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Review: Low transformation temperature weld filler for tensile residual stress reduction

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ABSTRACT

An attractive, alternative approach for the reduction of harmful residual stresses in weld zones is reviewed, which utilises low temperature, solid-state, displacive phase transformations in steel. The theory, latest concepts and practice for the design of such low transformation temperature (LTT) filler alloys are considered. By engineering the phase transformation temperature of the weld metal so as to take advantage of transformation expansion, the residual stress state within the weld zone can be significantly altered, most particularly where the weld thermally contracts with any movement of base parts constrained. To date, the technique has been shown to increase fatigue strength for some common weld geometries, which may enable engineering design codes to be favourably re-drafted where such LTT filler alloys are used.

1. Introduction

Welding integrity is crucial to many important industrial processes; welded structures in building construction, mining equipment, ships, agricultural machinery, bridges and off-shore platforms are just a few examples. Besides the efficiency of the process, equipment and operational costs are low, making the process favourable compared to other methods of joining. On the completion of welding, due to thermal contraction and geometric construction, a pattern of compressive and tensile residual stresses will be present in and adjacent to the weld zone on cooling to room temperature. The presence of tensile residual stress is said to be the main reason why the fatigue strength of a welded joint does not increase by strengthening the base steel [1]. In this review, the theory, latest concepts and practice for the design of welding alloys capable of offsetting such tensile, residual stresses in weld zones, generated from thermal contraction are presented. Such 'smart' alloys are particularly beneficial in mitigating tensile residual stress for constrained welds.

2. Theoretical and experimental basis of LTT weld filler alloys

2.1. Transformation under constraint

The mechanism by which the austenite transforms on cooling can be described as being either reconstructive or displacive movement of iron atoms to another lattice configuration. With displacive transformation, there is a homogeneous deformation of the original crystal arrangement into a new structure, which does not involve the bonds being broken and subsequent rearrangement of atoms as seen in reconstructive transformation to give allotriomorphic ferrite and/or pearlite. When cooling rate is rapid (e.g. most weld scenarios) or if the weld metal is heavily alloyed, the displacive transformation becomes prevalent where the resultant microstructure can be acicular ferrite, bainite or martensite. The microstructural characteristics of such phase transformations from the austenite phase are extensively reviewed [1–5], but most importantly, such transformation is always couple with tremendous shear and volume expansion.

For relatively large and heavy parts being welded, most base material flanking the weld will be constrained, thus thermal contraction on cooling and inhomogeneity of temperature distribution will induce residual stresses in the weld 'zone' (i.e. the weld and flanking heat-affected areas). In the usual case of long, thin weld run(s) between two parts, the highest tensile residual stress magnitude will be unidirectional. In order to counter-act the thermal contraction during cooling from the austenite with volume expansion, the transformation temperature can be engineered. Such residual stress/temperature relationships is shown schematically in Fig. 1a where the transformation start temperature is observed by the sudden decrease in stress, which can be attributed to the dilatation and shear strains that occur and compensate the accumulated thermal contraction.

Experimentally, this effect during welding can be clearly shown with constrained cooling tests, such as the Satoh test. The test involves a tensile test specimen, which heated so as to be fully austenitic which is then control cooled under unidirectional

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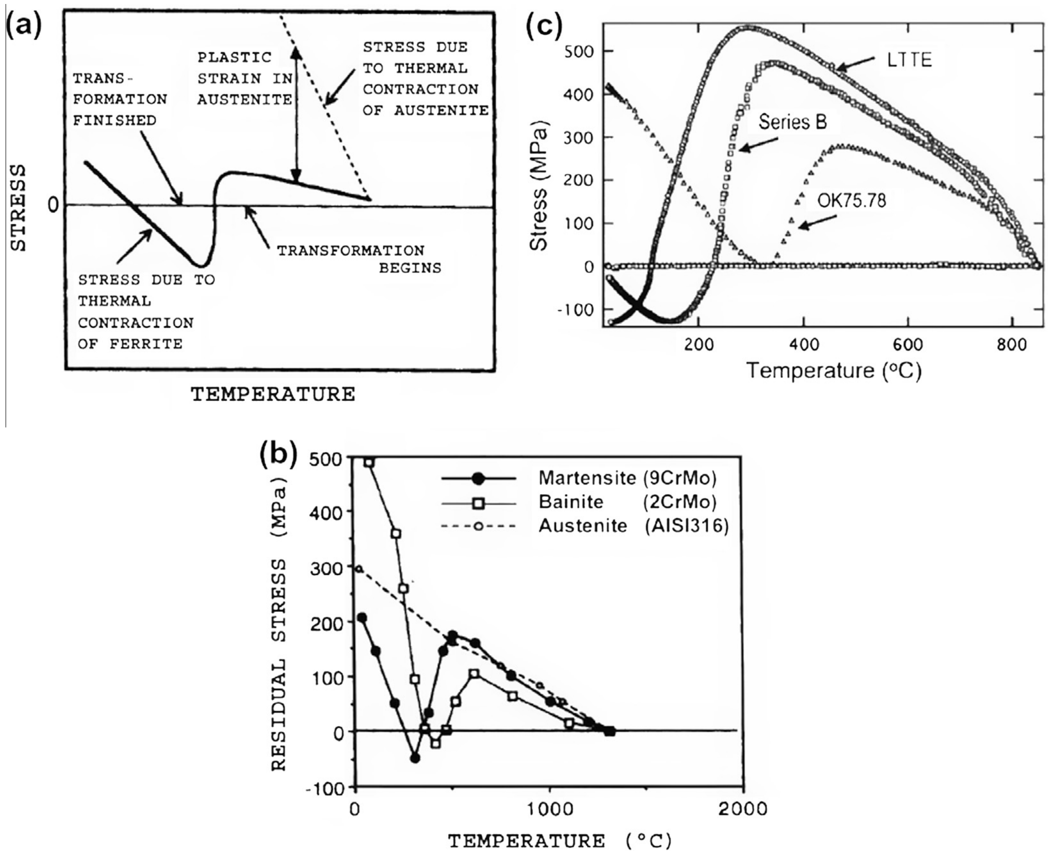

