WeldForming – a new inline process combination for the improvement of weld seam properties

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Abstract. The arc welding process reduces the components’ prospective lifetime due to the high heat input and the resulting inhomogeneous crystalline structure. In order to compensate this disadvantage, subsequent treatment processes decoupled from the welding process are state of the art. This paper presents the novel process combination, WeldForming, which uses the heat generated during the welding process for a subsequent forming process in the seam area. The goal is to change the microstructure of the welded joint by using thermal forming processes right after the welding by inducing recrystallization processes in order to avoid the classic zone formation - coarse grain, fine grain and intercritical zones. The process development is based on numerical simulations. For the first time, a numerical model was developed in which a welding and a rolling process can be combined in a single simulation model, taking into account the microstructural changes. The necessary material model for the description of the microstructural changes (recrystallization behaviour) is based on thermophysical simulations. A novel approach was the development of a material model for the filler metal G4Si1 in its cast-like state, reflecting the microstructure developing during the solidification of the weld metal. By combining the knowledge gained from the thermophysical simulation and the numerical process simulation, a process window for the novel methodology of WeldForming could be identified. On the basis of this, a test setup was developed with which the functioning of WeldForming was proven.

1. Introduction

In industry, welding is one of the most frequently used methods to join metal sheets and other product forms. Welding is a process in which two or more parts are joined permanently at their contact surfaces by a suitable application of heat or pressure, or a combination of both. Often a filler material is added to facilitate metallic continuity [1]. Depending on the initial geometry and material or other problem specifications, different welding methods may be used. In most cases, the joining zone and an optional filler material are partially liquefied in order to achieve metallic continuity after solidification.

In fusion welding, energy input is integral to all welding processes, which can lead to extensive transformations and changes of the microstructure and properties of these materials. This applies in particular to steel in the area of the weld metal [2, 3]. The characteristics of heat input during the welding process will lead to temperature gradients and different cooling rates during the solidification of the weld pool. This can cause an irregular distribution of alloying elements (e.g., segregation) and various microstructural features after solidification may evolve. The resulting weld seam
microstructure most closely resembles as a cast-like microstructure. The part of the base material which is altered by the weld thermal cycle is called heat-affected zone (HAZ). This zone is exposed to thermal cycles but is not melted. If high heat input welding, e.g. gas metal arc welding (GMAW) is applied to steels, the microstructure of the HAZ close to the fusion line becomes notably coarse and the toughness of this zone is strongly degraded [4]. Figure 1 shows the characteristic appearance of a weld seam in a cross-section.

The characteristic of the HAZ affects the mechanical properties of the weld seam. Depending on the welding process and the distance from the weld seam, microstructural imperfections may occur. This can in turn lead to undesirable properties of the whole assembly, e.g. the joint has inferior strength relative to the unaffected base material [5]. Experiments conducted on high-strength low-alloy steels by Mohandas [6] reveal the effect of the microstructural changes in the HAZ on the overall mechanical properties of the assembly.

When these steels undergo weld thermal cycles they exhibit softening in a certain region of the HAZ. The degree of softening in the HAZ is thereby a function of the weld thermal cycle, which is a characteristic of the welding process [7]. The softening characteristics also depend on the kinetics of the phase transformations of the steel and are a function of the chemical composition of the steel [8]. To reduce these negative effects of the welding procedure and restore properties, additional steps in the form of post-treatment processes (e.g., mechanical or thermal treatments) are typically necessary. The established processes are able to reduce residual stresses (stress relief heat treatment), notch sharpness, and near-surface weld seam defects (e.g., TIG melting) in the course of separate thermal post-processing steps. However, there is no targeted optimization of the weld seam microstructure available at present. All current post-processing processes are decoupled from the welding process and thus require subsequent processing steps. The introduction of the WeldForming process intends to make the additional decoupled post-treatment processes for welded components obsolete. The main advantage of the WeldForming process is the targeted adjustment of the microstructure and properties of a welded joint. The intention is to restore the mechanical properties of the joint by producing a base material-like microstructure all over the weld through recrystallization processes. This can be achieved through coupling a welding and a subsequent forming process, directly utilizing the heat from the welding process to initiate recrystallization. The thermal microstructure optimization by means of dynamic, metadynamic and static recrystallization will be stimulated by the forming process. In addition to the recrystallization processes, flattening of the weld seam will occur and increase the dynamic strength of the assembly by reducing critical notches. A schematic of the WeldForming process is shown in Figure 2.

