18G2A	0.18	1.42	0.38	0.012	0.021	–	–	–	–	0.028
1H18N10T	0.08	1.8	0.56	0.032	0.023	10.4	17.8	0.1	0.62	–

2. Materials and experimental methods

2.1. Materials and welding procedure

To determine the effectiveness of thermal and mechanical stress relief of welded joints made of ferritic and austenitic steels, similar and dissimilar steels were butt-welded, stress relieved and the residual stresses were measured [5]. A fine-grained low alloy 18G2A steel (P355N according to EN 10028-2) and an austenitic 1H18N10T steel (X6CrNiTi18-10 according to EN 10088-2) were used in the form of plates 12 mm in thickness. The chemical compositions of the steels are given in Table 1. Test joints having the dimensions shown in Fig. 1 were metal active gas (MAG) welded, semi-automatic welding with an active shielding gas). When welding the 18G2A steel joints the SG2 wire (G3S1 according to EN 440) and M21 (according to EN 439) shielding gas were used. The austenitic 1H18N10T steel and dissimilar 18G2A/1818N10T steel joints were welded with the 18Cr–8Ni–6Mn-type wire using Ar + 3%O_2 shielding gas. The temperature did not exceed 150 °C while laying the five bead welds. The joints were inspected by visual examination and radiography. Their quality satisfied the requirements for class B according to PN-EN 25817.

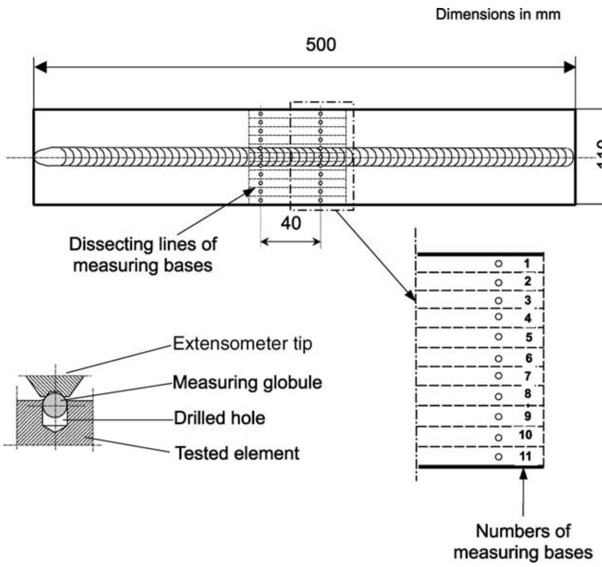

Fig. 1. Welded test plate geometry showing the location of the measuring bases.

2.2. Stress relief procedures

One test plate of each weld type was left without any treatment; the remainder were stress relieved, either by furnace annealing, or by mechanical prestressing in an automated materials testing machine. The conditions of stress relief are given in Table 2. Mechanical stress relief of the test plates composed of one steel has been performed at a stress equal to the corresponding yield strength. Test plates made of dissimilar steels were loaded to a stress corresponding to the yield strength of one of the materials, i.e. either that corresponding to 18G2A or 1H18N9T (Table 3).

2.3. Residual stress determination

Welding residual stresses were determined by trepanning [1]. To measure the distribution of longitudinal stress, measuring bases in the form of holes have been drilled in the test plates (Fig. 1, inset). The scheme of dissection is shown in Fig. 1.

3. Results for the as-welded and stress relieved joints

3.1. Weld metallography

On selected test joints metallographic examination has been undertaken. The macrostructure of the dissimilar steel

Table 2
Treatment of welded test joints

Welded test joint	As welded	Stress relieved by annealing[a]	Mechanical stress relieved
18G2A	×	650 °C	345 MPa
1H18N10T	×	850, 900 °C	234, 345 MPa
18G2A/1H18N10T	×	650, 850 °C	234, 345 MPa

[a] Soaking time 1 h, furnace cooled.

Table 3
Mechanical properties of steels used

Steel	Yield strength R_e($R_{0.2}$, MPa)	Tensile strength R_m (MPa)	Elongation A_5 (%)
18G2A	345	532	26
1H18N10T	234	656	47

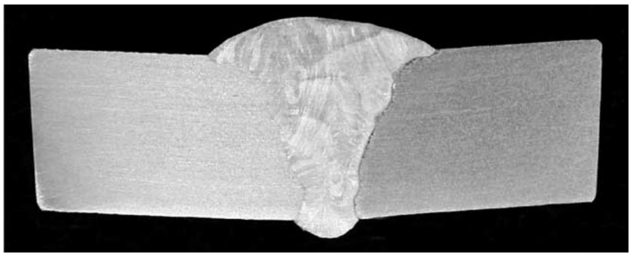

Fig. 2. Macrostructure of the dissimilar steel welded joint (18G2A—right, 1H18N10T—left) after stress relieving by annealing at 850 °C. Adler etched, 2:1.

weld (18G2A + 1H18N10T) after heat treatment at 850 °C is shown in Fig. 2. Microstructures of the area close to the fusion boundary of the ferritic 18G2A steel and austenitic weld metal are shown in Figs. 3 and 4, respectively, for the test joint stress relieved by annealing and by mechanically prestressing.

