Application of low-transformation-temperature (LTT) materials for stress reduction in electron beam welding

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In welding technology, the change of state from solid to liquid back to solid is used for safe joining using a localized effect of heat. Due to the thermal expansion, as well as due to structural transformations the outcome of this are residual stresses. The understanding of the process and the identification of the potential of time- and space-resolved phase transformations on the residual stresses is important to achieve high precision in the macro range. Therefore, the use of locally induced "Low-Transformation-Temperature" filler materials promises positive effects concerning local stresses and distortion. Influenced through specific time- and space-resolved heat treatment this "metallurgical injections" convert their structure in order to influence the residual stresses. Due to the time delay between the conversion of basic and additional material (injection) local stress fields can be generated and thus the residual stresses are affected. Material behaviour of this special LTT-Material used as filler in EB-Welding is examined for the first time.

Прилагането на материали с ниска температура на трансформация (LTT) за намаляването на стреса на материала при електроннолъчево заваряване (Уве Рейсген, Симон Олчок, Стефан Гач). *При заваръчните технологии превръщането на материалите от твърдо, в течно състояние и обратно в твърдо, се използва за успешното им свързване, като за целта се използва локализиран топлинен ефект. В резултат на топлинните разрешения, както и заради структурните трансформации се получава остатъчен стрес на материала. Разбирането на процеса и идентифицирането на потенциалните времеви и пространствени анализи на фазовите трансформации на остатъчния стрес на материала е важно за постигането на висока точност на макро ниво. Следователно, използването на локално индуцирани LTT пълнежни материали обещава позитивен ефект за намаляването на концентрирания локален стрес и деформации. Повлияни чрез специфично топлинно третиране на база времеви и пространствени анализи, тези „металургични инжекции" преобразяват структурата, с цел да се намали остатъчният стрес в материала. Заради времевите разлики между превръщането на основния материал и допълнителния (инжекцията) могат да се генерират локални стресови ефекти, които да повлияят на остатъчният стрес. За първи път е изследвано поведението на материала на този специален LTT –материал, използван като пълнеж.*

Introduction

Highest precision in the production by applying simplest possible process chains with only a few process steps is one of the main requirements of manufacturing companies in order to maintain and further develop stable and sustainable production in high wage countries, such as Germany, 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, for example, 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

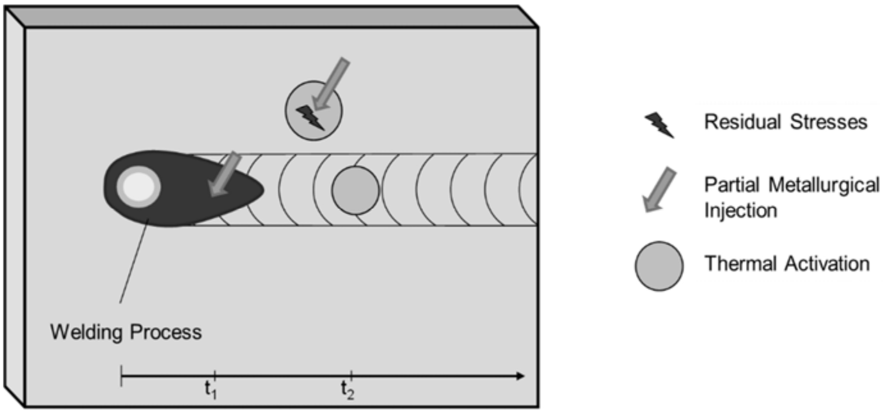

Fig. 1. Schematic representation of the welding process, metallurgical injection and thermal activation.

