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In-situ diagnostic in laser beam welds with digital image correlation – Reduction of residual stress and distortion in laser beam welds using low-transformation-temperature (LTT) filler materials

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Abstract

During welding the localized heat input results in high temperature gradients between the weld seam and the base material leading to thermally and transformation induced stresses. To counteract problems like residual stress and distortion, in the past few years low-transformation-temperature (LTT) materials have been successfully used as filler wire. When austenite transforms to martensite the surrounding base material prevents dilatation in the weld seam. Compressive stress builds up while reducing residual stress and distortion. Digital image correlation is used to visualize the resulting surface displacements or deformations as well as surface contractions and phase transformations during the cooling process. This visualization is key to understand and reduce the formation of residual stress and distortion in welds. The displacements after welding are always lower when using LTT filler material when compared to conventional wire, proving that LTT can be used to mitigate distortion during laser beam welding.

Keywords: low-transformation-temperature (LTT); digital image correlation; distortion, residual stress

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1. Introduction

One of the main requirements of manufacturing companies is highest precision in the production by applying simplest possible process chains with only a few process steps. This precision is a main requirement

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of manufacturing companies in order to maintain and further develop stable and sustainable production in high wage countries for competitive costs.

In the manufacturing of complex and highly precise parts, for example in mechanical engineering, vehicle engineering and electro-mechanics, this has already been achieved using highly precise machining processes.

If, however, the material is transferred into a molten phase within the process chain, as is the case in all fusion welding processes, the requirements made to the part precision can often no longer be fulfilled. In welding the change of aggregation state solid-liquid-solid is used for the material-binding joining of parts via locally restricted heat exposure at the welding point. In doing so, structural changes, heat residual stresses and transformation residual stresses develop due to the thermal expansion. If, during the cooling process, the welding residual stresses exceed the (temperature-dependent) yield point of the material, distortion is the result. A general solution approach for the reduction of residual stresses in welded parts is, besides cold forming (e.g. stretch forming, pressure testing or peening), the post-heat treatment of the parts, locally (autogeneous stress relieving) or globally, as in stress relief annealing. The latter is always connected with high additional costs since a component must be annealed up to 12 hours at a temperature of up to 600°C. Time- and cost-saving as well as energy-efficient approaches are in the focus of current research, Kromm, 2011.

In order to increase the precision of welded structures in situ, e.g. during the manufacturing process, it must therefore be ensured that at any time of the cooling process the overall residual stresses are, in their sum, lower than the yield point which is associated with the respective temperature. This is, for example, achieved by employing the volume increase during the $\gamma - \alpha -$ transformation of ferritic steels. A much stronger effect is achieved when transformation into the martensite phase occurs from the austenitic gamma phase (γ). If this transformation takes place at a very low temperature (such as 200 °C), i.e. when the residual stresses have already formed for a large part, this is called the low transformation temperature effect (LTT).

2. State of the Art

In the welding process, the material melts only locally resulting in high temperature gradients between the welded material and surrounding base material. The change of state from solid to liquid back to solid results in thermal expansion and structural transformations where residual stress and distortion is the outcome.

LTT-materials show expansion when reaching room temperature, resulting in compensation of the tensile stress that forms in the welded zone, Fig. 1.

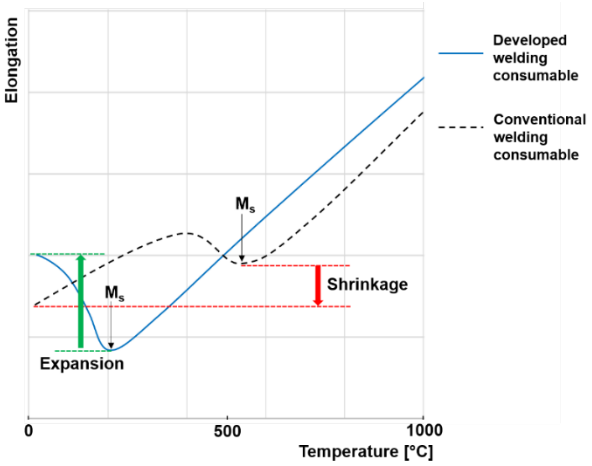

Fig. 1. Development of elongation depending on martensite start temperature M_s, Ohta et al., 1999

Reducing the martensite start temperature M_s to about 200°C will increase the expansion in the material compared to a M_s – temperature at over 500°C. When lowering it further, however, the expansion will decrease again, since the martensite finish temperature M_f will sink to temperatures below room temperature and thus the phase will not transform fully into martensite. As a result, the potential for the development of compressive stresses will not be fully exploited, Reisgen, 2016.