Metallographic examination of the test joints revealed a macrostructure free from unacceptable imperfections (Fig. 2). At the fusion boundary of the 18G2A steel a narrow darker line can be observed (Fig. 3). This corresponds to a carburized band (30 μm in width) in the austenitic weld metal adhering to the fusion boundary. Its origin is the reactive diffusion of carbon from the ferritic–pearlitic 18G2A steel into the chromium rich austenitic weld during the annealing process. Due to the carbon depletion a coarse grained ferritic zone is formed in the 18G2A steel, which is characterized by lower yield strength and notch toughness [7].

The microstructure of the 18G2A/1H18N10T steel joints after mechanical stress relief did not differ from the corresponding joints in the as-welded state.

3.2. Thermal and mechanical properties

The nominal mechanical properties of the two steels are given in Table 3. However, in view of the microstructural

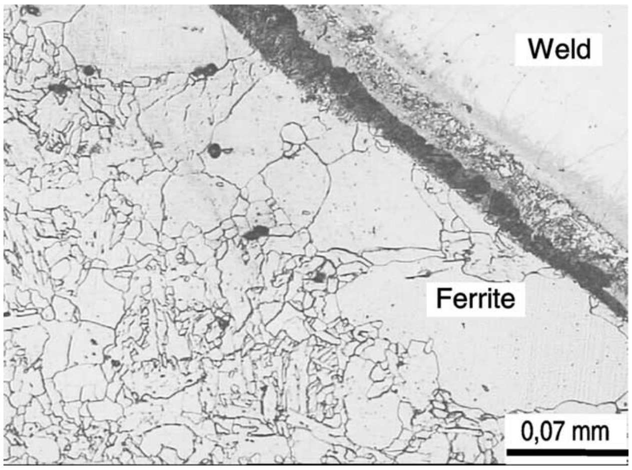

Fig. 3. Microstructure of fusion boundary area of dissimilar steel (18G2A + 1H18N10T) test joint after stress relieving by annealing at 850 °C. Dark band of carburised region in the weld metal and coarse grained ferrite (decarburised zone) on the 18G2A steel side. Nital etched.

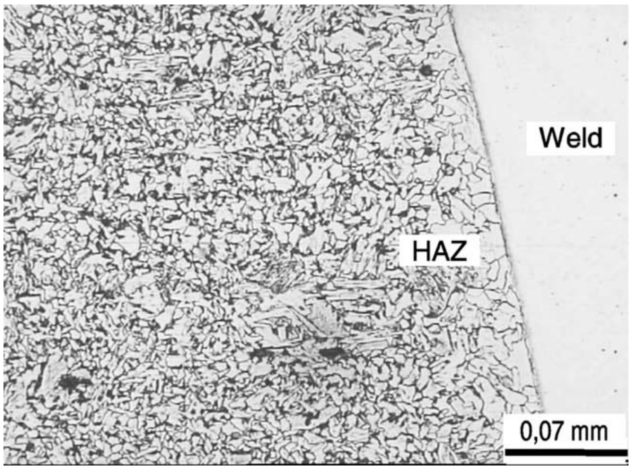

Fig. 4. Microstructure of fusion boundary area of dissimilar steel (18G2A + 1H18N10T) test joint after mechanical stress relieving. Fine ferritic–pearlitic microstructure in the 18G2A steel HAZ with only slight ferrite grain coarsening close to the fusion boundary. Nital etched.

changes that occur from parent plate to heat affected zone to fusion zone it is important to have information about the variation in properties across the welds. In Fig. 5 the variations in proof strength and hardness across a dissimilar joint are presented. The higher weld strength is presumably due to a combination of the filler wire with Mn addition and the microstructure characteristic of the solidified metal.

In order to model and interpret the stress relief processes occurring at elevated temperatures it is necessary to know the variation in the thermal expansion coefficient, Young's modulus and yield stress with temperature. These are shown in Figs. 6–8, respectively. Unfortunately, the thermal and mechanical properties representative of the materials in the heat affected zone at elevated temperatures are not available. However, in order to model and interpret the mechanical stress relief processes, the room temperature mechanical properties corresponding to these areas have been obtained and are shown in Fig. 9.