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 [1]. 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, i.e. when the residual stresses have already formed for a large part, this is called the low transformation temperature effect (LTT). For the best possible use of this LTT effect for the increase of the precision, process comprehension and the identification of the potential of the time- and space-resolved phase transformation of the residual stresses must be established. Within the framework of the project “Part precision by control of molten metal and solidification in production processes” (Precision Melt Engineering), the Collaborative Research Centre 1120 is working on this project. Within the framework of the sub-project A7 “Utilization of partial metallurgical injection for regulation of solidification forces in fusion welding processes” a new approach about the influence on residual stresses, filler materials which are locally induced in the molten material and which are, if required, still to be developed shall be applied and their effect on distortion shall be demonstrated and comprehended. These “metallurgical injections” shall be carried out very fast and punctual and shall, by simultaneous specific heat treatment, control the time- and space resolved structural change. The time difference between the transformation of base and filler material (injection) allows for the generation of local stress fields and to exert thus influence on the residual stresses. Within the framework of the project “Part precision by control of molten metal and solidification in production processes” (Precision Melt Engineering), the Collaborative Research Centre 1120 is working on this project. Within the framework of the sub-project A7 “Utilization of partial metallurgical injection for regulation of solidification forces in fusion welding processes” a new approach about the influence on residual stresses, filler materials which are locally induced in the molten material and which are, if required, still to be developed shall be applied and their effect on distortion shall be demonstrated and comprehended. These “metallurgical injections” shall be carried out very fast and punctual and shall, by simultaneous specific heat treatment, control the time - and space resolved structural change. The time difference between the transformation of base and filler material (injection) allows for the generation of local stress fields and to exert thus influence on the residual stresses. As heat source, the electron beam is used. The electron beam provides, due to its excellent modulation possibilities, the energy input for the required time- and space-resolved temperature gradients. It is, further, possible to vary the intensity distribution and the power density highly dynamical in order to influence, locally and graded, via the formation of a vapour capillary (keyhole) the molten pool dynamics and also the phase composition by specific evaporation of alloying elements. The aim of SFB1120 TP A7 is the reduction of the distortion of complex parts in situ by one order of magnitude via space- and time-resolved metallurgical and thermal control of the welding residual stresses. Fig. 1 depicts a schematic representation of the metallurgical injection with subsequent thermal activation. In order to achieve the aim, several aspects must be dealt with:

- Influence of energy input,
- formation of the molten metal and solidification on the welding residual stresses in beam welding
- Characterization of the potential of innovative LTT filler materials for the reduction of distortion. Analysis of the process-specific molten metal in correlation with the metallurgical injection.

A sub-ordinate aim is, therefore, to establish the LTT effect for the electron beam welding process.

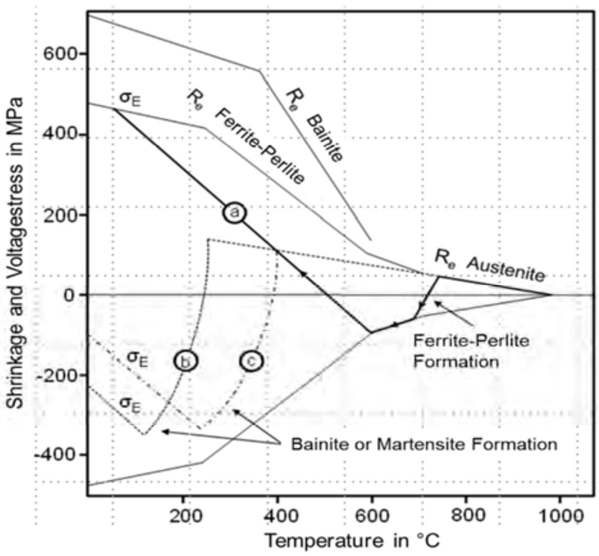

Fig. 2. Influence of the transformation temperature on the development of residual stresses [2]

Experimental conditions

1.1 Selection of materials

In The selection of the chemical composition of the wire is based on prior literature research and also on the results of preliminary tests. A low-carbon iron-based alloy with chromium and nickel contents of 10 % each have been chosen since the LTT effect has been demonstrated already in arc processes when this composition was used [1, 3, 4]. Based on these results, a filler wire is developed which fulfils the requirements made to the EB process. Table 1 depicts the optical emission spectrometry results (OES) of the filler material, measured in pure weld metal which has been re-melted to the form of welding pills in the induction furnace under argon shielding gas. As base material, the unalloyed steel S 355 J2 + N by Thyssen Krupp has been used. The results from the optical emission spectrometry are listed in Table 1.

Based on the chemical composition, the Schaeffler diagram postulates the structural composition of a material which is to be expected by means of the chromium and nickel equivalent, Fig. . The formalism for the calculation of the equivalents is depicted besides the diagram axes, the numerical values are listed in Table 1. The LTT-material (blue) is located in the austenite-martensite range, the base material S 355 (red) is located at the outermost boundary of the ferritic-martensitic mixed region. The composition of the weld metal of the dissimilar material joint will develop on the connecting line (broken line) between both base materials. The exact position is dependent on the chemical composition of the weld metal which means depending on the degree of dilution between the LTT material and the steel (S 355). Therefore, weld metal which consists of martensite contents and possibly of retained austenite, due to an incomplete phase formation, is to be expected.