In the newly developed WeldForming process, the post-treatment of the weld seam is carried out inline - directly after the welding process in one process stage. This means that no additional process steps are necessary and an additional heating (as in a stress relief treatment) is obsolete. The heat of the welding process is directly utilized, thus resources in the form of energy and time are conserved.
2. Experimental and materials

2.1. Experimental setup
In order to implement the WeldForming process experimentally, a water-cooled GMAW-welding torch was integrated into an existing Duo-Reversier cold rolling mill. The minimum possible distance, construction wise, between the welding torch and roll center is 130 mm, as shown in Figure 3. The welding speed in this setup is controlled, by adjusting the revolutions per minute of the rolling mill.

![Figure 3. Experimental setup for the WeldForming process.](image)

2.2. Welding tests
The basis for the development of WeldForming is the welding process. Welding tests have been carried out in advance to determine a process window in which a stable welding process with a high weld reinforcement could be established.

The welding tests are carried out on the normalized steel S235 (1.0037) with an overmatching design of the welded connection by the additional filler material G4Si1 (1.5130). This means that the additional filler wire used for welding is higher alloyed than the base material. The two plates (thickness: 4 mm) are butt-welded together with a sheet-thickness-dependent seam geometry according to DIN EN 9692-1 and with a defined weld reinforcement and excess penetration. The reference welds are carried out on a FroniusTransPuls Synergic 5000 CMT R welding power source with a connected VR 700 CMT wire feeder. To ensure the required reproducibility of the results, the welding torch is guided by a six-axis articulated arm robot produced by Comau.

Figure 4 shows cross-sections of welding seams and the corresponding process parameters for different welding speeds of 0.7 m/min, 0.9 m/min and 1.4 m/min. It can be seen that at lower welding speeds of 0.7 m/min and 0.9 m/min, a higher weld reinforcement can be achieved. The welding arc burns longer at one point and more filler material can be melted per time unit. However, if the welding speed is too low, there is a risk of melt pool overheating, resulting in weld defects.

The cross-sections of the specimens with a welding speed of 0.7 m/min and 0.9 m/min show a comparable seam geometry regarding the weld reinforcement. However, the sample of the lower welding speed shows a lower penetration. This can be recognized by the flat seam flanks in the upper part of the sample. This means that less base material is melted and less thermal energy is introduced in the joint area.

The welding power is almost identical for the welding speeds of 0.7 m/min and 0.9 m/min with approx. 9.0 kW. A maximum welding power of 11.4 kW is achieved at a speed of 0.9 m/min.

To which extent the differences in the seam geometry, the welding power and the thermal in- and output influence the process will be numerically analysed in the presented paper.
2.3. Material characterization

The aim of the WeldForming process is to transform the brittle, cast-like microstructure in the weld metal into a finer-grained and thus ductile structure. To predict this transformation numerically (see chapter 3.4), it is necessary to determine the flow curves and the recrystallization behaviour. For this, thermo-physical material tests were carried out by using the forming and quenching dilatometer DIL 805 A/D. The initial microstructure of the cylindrical samples has to be identical to the cast-like microstructure of the weld metal after the welding process. For this, an adjusted melting process of the filler material with subsequent cooling (cooling rate similar to the welding process) was performed (see [10]).

To determine the flow curves cylindrical upsetting tests were done. The dynamic recrystallization behaviour of the filler material in cast-like microstructure was also determined by upsetting tests. The static as well as the metadynamic behaviour were determined by relaxation tests using the forming and quenching dilatometer.