The martensite starting temperature is determined by the alloying elements in the material. With higher proportions of carbon, manganese, nickel, chromium and molybdenum, the martensite start temperature shifts to lower values and vice versa. In the literature different equations exist to determine the M_s – temperature mathematically. In this thesis the formula according to Steven and Haynes is used, Steven and Haynes, 1956.

$$M_s\,(°C) = 561 - 474*C - 33*Mn - 17*Ni - 17*Cr - 21*Mo \qquad (1)$$

The formation of residual stresses in a weld seam results in superposition of phase transformation stresses and shrinkage stresses, Fig. 2. Thermal shrinkage causes tensile stress along the weld seam (dotted line). These tensile stresses are compensated by compressive stresses resulting in a reduction of the tensile stresses. These compressive stresses are caused by phase transformation stresses (dashed line), which only occur as soon as the temperature falls below the melting point and phase transformations occur. With a greater distance to the weld seam, the compressive stresses revert to tensile stresses and both add up to a resulting stress diagram, Schulze, 2010.

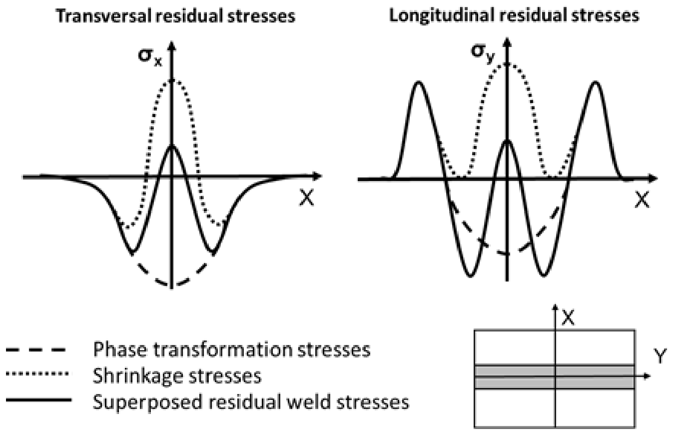

Fig. 2. Stress development dependent on phase transformation stresses and shrinkage stresses, Schulze, 2010

3. Welding Trials

Using digital image correlation, strains taking place on the surface of the plate can be illustrated. The development of strain in a low-alloy steel was investigated. A high-alloy and a low-alloy filler material were used for this purpose. With higher alloying elements, the martensite start temperature was to be reduced to lower temperature ranges and compensation by volume expansion was to take place.

3.1. Material

Two plates with the dimensions 25 x 100 x 5 mm were butt welded. A rectangle with 0.8 x 0.5 mm dimensions was chosen for the seam preparation, Fig. 3. For a filler wire with 1 mm diameter, the volumes of seam preparation and wire were approximately identical. As the base material S235JR was chosen and two filler wires were used: G19 9 L Si with high Cr and Ni content and Purus 42 both from the company Esab.

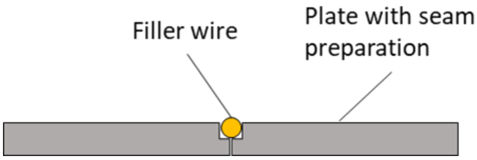

Fig. 3. Seam preparation and filler wire

The chemical composition of the materials were measured using an Optical Emission Spectrometer (OES), Table 1.

Table 1. OES analysis: Chemical composition of the used material in mass percentage (not all elements are listed)

Material	Fe	C	Si	Mn	Cr	Ni	Mo	P	S
S235JR	98.2	0.08	0.06	1.01	0.41	0.04	0.01	0.03	0.003
Purus 42	97.4	0.09	0.9	1.35	0.02	0.02	<0.005	0.01	0.02
G19 9 L Si	67.6	0.02	0.76	1.61	19.61	9.68	0.17	0.02	0.01

3.2. Experimental setup

For the welding tests, a Trumpf TruDisk 16002 disk laser was used as beam generator. A 2-camera system was used for digital image correlation recording. With this system three dimensional recording of movement are possible. To protect the cameras from spatter or smoke, a crossjet was mounted just below them. For illumination two XLamp CXA3590 LED Arrays from CREE with illumination performance over 10,000 lumen were used. The samples were tack welded and fixed at one point with a clamp. This protected against displacement while welding and still allowed free expansion during and after the welding process.

To measure the strain on the surface of the sample, a statistically distributed pattern with high contrast was applied. For this purpose, the surface of the sample was coated with white lacquer and black lacquer was applied with a randomized dot pattern using an airbrush. In order to achieve a relatively high resolution, the recorded area must not be too large. The recorded area was approximately 30 x 20 mm. Since the sample is symmetrical, only one half of the sample was painted and recorded. This allowed as much information as possible over the entire sample width. Evaluation was carried out using the software ISTRA 4D from DANTEC DYNAMIC. To measure the temperature, a type K thermocouple was applied about 2 mm from the centre of the weld seam, Fig 4.