1.2 Specimen preparation and test

The welding tests are carried out on specimens of the base material S 355 J2 + N with the measurements 100 mm x 50 mm x 5 mm (length x width x height). For specimen preparation, the LTT welding wire (diameter 1.6 mm) is positioned into a metal-cut groove which has a width and depth of 1.6 mm and then fixed by welding spots. The cylinder-shaped wire fills the groove only up to 78.54 % which points to weld sinkage. In the direct vicinity to the groove, thermocouples of the type K are fixed within a defined distanced where they serve for the documentation of the cooling behaviour, Fig. 3. Afterwards metallurgical evaluation of the tests is carried out. The welding tests are carried out with an oscillating electron beam with an energy-per-unit length of E = 96 J/mm at welding speed of 15 mm/s. It is guided centrically over the LTT wire which is positioned in the groove and is welding this wire with the base material.

Discussion of results

The welded seam is characterised by uniform ripples, insignificant weld reinforcement and also undercuts. Weld sinkage which would have been expected due to the small volume filling of the cylinder-shaped wire in the square groove is not observed, Fig. 4. This points to a relatively high degree of dilution which allowed for the filling up of the missing volume by base material S 355. The transverse section confirms the sufficient fusion behaviour of the weld metal with the base material. Cracks are not observed which can be considered to

Table 1

Chemical composition of the materials used: S355 and the LTT-wire, determined by OES analysis

Chemical Composition in Percent [wt.%]								Cr.-Equ. [%]	Ni.-Equ. [%]
	C	**Si**	**Mn**	**Cr**	**Mo**	**Ni**	**Fe**		
S355	0.0973	0.0232	0.777	0.0078	0.005	0.0152	98.9	0.05	3.32
LTT	0.0502	0.354	0.928	10.12	0.248	10.87	76.6	10.9	12.84

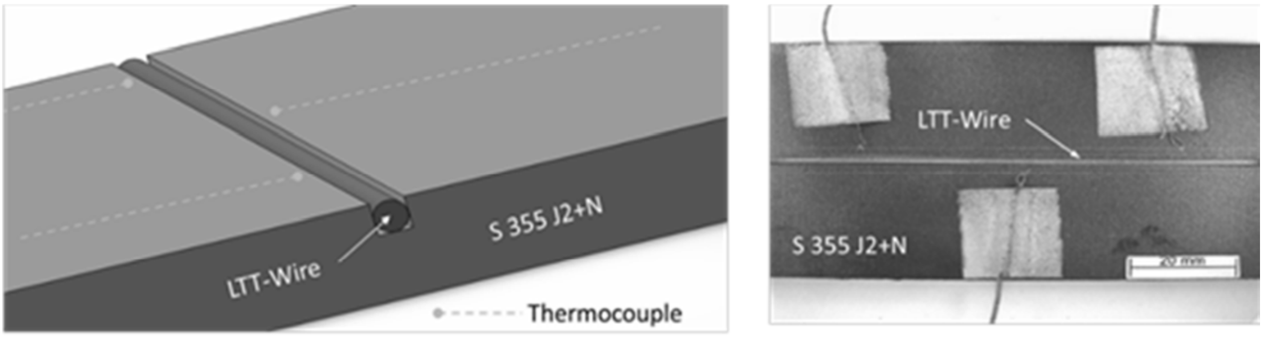

Fig. 3. Specimen preparation

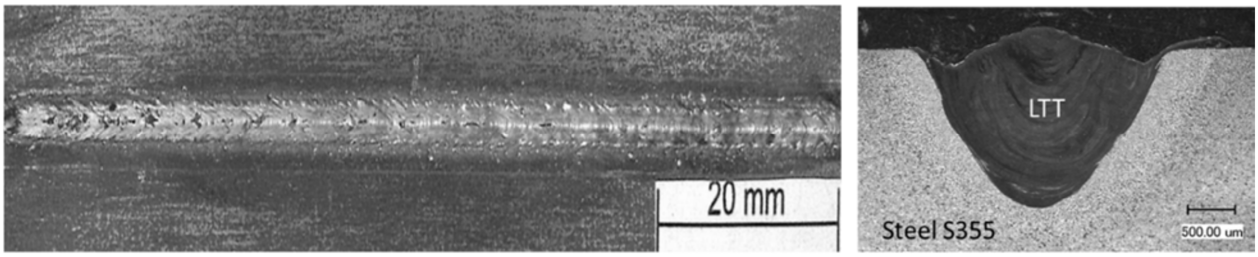

Fig. 4. Weld appearance- Seam top (left); Cross-section (right)

be an indicator for the presence of retained austenite. The highly different colours of weld metal and HAZ have been caused by the etching. Hardening takes place, in the HAZ and also in the weld metal, Fig. 5.