In the end, the entire recrystallization kinetics are modelled according to the JMAK theory (see [11]). Figure 5 shows an example of temperature depending flow curves and dynamic recrystallization kinetics for a strain rate of $1 \text{s}^{-1}$. The hot flow curves were determined by compression tests up to a maximum plastic strain of 0.7. This is sufficient for the selected test conditions, since the steady-state range has already been reached and the yield stress remains almost constant for plastic strain higher than 0.6. The yield stress was assumed to be constant for plastic strains over the experimentally recorded range of 0.7. This is permissible according to [12], since the hardening and softening speeds in the steady-state range are almost identical.

![Flow curves and dynamic recrystallization for a strain rate of $1 \text{s}^{-1}$ of weld metal.](image)
3. Numerical process development

3.1. Principal approach
In order to reproduce the novel methodology of WeldForming realistically, a numerical model was developed in which a welding and a forming process (hot rolling) can be combined in a single simulation model, taking into account the microstructural changes. For a realistic numerical simulation of the process in advance, the approach shown in Figure 6 is used. At the beginning, the welding process was numerically simulated and compared with the reference process (see chapter 3.2). In this way, a suitable heat source and the necessary parameters can be determined iteratively. Subsequently, a numerical simulation of a hot rolling process was performed, including a comparison with the reference test. This was done in order to determine suitable cross-linking parameters, friction models and coefficients, time increments and heat transfer coefficients (chapter see 3.3). On the basis of the validated individual processes, the rolling model was then extended by the heat source and the associated heat source parameters, so that the new WeldForming process can be reproduced realistically.

![Validated welding simulation and validated hot rolling simulation](image)

**Figure 6.** Procedure for the simulation of the WeldForming process based on validated single processes.

3.2. Simulation of welding process
The simulations of the welding processes are carried out with the simufact.welding software tool. In order to ensure a realistic numerical representation of the welding process, reference tests were carried out (see chapter 2.2). On the basis of the tests, the weld seam geometry was analysed and transferred to the Finite-Element (FE) model. Furthermore, temperature measurements were carried out in order to obtain verification data for the simulation adjustment. These data are necessary to simulate the welding process using a simplified model for the heat source. For the arc-welding process used, a heat source model according to GOLDAK is recommended [9]. The welding process with a welding speed of 0.9 m/min is used as reference process. Figure 8 on the left shows the points where the temperature was measured by using thermocouples type K. By iteratively adjusting the geometric parameters for the heat source (shown in Figure 7), the temperature curve can be calculated realistically, as shown in Figure 8, right. Figure 7 shows the geometric parameters used for this purpose. The welding parameters of the reference process which are necessary for the simulation are shown in Figure 4.
Figure 7. GOLDAKS double ellipsoid heat source model and used parameters.

Figure 8. Measuring points for temperature measurement and comparison of measured and simulated temperature curves.

Advanced validation of the heat source model is necessary. With the validated model a realistic numerically prediction of the thermal heating during the simulation of WeldForming is possible.

3.3. Simulation of hot rolling

The simulation of the hot rolling process was performed with the FE-tool simufact.forming. Figure 9 shows the structure of the simulation model for the hot rolling process. It can be seen that the roll intake and outtake areas are also modelled, since heat transfer from the hot sheet to the roll table takes place before, during and after the rolling process. The heat transfer coefficient between roll table and sheet is set to 2000 W/(m²∙K) and between rollers and sheet 3000 W/(m²∙K). The heat transfer to the environment was also considered with 50 W/(m²∙K).

Figure 9 on the right also shows the modelled weld seam and the cross-linking of sheet and weld seam. The flow curves of the materials were implemented for the necessary forming temperatures (700 - 1200 °C in Δ 100 °C) and forming speeds of 1 s⁻¹ and 5 s⁻¹. The heating caused by plastic deformation was also considered. It was assumed that ca. 90 % of the plastic work are converted into heat. The validation of the hot rolling process was carried out by a comparison of the force-time curves calculated and measured in reference processes. Furthermore, the seam geometry after rolling was also compared to the simulation results. During the reference tests, the welded sheets (welding speed: 0.9 m/min; seam geometry see Figure 4, middle) were heated up to 1100 °C and 1200 °C in the chamber furnace and then the entire weld sample was rolled to a sheet thickness of 3.9 mm.
Figure 9. Simulation model for the hot rolling process (left) and modelled weld seam (right).

