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Reduction of distortion during laser beam welding by applying an in situ alloyed LTT effect and considering influencing factors

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Abstract

In rail vehicle construction, austenitic stainless steels are used to achieve lightweight design concepts, as the higher specific strength of the material allows the thickness of parts to be reduced. However, when these are welded to create complex structures, increased welding distortion occurs even with low-heat joining processes such as laser beam welding.
In order to reduce distortion, an in situ low transformation temperature (LTT) effect has been achieved using commercially available materials rather than specially manufactured LTT alloys. The LTT effect introduces compressive stresses into the weld seam, which counteract the formation of welding distortion due to tensile stresses. However, in the case of complex structures, several other factors influence the formation of distortion. The influence of the LTT effect and other factors such as tack welding, clamping and cooling conditions were analysed by distortion measurements and a maximum distortion reduction was determined.

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Keywords: Laser beam welding; low transformation temperature (LTT), welding distortion

1. Introduction

Modern railway vehicles are increasingly being manufactured from high-alloy, corrosion-resistant CrNi steels. These are used for lightweight construction due to their high specific strength and the resulting possible reduction in material thicknesses as well as their good corrosion resistance. However, the physical properties, high thermal expansion and low thermal conductivity, lead to increased distortion in welding production, even when using low-heat processes such as laser beam welding. Welding distortion is particularly problematic with long and flat components, as it makes assembly more difficult. Furthermore, the high visual demands placed on rail vehicles, coupled with the necessity for reworking and straightening, result in significant costs and time expenditure. The phenomenon of welding distortion can be attributed to the local state of stress that is generated during the welding process. If the stresses that are present at a given temperature exceed the temperature-dependent yield point, plastification and distortion will occur [1–3]. In the welding process, the inhomogeneous temperature distribution leads to the development of compressive stresses during heating and tensile stresses during cooling, as the expanding/contracting warmer areas are hindered by the colder areas [4]. In particular, the tensile stresses that arise in the seam during cooling lead to the formation of distortion. To prevent this, the tensile stresses can be superimposed by compressive stresses to counteract the formation of distortion in the build-up. This can be achieved by inducing a phase transformation from austenite to ferrite / pearlite / bainite / martensite, as this leads to volume expansion due to the different packing density between FCC and BCC [5]. The initiation of a martensitic phase transformation at a reduced martensite start temperature (Ms) has been established as a method of introducing the highest compressive stresses. The reduced Ms has two main advantages. Firstly, higher compressive stresses can be introduced at a reduced

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temperature, as the temperature-dependent yield strength is higher [6]. However, the low transformation temperature also leads to less shrinkage after transformation due to the smaller remaining temperature interval. The utilisation of a martensitic phase transformation at a low transformation temperature is also referred to as the low transformation temperature (LTT) effect. The Ms temperature can be influenced by varying the alloy content in the seam. In the case of high-alloy CrNi steels, this is done by reducing the alloy content. In previous studies, the authors developed an in situ alloying process for the purpose of controlling Ms in CrNi steel [7, 8].

The primary objective of the present study is to investigate the influence of different alloys with LTT effect on their distortion-reducing properties. Additionally, it is well documented in the literature that the general boundary conditions of the welding process, such as the number of tack welds, clamping force, or cooling conditions, may have an influence on the welding distortion [9–11]. In order to identify a possible influence on the test series, these parameters were also fundamentally analysed.

2. Materials and experimental setup

In the welding trials, an austenitic CrNi steel 1.4318 (X2CrNiN18 7/ ASTM 301LN) was welded as a double-sided fillet weld with various filler wires, Fig. 1 a) and b). The reference joints (no LTT) were welded with a G19 9 (EN ISO 14343-A: G 19 9 L Si). Various LTT alloys were produced in situ by adding unalloyed or low-alloyed filler metals G3Si1 (EN ISO 14341-A: G 3Si1), G4Si1 (EN ISO 14341-A: G 4Si1), ER80S-B8 (DIN EN ISO 21952-A G CrMo9), ER90S-B3 (DIN EN ISO 21952-B G 2C1M), Table 1.