The hardness of the weld metal does not comply with that of classical martensite which is higher than 550 HV [6]. Here, the minor hardness points to existing retained austenaustenite and also to influence on the hardness by the alloying elements chromium and, above all, nickel. The latter could be caused by a presence of nickel martensite. The hardness values are rising in the direction of the HAZ of the LTT filler material continuously within one millimetre and are levelling off to a hardness of 400 HV 0.2 in the weld metal. Although the hardness is increased compared with the base material it does not reach critical hardening which may result in crack formation. Coarse grain development in the base material can be excluded since the cooling in electron beam welding is very fast and thus only minor grain growth is possible. The steady increase might be an indicator for the presence of compressive stresses which are induced by the martensitic transformation which occurs at a later point in time. Energy-dispersive-X-ray analysis (EDX) across the weld seam allows the evaluation of the chemical composition of the weld metal, Fig. 6. The iron content is displayed at the secondary ordinate, in favour of a better resolution of the alloying elements. In the edge regions, the composition of the uninfluenced base material S 355 J2 + N without significant content of (light blue) are increasing and are fluctuating in the region of 1 % around the respective mean which is within the range of measurement uncertainty. The mean value is, in the case of chromium approximately 5.5 % and in the case of nickel approximately 4.0 %. In comparison with the chemical analysis of the filler material (compare Table 1), a reduction of the alloying content by approximately 50 % shows which is caused by the dilution whit the base material. During the welding process, the material is liquid for just a few fractions of a second and cools with high cooling gradients which makes the influence of diffusion insignificant. It is not possible to determine the carbon content in the welded structure by EDX measurement. In the nickel equivalent, the carbon content is considered with a factor of 30 and has thus great influence. Therefore, the exact classification of the composition in the Schaeffler diagram is subject to uncertainty. If a dilution of 50 % is assumed, i.e. a carbon content which is with 0.074 % C between the contents of the base materials, a position is achieved which is in the vicinity of the theoretical mixture line of the two base materials in the martensitic region, Fig. . The micrographs support the assumption that martensite with a certain content of retained austenite is developing, Fig. . The retained austenite content is due to the incomplete martensite formation. Cooling to room temperature does not result in the martensite finish temperature. In the micrographs, small dark grains are perceived at the grain boundaries which are surrounded by light regions. The dark regions stand for martensite while the light regions stand for austenite. While the grain structures in the weld centre seem to have a round shape (Fig. , right), they start developing longitudinally stretched shapes at the weld transition in direction of the HAZ (Fig. 8, centre). This is (analogously to [1]) to be attributed to a directed conductive heat dissipation into the surrounding material.

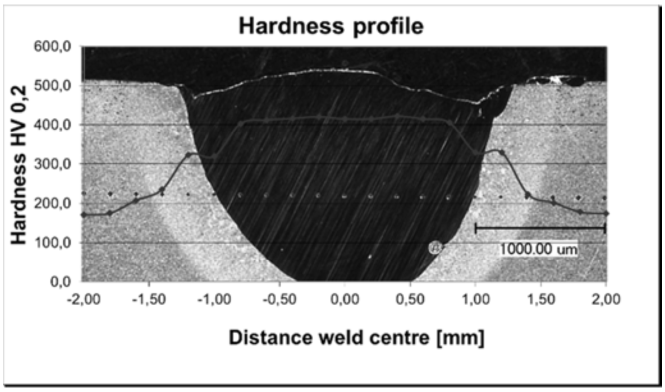

Fig. 5. Variation in hardness of the weld seam

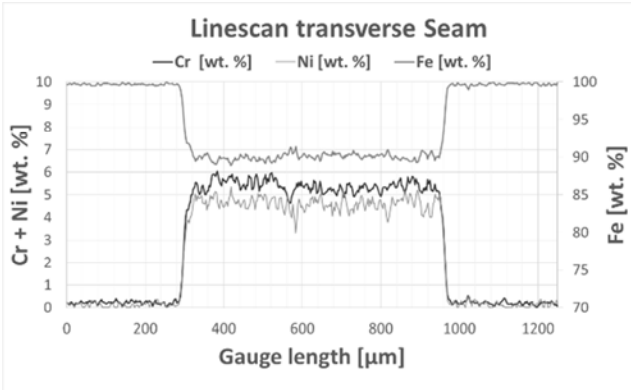

Fig. 6. EDX analysis of the weld metal.