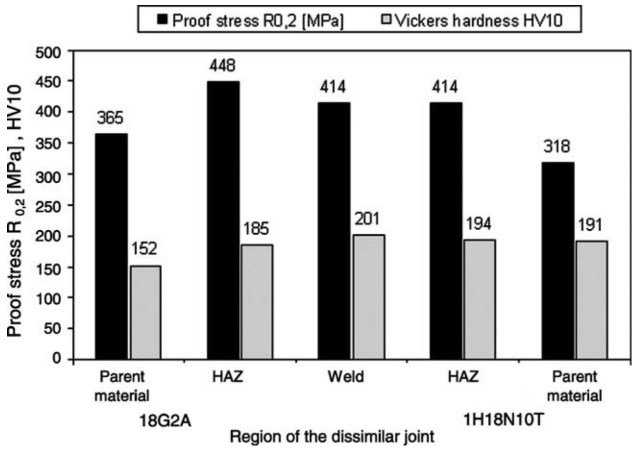

Fig. 5. Variation in proof stress and hardness measured after welding across dissimilar weld.

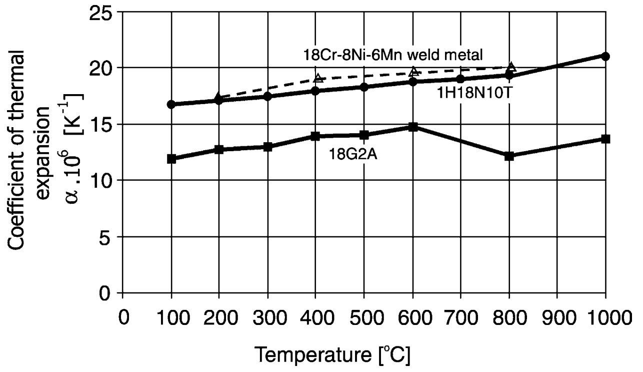

Fig. 6. Variation in coefficients of thermal expansion with temperature [6,8].

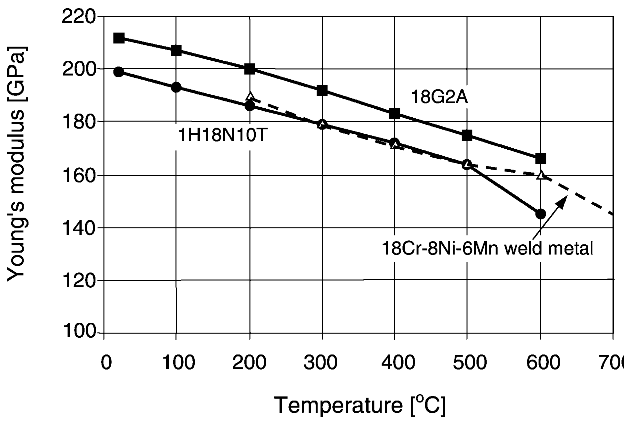

Fig. 7. Temperature dependence of Young's modulus for ferritic and austenitic steels [6].

3.3. Residual stresses in as-welded and stress relieved joints

The longitudinal residual stresses as determined at each of 11 locations by trepanning are shown in Figs. 10, 11, and 13 for the as-welded, heat treated and mechanically stress relieved joints, respectively. Unsurprisingly, the residual stress distributions in the as-welded test plates (without any stress relief treatment) show a maximum tensile stress on the weld axis (Fig. 10), reaching a value of

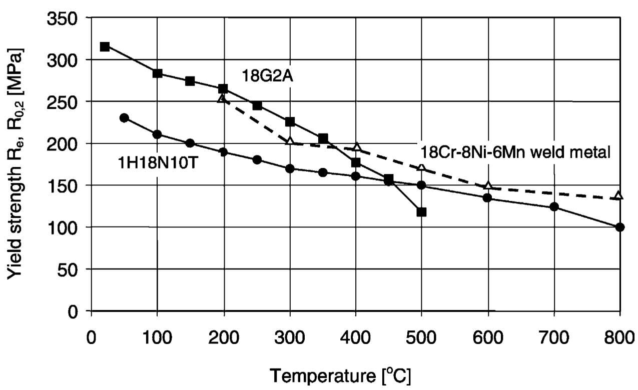

Fig. 8. Temperature dependence of yield strength for ferritic and austenitic steels [8,9].