Figure 10 shows the comparison between the calculated and measured force-time curves at an initial sample temperature of 1200 °C and 1100 °C. It is apparent that both the qualitative and the quantitative force-time curves correspond very well and that the average deviation is less than 10 %. In addition to the comparison of the rolling force curves, the levelled seam was used as an optical comparison criterion. There is again a high qualitative agreement between simulation and experiment (see Figure 11). Finally, due to the constant comparison between simulation and experiments, a realistic simulation model for the hot rolling process could be developed.

Figure 10. Comparison of simulated and measured force-timecurves for rolling temperatures of 1200 °C and 1100 °C.

Figure 11. Comparison of the levelled seam after hot rolling at 1100 °C.

3.4. Simulation of WeldForming

The combined WeldForming simulation was done in the FE-tool simufact.forming. The basis is the FE model of the hot rolling process, which is extended by the validated GOLDAK heat source of the welding simulation. Since the FE tools simufact.forming and simufact.welding use the Marc-Solver, such an extension is possible.

The main goal of the WeldForming process simulation is the numerical determination of a process window, in which the WeldForming can be realized experimentally. The aim is to achieve a homogeneous microstructure by means of recrystallization in the welding zone. The recrystallization behaviour is essentially influenced by the plastic strain, the forming temperature and the strain rate.
Since the welding speed influences the seam geometry (and thus the plastic strain), the thermal in- and output (and thus the forming temperature) and the rolling speed (and thus the strain rate), the welding speed is an essential influencing factor in the microstructure homogenization by recrystallization. With the help of numerical simulations, the influence of the welding speed on the plastic strain, forming temperature and strain rate, as well as the resulting fraction of total recrystallization, will be analysed. The distance between the centre of the roll and the welding torch is set to the currently minimum possible distance of 130 mm.

Figure 12 shows the distribution of the plastic strain in the seam area. The evaluation area is located in the middle of the specimen, after a welding length of 100 mm. It can be seen that at a welding speed of 0.7 m/min and 0.9 m/min, a similar plastic strain is achieved by rolling of the weld seam, because the weld seam geometry before rolling/after welding is similar (see Figure 4). The rolling of the seam, which is welded with a speed of 1.4 m/min, leads to a lower plastic strain in the seam area, since the weld reinforcement is significantly smaller.

![Plastic strain distribution](image)

**Figure 12.** Comparison of plastic strain distribution after the WeldForming at different welding speeds.

The analysis of the occurring strain rates in the forming area shows that a higher welding speed leads to higher strain rates (see Figure 13). The strain rate has a significant influence on the dynamic recrystallization behavior. Because of that the recrystallization kinetics (see chapter 2.3) for a range of 0.5-5 s⁻¹ was determined.

![Strain rate distribution](image)

**Figure 13.** Comparison of strain rate distribution for WeldForming at different welding speeds.

The welding speed also influences the thermal in- and output in the seam area. On the one hand, a high welding speed means that due to a shorter process time less heat can be dissipated to the contacting tools and the environment. On the other hand, the higher welding speed results in less heat being introduced by the welding process, since the welding process time and power depend on the welding speed. Furthermore, the volume of liquefied material is smaller at higher welding speeds, so that less “hot” welding material and thus thermal energy is introduced. Figure 14 shows the temperature distribution during the process in a half-section. It can be seen that at a welding speed of 0.9 m/min a temperature of 890 °C is reached in the rolling gap, whereas for a welding speed of 0.7 m/min and 1.4 m/min, only 740 °C and 780 °C respectively are reached, which is significantly lower. The
welding speed of 0.9 m/min thus represents the optimum parameters to achieve the highest possible temperature in the rolling gap.