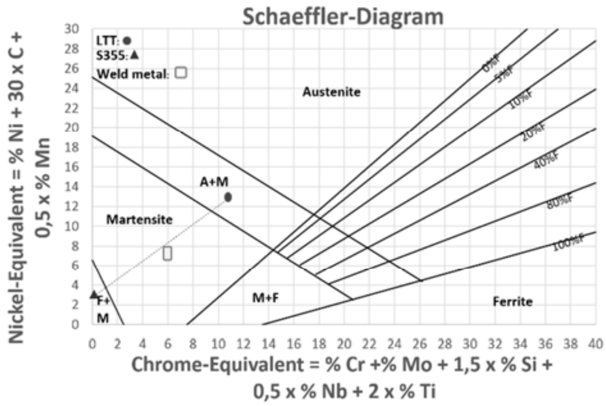

Fig. 7. Position of the weld metal in the Schaeffler diagram

Conclusions

In this paper, the first application of Low-Transformation - Temperature Materials (LTT) as filler material in the electron beam welding process is introduced. The selected alloy compensation in the austenite martensite mixed region is most promising. In the welding tests, a martensitic structure with a defined degree of retained austenite is setting, dependent on the degree of dilution of the unalloyed base material and the LTT welding wire. The alloy composition of the weld metal is dependent on the degree of dilution. Under the conditions which have

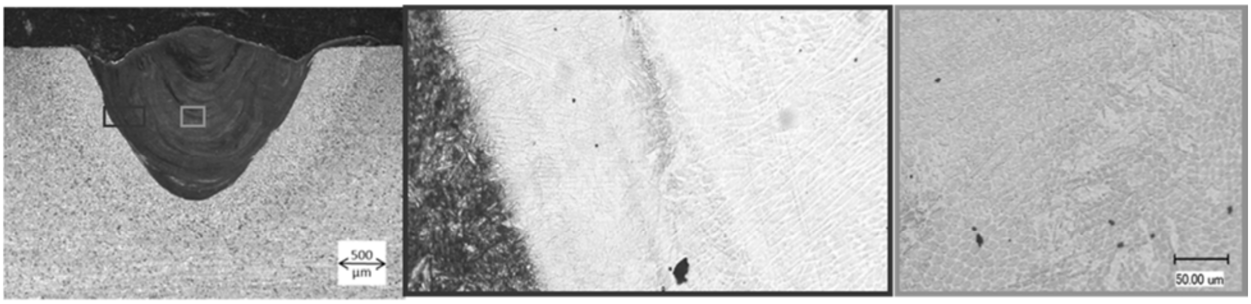

Fig. 8. Overview macrograph (left) micrographs HAZ (centre); weld center (right)

been chosen within the framework of this publication, the enrichment of alloying elements, especially of chromium and nickel by approximately 50 % took place, compared whit the pure LLT wire. The influence of heat dissipation into the surrounding material can be observed. Especially at the weld edge region, the grains are, in the direction of the HAZ, taking on longitudinal shapes while, in the weld centre, they have a globular structure. The hardness values are increasing in the HAZ in the region adjacent to the welded seam which might be an indicator for compressive stress caused by phase transformation. In the welded structure, the hardness values do, with round about 400 HV, not achieve the level of a completely martensitic structure which points to the existence of retained austenite and/or which might be caused by the influence of the alloying elements chromium and nickel, e.g. forming a nickel martensite. Hardness cracks are not observed which points to the toughness-increasing effect of retained austenite. The first application of LTT filler material in electron beam welding has thus been achieved. More detailed tests about the setting of the LTT effect at different transformation temperature and its effect on the residual stress state must still be carried out. A positive influence of the residual stress state and the distortion are not to be expected, they are, however, still subject to further investigations.

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