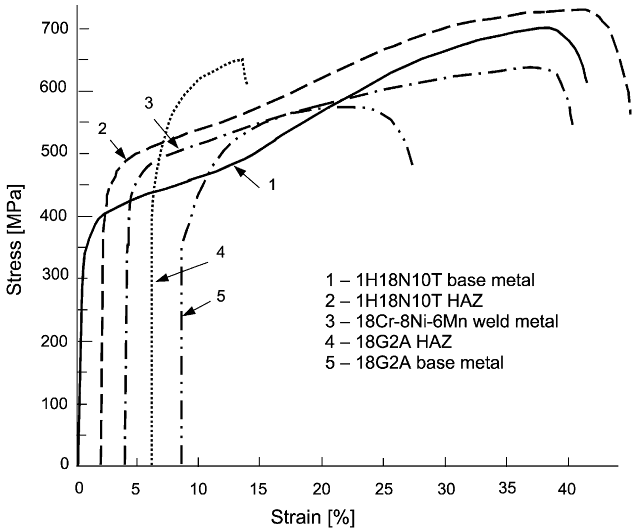

Fig. 9. Stress–strain curves for the individual regions cut from a dissimilar welded joint (tensile test specimens 2 mm × 1 mm). The curves have been displaced for clarity.

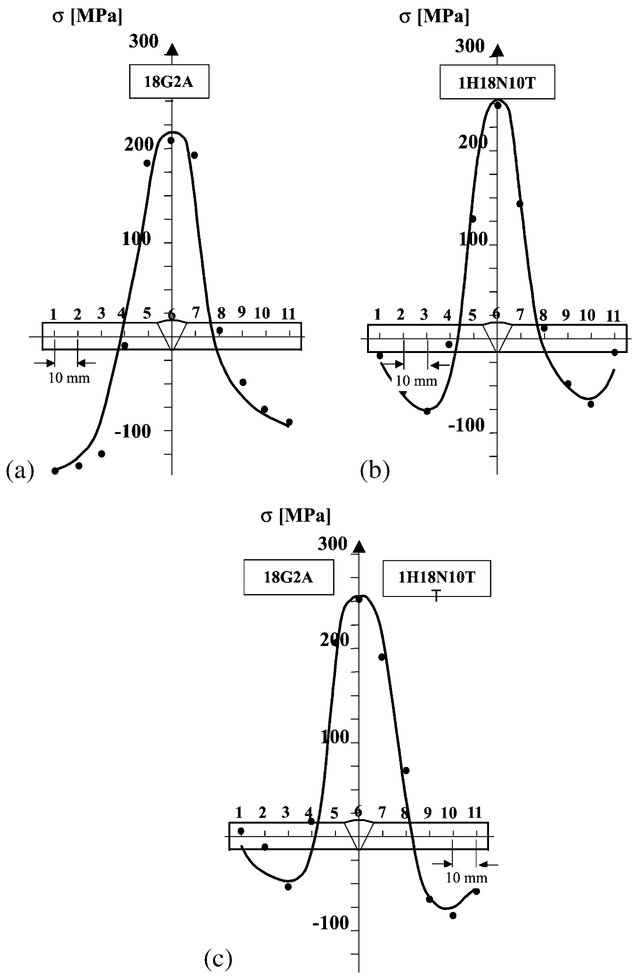

Fig. 10. Distribution of residual stresses in as welded joints as measured by trepanning.