Fig. 1. Effect on residual stress with cooling; the balance of phase transformation expansion and thermal contraction. (a) Stress temperature schematic (after [6]) (note – thermal expansion coefficients for ferrite, $13 \times 10^{-6}\,K^{-1}$; for austenite $21 \times 10^{-6}\,K^{-1}$ [97]). (b) Satoh test results for final residual stress of different steel phase types on cooling (after [6]). (c) Satoh test results for conventional (OK75.78) and LTT weld filler alloys (LTTE & Series B). Samples had cooled from 850 °C at 10 °C s^{-1} (after [8]). Respective chemical composition data estimated transformation start temperatures and properties are shown in Tables 1 and 2.

restraint. Some results [6–8] are shown in Fig. 1b for different types of steel (martensitic, bainitic and austenitic, respectively). It can be seen that the fully austenitic steel has a near-linear thermal contraction slope, while those of the bainite and martensite transformation reflect the reduction in residual stress; however the beneficial offset in contraction strain is negated by the continued cooling to ambient after the transformation product has been exhausted. These observations led to the conclusion that the final stress state of a welded component is not only affected by transformation temperature, but it has the potential to be reduced by lowering the transformation temperature. Fig. 1c shows the effect on stress in such a reduction in transformation temperature with two alloys (LTTE and Series B). It can be seen that the stress is being driven into compression or near zero stress at room temperature, compared to that of a conventional filler alloy (OK75.78) which has a tensile stress at room temperature after transformation at ~450 °C.

The effect of the phase transformation temperature of various weld filler alloys, on the residual stress distribution within the weld zone, was investigated by both Wang et al. [9] and Murata et al. [10]. Murata et al.'s results (Fig. 2) showed that once the transformation temperatures get sufficiently low, not only are tensile residual stresses reduced to zero, but compressive residual stresses can be generated with cooling to at room temperature. These reach a maximum when the transformation of the filler alloy occurs around 200 °C. Below that temperature, the transformation and associate volume expansion are not complete on cooling to ambient temperature thus not fully cancelling the tensile residual stresses from restrained contractive cooling. If the phase transformation is absence (e.g. if an austenitic, weld filler alloy is used), then the tensile stress is expected to increase progressively due to uninterrupted thermal contraction.

Although significant research in this area only started two decades ago, it has been known for a longer period that tensile residual stresses in weld zones can be reduced by the use of 9% Ni filler alloy with a M_s of 350 °C [11] and compressive residual stresses can be obtained when the transformation temperatures are even lower (e.g. $M_s = 250$ °C), as observed in filler alloy for maraging steels [12,13].

2.2. Unconstrained tests

For a linear weld run, the magnitude of the residual stresses generated during cooling in longitudinal and transverse direction will differ (Fig. 2) with transformation start temperature. This figure illustrates that difference, plus the resultant angular distortion, from flat weld test sample [10]. This was shown clearly where unconstrained plates were V-notched and welded along the complete plate lengths [14]; angular distortion was reduced 45% by using an alloy with a transformation temperature range of 350–422 °C compared with one with a range of 400–802 °C. Further, distortion was minimal when using a filler alloy with a transformation start temperature of between 250 and 300 °C. Such differences were also found valid for multi-pass welding [15]. The simple experimentation clearly shows that the use of such novel, LTT weld filler alloys will not only reduce harmful tensile residual stresses in constrained weld zones, but also minimise the weld zone distortion.