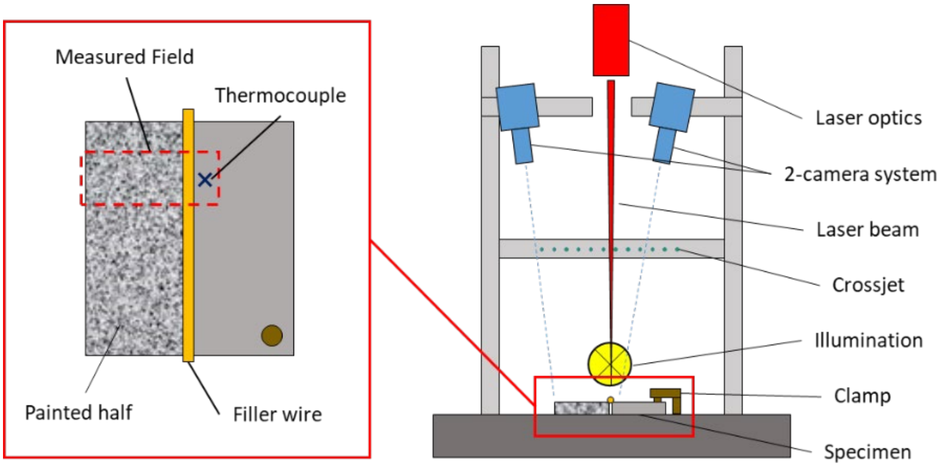

Fig.4. Experimental setup

4. Results and discussion

The Lagrange Strain of samples were compared, which were welded with a matching and dissimilar filler wire. The reason to combine a higher alloyed filler wire in the weld seam is to create a microstructure in situ whose properties represent an LTT alloy. Thus the advantages of LTT can be used with conventional wires.

During and after the welding process the Lagrange Strain is recorded until the room temperature is approximately reached. A measurement is made at a point about the height of the thermocouple and at a distance of about 12 mm from the centre of the weld seam.

First an expansion occurs in the weld seam. In the case of matching composition welding, the elongation initially remains at the same level and decreases only slightly over time. In the case of dissimilar composition welding, the elongation also increases during welding and gradually decreases during cooling. The elongation is compensated over time until the initial position is reached. It is noticeable that in the range of about 100 °C there is a significant drop in the strain curve. This sudden drop could indicate the phase transformation in martensite.

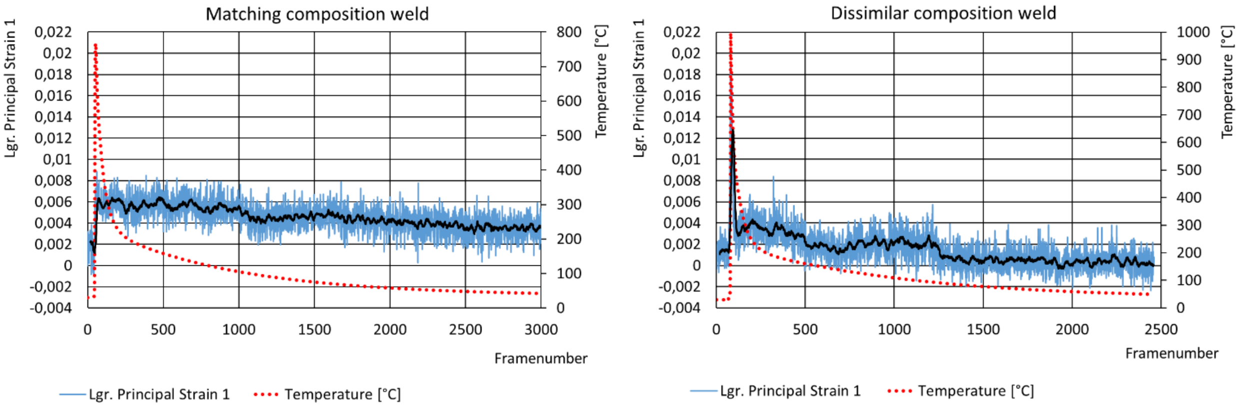

Fig.5. Comparison of the expansion curves of matching and dissimilar composition welds

With the values of the OES analysis, the M_s – temperature in the base material can be calculated exactly using Formula 1. In the base material, the transformation into martensite begins at about 482.57 °C.

Further investigations regarding the remaining alloying elements in the weld seam and the resulting M_s – temperature still have to be carried out.

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