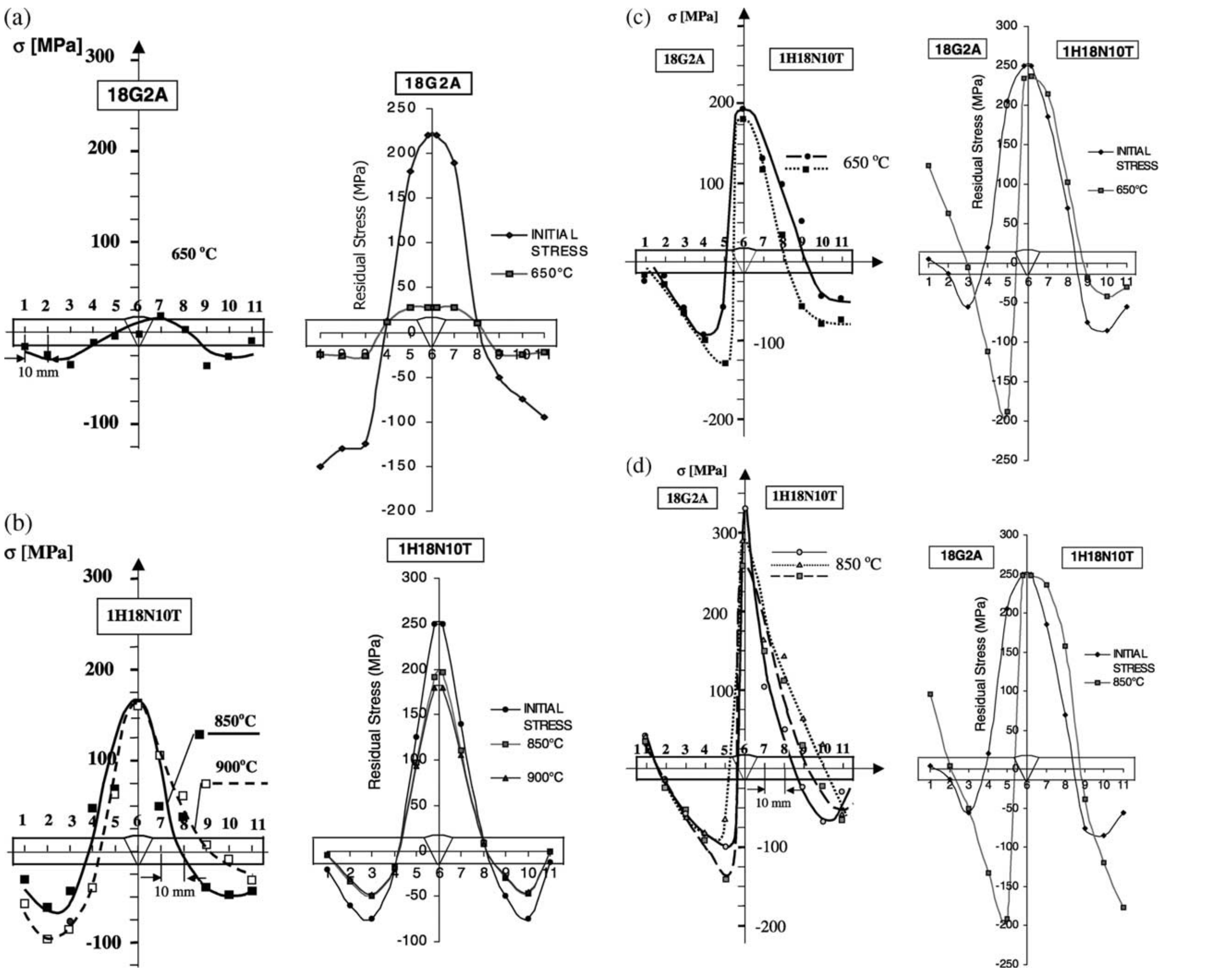

Fig. 11. Distribution of residual stresses across the measuring bases in welded joints stress relieved by annealing as measured (left hand side LHS) and predicted (right hand side RHS) for (a) 18G2A after 650 °C; (b) 1H18N10T after 850 and 900 °C; (c) 18G2A–1H18N10T after 650 °C; (d) 18G2A–1H18N10T after 850 °C.

210 MPa in the 18G2A ferritic–pearlitic steel joint (Fig. 10a) and about 250 MPa—in the 1H18N10T (austenitic) and dissimilar 18G2A/1H18N10T steel joints (Fig. 10b and c). The difference in the peak weld stresses are primarily as a result of different thermal expansion coefficients (Fig. 6) and yield strengths (Fig. 8), as well as different temperature fields during welding [3] for the ferritic–pearlitic and austenitic materials. Note that the longitudinal stress in the austenitic steel is approximately equal to the yield strength while that in the ferritic–pearlitic steel is not.

3.4. Finite element modelling

Finite element modelling has been applied to simulate residual stress relief by annealing and mechanical pre-stressing in turn. Plane stress 2D models have been set up within ABAQUS having the appropriate initial residual stress distribution taken from Fig. 10 for each of the three as-welded plates. The plane including the longitudinal and transverse directions (Fig. 1) is modeled, as it is assumed that the stress in the through thickness direction is zero. The material properties have been specified as those according to the parent and heat affected zone materials. Due to the unavailability of the data the variations in properties with temperature of the material in the heat affected areas have not been accounted for. Instead the heat affected zones have been ascribed the temperature dependent properties of the corresponding parent. Time dependent creep at high temperatures is not included in the finite element calculation. These simplifications will affect the reliability of the thermal stress relief model, but not that of the mechanical stress relief. In all the models, isotropic hardening has been employed to define the plastic behaviour of the materials.

4. Discussion of stress relief procedures

4.1. Thermal stress relief

Clearly annealing at 650 °C is very effective for the 18G2A steel joint, leading to a reduction of the order of 90% (Fig. 11a (LHS)), which agrees well with the corresponding finite element prediction in Fig. 11a (RHS). This is the result of the very low yield strength at high temperatures (Fig. 8), causing extensive material flow in the highly stressed regions. A much lower level of residual stress relief takes place in the solely austenitic welded joints (about 30%, Fig. 11b). This can be explained by the low rate of yield strength decrease with increasing temperature (Fig. 8). After annealing at a higher temperature (900 °C) there is no further stress reduction, and even some higher values were measured in the parent material. In this case the finite element model predicts a slightly larger residual stress at the weld line than is observed in practice, as seen in Fig. 11b. This could either be due to a failure to account for differences in properties between weld/HAZ and its parent, or due to the fact that time dependent creep has not been included in the model.