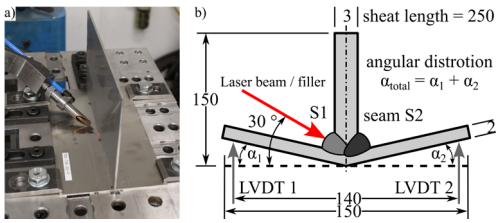


Fig. 1 a) Welding setup, b) position of the LVDT sensors

Two distinct test series were welded. In the initial series, the torque of the four clamping screws (0, 12.5, 25, 50, 100 Nm), the cooling time between seams S1 and S2 (30 s, 675 s) and the number of tack welds on either side (2, 3, 5) were varied for the standard joint. In the second series, the wire input volume (FV) was increased in 5 steps for the standard as well as for the LTT joints in order to obtain 6 different alloys each wire, Table 2.

Table 1: Chemical composition of used materials.

Material	Chemical composition [m %]					
	C	Cr	Ni	Mo	Mn	Si
1.4318	0.038	17.49	6.42	0.16	1.20	0.46
G 19 9	0.026	19.84	10.14	0.026	1.84	0.75
G3Si1	0.068	0.045	0.019	0.008	1.44	0.86
G4Si1	0.081	0.047	0.021	0.006	1.69	0.93
ER90S-B3	0.070	2.44	0.029	1,0	0.54	0.53
ER80S-B8	0.109	8.73	0.13	1.02	0.50	0.54

A Trumpf TruDisk 16002 with a 300 µm fibre and optics from Kugler with an aspect ratio of 1:3 was utilised, resulting in a focus diameter of 900 µm. All welding trials were conducted with a constant laser power of 2240 W and welding speed of 1.5 m/min. After cooling, the Cr content, the seam geometry and the resulting angular distortion ($\alpha_{total} = \alpha_1 + \alpha_2$, Fig. 1 b) were measured. The Cr content influences the LTT effect and the process-related seam geometry influences the shrinkage conditions of the seam. To analyse these influences on the angular distortion, the measurement results for reference alloys and alloys with LTT effect are compared with each other.

Table 2: Wire feed speed (v_w) used to achieve the same input volume (FV) for a given wire diameter (D). $FV = 1/4 * \pi D^2 * v_w$.

Filler	Diameter D [mm]	Wire feed speed v_w [m/min]	**Input filler volume FV [mm² x m/min]**
G 19 9	1,0	1.32/ 1.50/ 1.68/ 1.86/ 2.04/ 2.22	**1.04/ 1.18/ 1.32/ 1.46/ 1.60/ 1.74/**
G3Si1	1,0		
G4Si1	1,0		
ER90S-B3	0,9	1.63/ 1.86/ 2.07/ 2.30/ 2.52/ 2.74	
ER80S-B8	0,9		

3. Results and discussion

3.1. Factors for development of welding distortion

Based on typical welding conditions with a tack-welded and clamped specimen, the influence of boundary conditions on the welding distortion was analysed. A clamping screw torque of 50 Nm, a number of three tack welds each side of the sample and a process-related interruption of 30 s between the welding of seams S1 and S2 were used. Based on this, one parameter each was varied.

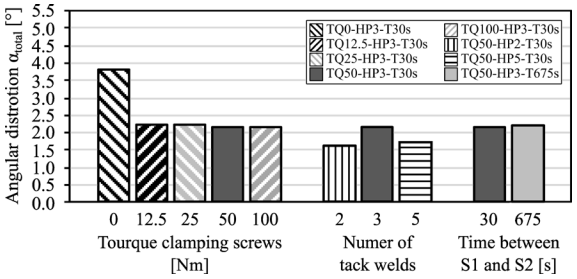


Fig. 2: Influencing factors on welding distortion. Reference alloy (G19 9) with FV = 1.32 mm² x m/min used.

Firstly, the influence of the tightening torque of the clamping screw on the welding distortion was investigated. It was found that an unclamped specimen (only movement impeded) distorts up to 3.7 °, Fig. 2. The application of clamping screws shows a significant reduction in angular distortion, whereby no dependency is recognisable with the selected torques (constant ~2.2 °). As a second factor, the number of tack welds each side was varied. The results did not show a uniform picture, with 2 and 5 tack welds leading to less distortion than 3 tack welds. The third parameter that was varied was the cooling time between S1 and S2. Based on the process-related interruption of 30 s, a longer interruption of 675 s did not lead to a change in angular distortion. The selected variation of the parameters did not result in a significant influence on the welding distortion, indicating that

the influence of the welding process is dominant. The absence of clamping, which has no industrial relevance, allows for free shrinkage, resulting in a significant influence. The selected standard parameters (50 Nm, 3 tack welds each side, 30 s between S1 to S2) were used for the next series of tests.