![Figure 14. Comparison of temperature distribution for WeldForming at different welding speeds.](image)

The parameters that were previously investigated separately have a significant influence on the recrystallization behaviour in the weld area. Using the material model developed on the basis of the JMAK theory, the total fraction of recrystallization can be calculated in the simulation. Figure 15 shows the total recrystallization behaviour at the investigated welding speeds. The highest fraction of total recrystallization is achieved at a welding speed of 0.9 m/min. According to this there is an optimum process window in which the combination of welding parameters and forming of the resulting weld seam lead to a maximum of recrystallization. A general statement that a high or low welding speed leads to the best possible result cannot be made.

![Figure 15. Comparison of total recrystallization after WeldForming with different welding speeds.](image)

The simulation provides a parameter set with which the WeldForming process can now be implemented experimentally. The experimental results of the simulation are discussed in the following chapter.

4. Experimental results

On the basis of preliminary experimental and numerical investigations, a suitable welding speed could be determined at which a total recrystallization of approx. 75 % was numerically predicted. In order to validate this experimentally, the WeldForming process was performed with a welding speed of 0.9 m/min and the corresponding parameters (Figure 4, middle). The analysis of the microstructure in the seam area was done by light microscopy. The point of investigation is thereby identical to the simulation and located in the middle of the sample.

Figure 16 shows the real test setup as well as the microstructure as welded (Figure 16, left) and the microstructure after WeldForming. It can be seen that the typical cast-like structure of the weld metal can be transformed into a grain structure by means of recrystallization processes (Figure 16, right). Thus, the functional principle of the novel methodology of WeldForming is proven. However, it can also be seen that elongated grains caused by the rolling process are present in the microstructure. This suggests that the recrystallization process is not yet fully completed. This in turn correlates with the preliminary results of the numerical investigations, in which a total fraction of recrystallization of approx. 75 % was calculated.
Figure 16. Real experimental setup, microstructure as welded (left) and microstructure after WeldForming (right).

In addition, the intake and outtake temperatures (50 mm before and after the centre of the roll) were measured with a pyrometer. Figure 17 shows the measured inlet and outlet temperature as well as the numerically calculated inlet and outlet temperature. The difference between the measured and calculated temperatures is less than 15%, so it can be assumed that the temperature distribution in the component and its development during the process is reproduced realistically. Furthermore, the analysis of the inlet and outlet temperatures shows a rapid decline in temperature from 1130 °C to 440 °C as a result of the contact between the weld seam and the cold rolls of the rolling mill during the process. The high cooling rate prevents static recrystallization effects, which should follow the forming process, as the temperature falls below the required level needed for a static recrystallization. The required temperature to initiate the static recrystallization according to the modelling after the JMAK theory (see chapter 2.3) is approx. 650 °C, taking into account the previous forming conditions.

Figure 17. Measured and numerically determined in- and outgoing temperature.

5. Conclusions
For the first time a numerical process coupling of a welding and hot rolling process in one single simulation model was carried out, in the context of the present work. It is based on verified individual processes, taking into account the microstructural changes (recrystallization effects) in the welding area. On the basis of the simulation model, the influence of the welding speed on the degree of deformation, the forming temperature and the deformation rate was analysed to finally evaluate the recrystallization effects. The first assumption that a high welding speed improves the recrystallization behaviour (since less welding heat is dissipated due to the shorter process time) could be refuted. It was shown that at a welding speed of 0.9 m/min approx. 75% of the microstructure recrystallizes, whereas at a welding speed of 0.7 m/min approx. 50% recrystallizes, and at a welding speed of 1.4 m/min only approx. 30% recrystallizes. On the basis of the numerical findings, the welding process was implemented experimentally. It was proven that it is possible to transform the cast-like
and brittle microstructure of the weld metal into a recrystallized grain structure as a result of hot forming. However, with the current machine concept it has not been possible to achieve a complete recrystallization. For this reason, the welding torch will be adjusted in future work to achieve a minimum distance between the centre of the roll and the welding torch of approx. 110 mm. According to numerical investigations, this distance is necessary in order to guarantee complete recrystallization in the seam area.

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