A much more complex distribution of residual stress can be observed in the dissimilar 18G2A/1H18N10T steel test joints (Fig. 11c and d). After stress relieving at 650 °C the maximum stress of 190 MPa is approximately 30% lower than that measured in the as-welded joint (Fig. 11c). The compressive residual stress in the 18G2A has increased in magnitude and moved much closer to the weld. The overall shape of the finite element curve in Fig. 11c (RHS), including the asymmetry and the inward movement of the compressive peak in the 18G2A, is in good agreement with the experiment, although the residual stress at the weld line at 650 °C is somewhat higher than observed in practice. By raising the annealing temperature to 850 °C no further stress reduction takes place. Indeed, the measured peak stress is actually recorded as larger than at 650 °C lying somewhere between 270 and 330 MPa according to sample. This cannot be predicted by the model without invoking a phase change or larger high temperature strength in the ferrite or weld metal. The latter might also explain why the measured peak is so much narrower than predicted.

When considering these curves it should be remembered that the shape of the final residual stress curve is caused by the superposition of the stresses remaining at the annealing temperature (due to the significant residual strength of the austenite at temperature, Fig. 8) and those regenerated during cooling (due to the difference in thermal expansion between the two materials, Fig. 6). Upon heating the welded joint to the stress relieving temperature, the tensile stress in the austenitic weld metal and adjacent plate is lowered as a result of the higher coefficient of thermal expansion (CTE) of the weld metal

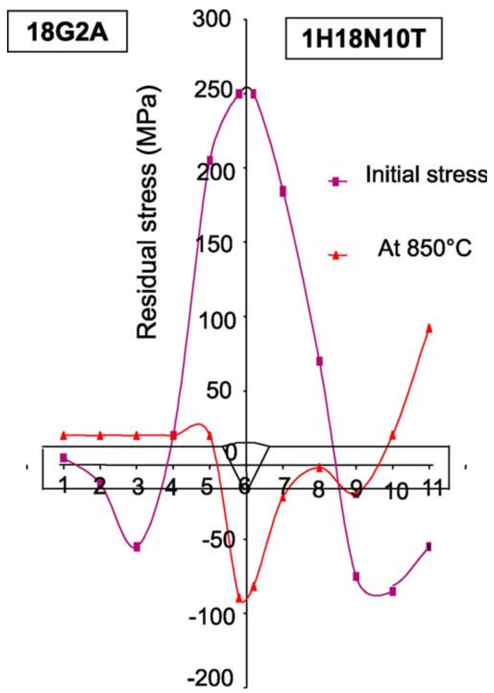

Fig. 12. The residual stress in 18G2A–1H18N10T joint at 850 °C.

and the 1H18N10T steel as well as the difference in the yield strength of the ferritic and austenitic steels. At 850 °C compressive stresses are generated in the austenite near the weld line due mainly to the bending moment exerted on the austenite by the lower CTE of the lower yield stress constraining ferrite (Fig. 12). During cooling from the stress relieving temperature the CTE effects reverse to impose a large bending moment in each phase being tensile on the ferrite side and compressive on the austenite side of each material, with the ferrite in net compression the austenite in net tension. This produces large tensile residual stresses in the austenitic weld and near weld region (Fig. 11c and d).

4.2. Mechanical stress relief

Comparison of the residual stresses in the welded joints after mechanical stress relief (Fig. 13), with those for the as-welded state, shows a wide range of behaviours. In the solely 18G2A ferritic steel joint, loaded to the physical yield point R_e of the parent plate (345 MPa), the residual stress has been reduced by 75% (Fig. 13a, LHS). The corresponding finite element model in Fig. 13a (RHS) exhibits a very similar residual stress distribution profile. The model confirms that stress relief is caused by extensive reduction of the misfit strain by macroscopic plastic flow predominantly within the weld region (Fig. 14). The original misfit can be estimated quite simply by approximating the initial residual stress in Fig. 10a to be split into three equally sized regions; the outer two in 100 MPa compression, the central region in 200 MPa tension. With a modulus around