3.2. Cross-sections and Cr content

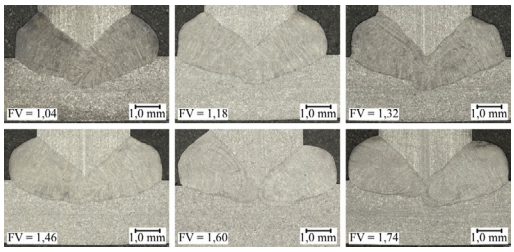


Fig. 3: Resulting cross-sections for the different wire volumes FV in mm² x m/min. Example showing the alloys 1.4318 + G3Si1.

In order to produce different alloy compositions, the input volume of filler was varied in the second series. The volume was increased from FV = 1.04 mm² x m/min up to an FV of 1.74 mm² x m/min. This increased the weld head area and reduced the welding depth of the seams. However, the selected laser power was sufficient for a full connection, Fig. 3.

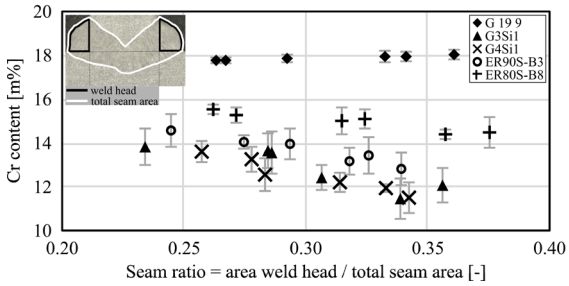


Fig. 4: Resulting Cr content in relation to the resulting ratio of the weld head area / total seam area. The error bars indicate the standard deviation of the energy-dispersive X-ray spectroscopy (EDS) measurements of the Cr content.

The ratio between the weld head area (seam S1+S2) and the total weld seam area is defined as the weld seam ratio. This ratio represents the proportions between the filler wire introduced and the total molten material, which defines the resulting Cr content. For the reference 1.4318 + G19 9, the Cr content increases with an increase in the ratio, Fig. 4. In contrast, in all other alloy systems (LTT), a wire with a lower Cr content is used, which leads to a reduction in Cr with an increase in the seam ratio. The alloys with the wire ER80S-B8 achieve the highest alloy content, as the wire also has the highest Cr content. The differences in the gradient for the decrease/increase can be attributed to the differences in Cr between the base metal and the filler. Consequently, the smallest difference (1.4318 + G19 9) results in a low slope, while the largest difference (1.4318 + G3Si1) leads to a higher slope. In conclusion, a Cr content of between 11.4 m% Cr (G3Si1) and 15.6 m% Cr (ER80S-B8) was achieved for the alloys with LTT effect.

3.3. Influence of the LTT effect on the angular distortion

In order to assess the influence of the LTT effect on the angular distortion, the samples were measured after cooling. During welding, the same filling volumes were welded for all alloy systems. However, process-related deviations can occur due to the dynamic nature of welding. This is exemplified by the seam ratios, which exhibit fluctuations. When considering alloys with G19 9 (no LTT), it can be observed that an increase in the seam ratio leads to an increase in welding distortion. This is due to the larger weld heads, as higher volume shrinkages act with maximum leverage and no transformation influences are to be expected. The increase in the seam ratio of 37 % is accompanied by an increase in angular distortion of 31 %, Fig. 5.

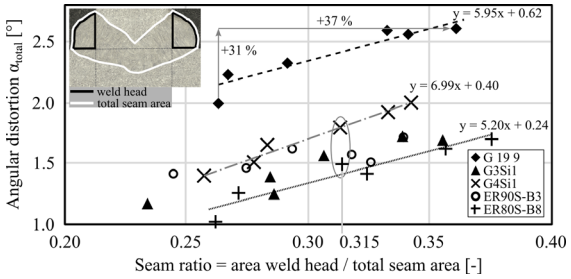


Fig. 5: Behaviour of the angular distortion in relation to the ratio of the weld head to the total seam area.

For the alloy with LTT effect, a comparable increase in the seam ratio is observed. The LTT sample with the largest distortion (G4Si1, ratio 0.34) has a similar distortion as the reference sample with the smallest ratio. Given the comparable ratios observed amongst the alloys, the reduced angular distortion can be attributed to the resulting Cr content and the associated LTT effect.