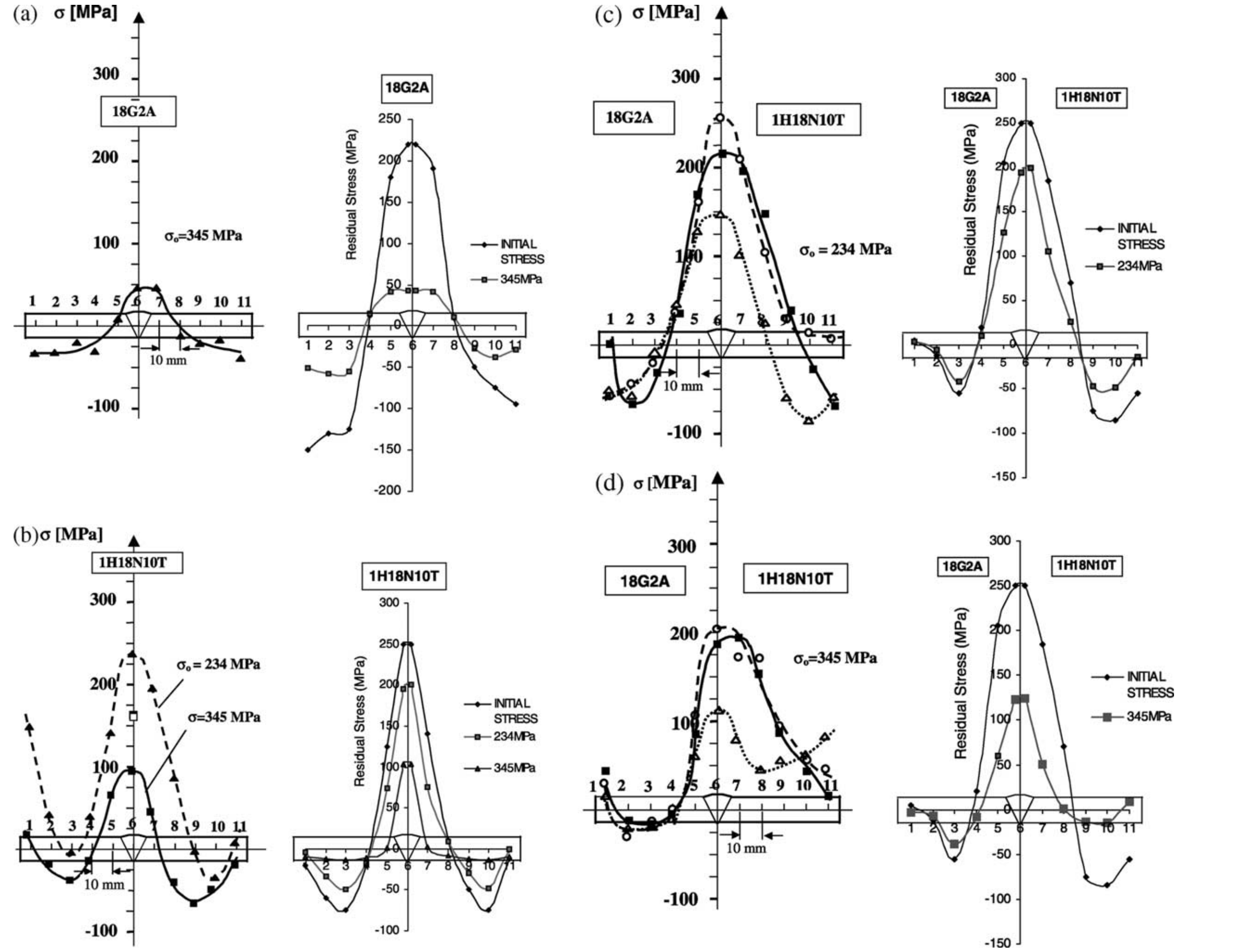

Fig. 13. Distribution of residual stresses across the measuring bases in welded joints stress relieved by mechanical prestressing as measured (LHS) and predicted by FE (RHS) for (a) 18G2A stressed to 345 MPa; (b) 1H18N10T stressed to 234 MPa; (c) 18G2A–1H18N10T stressed to 234 MPa; (d) 18G2A–1H18N10T stressed to 345 MPa.

200 GPa, the misfit between the central and outer regions required to achieve this stress would be approximately 0.15%. This is consistent with a tensile plastic strain within the central region predicted by the finite element model of 0.1% reducing the residual stress in the ferritic weld to 30% of the initial value.