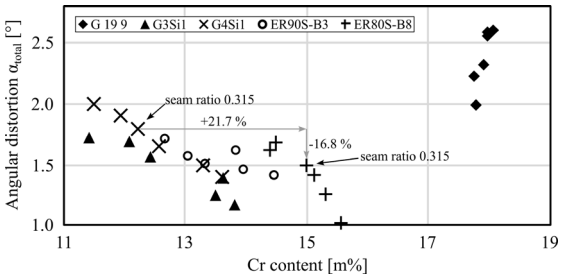


Fig. 6: Influence of the Cr content on the resulting angular distortion.

For instance, comparing two LTT alloys with the same seam ratio of 0.315 (marked in Fig. 5 and Fig. 6), the alloy G4Si1 shows a Cr content of 12.32 m% with a distortion of 1.79°, while the alloy ER80S-B8 shows only 1.49° with 15.0 m% Cr. Here, an increase of 2.68 m% Cr (+21.7 %) results in a reduction in angular distortion of -0.3 ° (-16.8 %). This can be observed in both the seam ratio (Fig. 5) and the alloy content (Fig. 6).

An analysis of the regression lines (Fig. 5) for the reference alloys with G19 9, the LTT alloy ER80S-B8 with the highest Cr content and G4Si1 with the lowest Cr content shows similar slopes. The calculated distortion values for the seam ratios between 0.25 and 0.35 (step 0.1) indicate a reduction in distortion between ER80S-B8 and G19 9 of 43.0 % ± 1.64, for

G4Si1 to G19 9 of 26.8 % ± 2.4 % and from ER80S-B8 to G4Si1 of 22.1 % ± 0.3 %. This reduction in distortion can be attributed to the increased Cr content and the associated greater volume expansion due to the LTT effect.

3.4. Formation of distortion during the welding process

The development of welding distortion was recorded for all samples during the welding process. The differences in behaviour between reference alloys and LTT alloys is shown using two representative samples (G19 9 and ER80S-B8, both FV=1.32 mm² x m/min) as examples, Fig. 7.

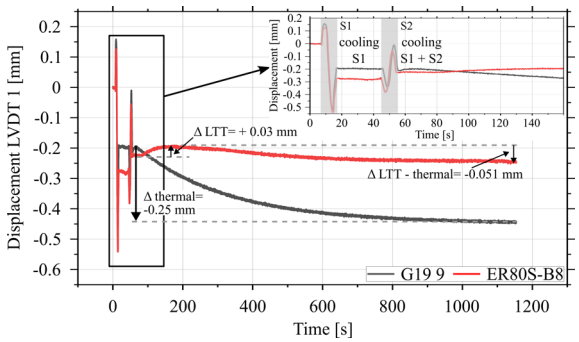


Fig. 7: Displacement LVDT sensor 1 during the welding process.

The LVDT sensor 1 is positioned in the center of the sample in the welding direction. The welding process of seam S1 initially results in the formation of a high point and then a low point in the displacement. During the cooling phase between seam S1 and S2, no further development of distortion occurs, which is presumably due to insufficiently high reaction forces. This is followed by the welding of S2, resulting in the formation of a low point first and then a high point. Up to this point, no qualitative differences between the two alloys can be discerned. However, with the initiation of the cooling phase following S2, thermal volume shrinkage occurs in the reference sample, resulting in high displacements (Δ thermal, -0.25 mm). In contrast, in the LTT sample, there is a superposition of thermal volume shrinkage and volume expansion due to the LTT effect. Initially, the displacement is reduced, indicating a dominance of the LTT effect (Δ LTT, + 0.03 mm). After this, the thermal shrinkage becomes dominant, resulting in an increase in the displacement, although influenced by the LTT effect (Δ LTT – thermal, -0.051 mm). Finally, there is less distortion due to the LTT effect.

4. Conclusion

The development of welding distortion was investigated in four alloy systems with LTT effect and a reference alloy system. It was shown that the angular distortion of the reference alloy is strongly dependent on shrinkage conditions. Thus, a high filler wire volume leads to a larger seam ratio of weld head to total seam area (+37 %) and a large increase in angular distortion (+31 %).

For the LTT effect, on the other hand, the alloys with a higher Cr content (with comparable seam ratios) show lower distortion. The ER80S-B8 alloy system with the highest Cr content therefore shows the lowest distortion. This means that ER80S-B8 achieves an average distortion reduction of 43 % compared to the reference for a seam ratio of 0.25 to 0.35, while G4Si1 only achieves 22 %. The influence of the LTT effect can also be seen in the measurement recordings of the LVDT sensor during the welding process. Here, the superimposition of shrinkage and transformation reduces the total distortion of the specimen.

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