For the austenitic 1H18N10T steel joint on the other hand, welded with austenitic filler metal, only a 10% reduction in residual stress is observed after applying a load equal to the 0.2% offset yield strength (234 MPa) of the parent material (Fig. 13b, LHS). The corresponding finite element model (RHS) is in good agreement with the experimental result. The model confirms that the low effectiveness of the process is the result of the higher weld metal proof stress. Indeed the weld region is predicted to undergo just 0.02% plastic strain. By raising the loading stress to 350 MPa, a 60% reduction of the maximum value of the residual stress is achieved in practice again in good agreement with that predicted by the FE model, where the whole plate is plastically deformed and

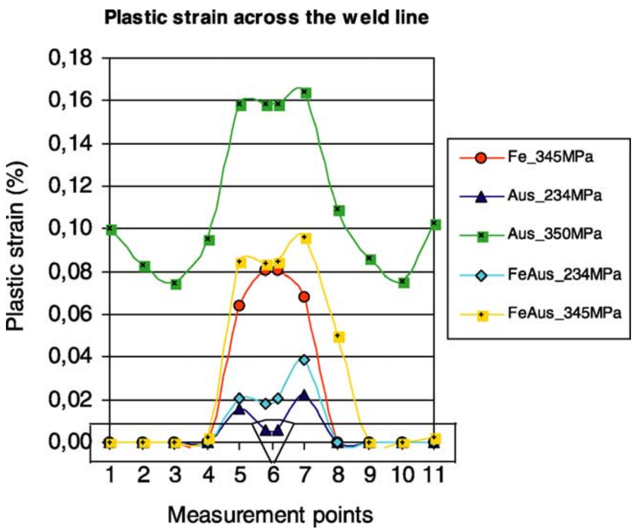

Fig. 14. Plastic strain across the weld line for each of the mechanical stress relief model.

the misfit between the weld region and the plate reduced by about 0.09% tensile plastic strain corresponding to a 60% reduction.

Three welded joints comprising dissimilar steels were stress relieved by applying loads corresponding to the yield strength of the austenitic steel (234 MPa) and three loaded to the yield strength of the ferritic–pearlitic steel (345 MPa). The experimental results (Fig. 13c, LHS, d(LHS)) show a wide scatter in the measured residual stress values. The reductions in peak tensile residual stress were as follows: 0, 12, 40 and 20, 24, 55%, respectively, for joints prestressed to 234 and 345 MPa. The corresponding FE simulations predict a residual stress distribution after a prestress of 234 MPa that agrees very well with the average of the experimental plates (20% reduction in the peak stress). The modeling indicates that at this lower load the initial compressive residual stresses mean that neither plate strains plastically far from the weld and that within the weld region the maximum plastic strain on the austenitic side of the weld is only 0.04% strain (~25% of the original misfit strain, Fig. 14), as was the case for the 1H18N10T test joint (Fig. 13b). After a prestress of 345 MPa residual stress relief is predicted to be more successful with ~50% reduction in the peak stress. This agrees very well with the experiment results in Fig. 13d (LHS). As the yield strength in the heat affected zones of both steels are larger than in the parent (Fig. 5) and the residual stress in the parent is initially in compression, the plastic strain in the weld region at the 345 MPa is not as great as one might expect from the parent properties. It is also worth comparing the final residual stresses in this weld with those for the ferritic weld after 345 MPa since the plastic misfit generated in each case is approximately the same and yet stress relief is considerably more successful in the latter. In part this is because upon unloading, the plate bends slightly with the austenitic side of each phase in tension and the austenitic region in net tension overall (Fig. 13d). This is due to the preferential straining in the 1H18N10T side of the weld represented by a shifting of the peak in Fig. 14 towards the austenite because of the lower yield strength.

5. Conclusions

The following conclusions can be drawn

- The distribution of residual stresses and their magnitude in as-welded dissimilar joints between ferritic–pearlitic and austenitic steels are similar to those measured in joints made of only one of the two materials.
- Welded joints made of these dissimilar steels should not be stress relieved by thermal annealing, due to the very low effectiveness of the process. This is because cooling generates thermal expansion misfit stresses, which can even increase the final residual stress state after cooling.
- The effectiveness of mechanical stress relieving of dissimilar steel welded joints is lower than that of similar steel joints. If mechanical stress relief is to be applied, the joints should be prestressed to a load equal to the yield point of the higher strength steel. If possible it would be better to plastically stretch the joint to a prescribed plastic strain rather than stress. The modeling suggests that in this case a plastic strain of around 0.05% is sufficient since this would introduce plastic strain right across the plate (Fig. 14). However, such a treatment would not completely relax the stress because global yielding occurs before the total weld misfit strain (around −0.15%) has been annihilated. For dissimilar welds it is likely that some residual stress would be reintroduced upon unloading.
- Mechanical stress relieving of dissimilar welded joints can introduce a bending moment into the weld at high loads. The difference in the yield strength of materials causes the preferential straining in the lower strength plate.
- Temperature and time dependent thermal and mechanical properties of heat affected zone materials are essential for accurately simulating the thermal stress relieving process using the finite element method.

Acknowledgements

The authors thank The State Committee for Scientific Research (KBN) in Poland for financing the research project. The Polish authors also thank the Director of the Institute of Welding and their colleagues for helpful discussions and inspiration. PJW is grateful for a Royal Society-Wolfson Merit Award.

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