International Journal of Emerging Technology and Advanced Engineering
Website: www.ijetae.com (ISSN 2250-2459, ISO 9001:2008 Certified Journal, Volume 7, Issue 7, July 2017)

Influence of Cross Wedge Rolling on the Coating Quality of Plasma-Transferred Arc Deposition Welded Hybrid Steel Parts

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***Abstract*— Plasma-transferred arc welding (PTA) is a flexible welding process to coat metallic materials with a wide variety of material combinations. At the University of Hanover, this process is currently being qualified for the production of hybrid semi-finished parts for bulk forming products. The technology provides many answers to the questions about cost-effective manufacturing methods in the field of high-performance components. The process shown is a combination of a welding and cross wedge rolling (CWR) process, which is intended to create homogeneous coatings from steel with high carbon equivalents (CEV>0.5). Weak points due to inhomogeneities in later components must be avoided when the parts are used in tribological applications, so the production process has to be very reliable. Therefore it is necessary, that important properties of the joining zone between the material partners such as the coating thickness and metallic microstructure are well known and can be controlled.**

The deformation of the weld seams and the microstructure is optically examined. It is shown, that it is possible to convert the original casting structure of the welded layer into a forming structure. The investigations provide a first overview of the possibilities to influence the coating quality by forming processes in the production of welded hybrid semi-finished steel parts.

***Keywords*— Plasma-transferred arc, quenched steel, hybrid parts, forging, cross wedge rolling**

I. Introduction

The pressure to improve the performance of technical components is rising steadily. The expectations of the market can just be met by components which have a higher functionality at a lower weight and size. But the established production processes for formed steel parts are slowly coming to their limits. The reason for this can be found in the widely use of monomaterial billets. These components and their respective material characteristics only allow a compromise with regard to the requirements on the later workpiece.

To increase the production quality, efficiency and also the performance of mechanical components in a significant next step, new hybrid parts that combine various materials in one workpiece can be one solution. These parts offer the possibility, that a specific material, which is optimally suited for a particular load condition, is located exactly there, where it is required.

Due to this change of the materials used, new challenges are opening up by the production of hybrid parts that can make process adjusting necessary. In case of the welding deposition process, new materials have to be tested and qualified if they are suitable to be coated on defect-free. The joining zone should be able to withstand the strong forces in the following CWR-process. During the whole process chain, a strong mixing between the base material and the coating material should be avoided. There is the possibility, that the use of hybrid materials can complicate the tool design and calculation of the tool life during forming operations, since unequal forming characteristics can result from the hybrid billets which makes it more difficult to define suitable simulation parameters.

For the production of hybrid semi-finished parts different approaches can be taken out. One is e.g. to join cylindrical billets made of different materials at their ends and produce serially arranged parts. Also it is possible to produce parts that are coaxially arranged, which means that a core material exists in the middle of the workpiece which is equipped with a hard-metal-coating on the surface.

This paper describes a possible way to produce coaxially arranged semi-finished parts by PTA-welding and evaluates the influence of the subsequent CWR on the coating properties. For the core material an unalloyed steel was used. The coating material consists of a quenched and tempered low alloyed steel. The investigation presented focuses on the analysis of the microstructure and the shape change of the PTA deposition welded coating before and after CWR.

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II. MOTIVATION

A property common to all welding processes is the problem of heat affected zones. These zones always occur inside of welded steel materials nearby to areas where the metal was molten and huge amounts of heat have been transferred into the crystal structure. The solidified weld seam also differs greatly from the basic material in form of a cast structure. The effects on the microstructure, especially under the regard of mechanical performance, mostly lead to a decrease of quality. A chance to make the effects of a welding process negligible, is a forming process that follows after the deposition welding. If the process is strong enough, it causes a complete recrystallization of the microstructure which can be significantly more advantageous for later mechanical applications as well as processing steps. Deposition welding with subsequent CWR has not been part of investigations so far.

III. STATE OF THE ART

Plasma-transferred arc welding. Nowadays several methods to apply metal layers and coatings are established in industry. Some of the most frequently used procedures are e.g. submerged arc deposition welding (SAW), gas metal arc welding (GMAW), plasma-transferred arc (PTA) or electro-slag (ESW) and laser deposition welding (LW) [1].

For the production of semi-finished parts for forging processes, PTA deposition welding is evaluated as the most appropriate joining process. The reason for this is the possibility to weld a large variation of metallic alloys, a high process stability and a precise process control. Another great advantage is the use of powder as a filler material. Many of the hardest coating materials available at the market that offer the toughest properties e.g. in wear resistance or hardness can in many cases just be purchased in powder form, e.g. rolling bearing steels and tempering steels.

To weld these kind of steels mostly is a challenge, because the carbon equivalent is usually quite high (>0.5). In regard to the general recommendations of the common literature, these steels are considered mostly as “not weldable” or at least “difficult to weld” [2]. This evaluation, however, is based on massive workpieces rather than the welding of powder, which is why conventional problems do not necessarily have to occur.

Figure 1 gives a brief overview of the welding process. PTA uses a plasma-electric arc as heat source that is generated between a water-cooled tungsten electrode and the workpiece. A copper electrode helps to ignite the process at the beginning by a pilot arc, which generates plasma that is directed to the surface on the workpiece. The whole process works in an argon atmosphere as a shielding gas, which also has the task of transporting the metal powder into the welding zone, by the powder feeding system.

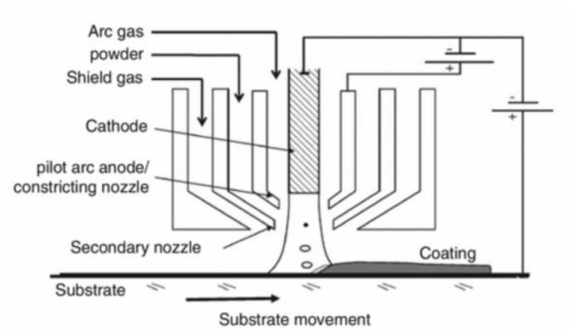

Fig. 1: Scheme of the PTA process [3]

However, compared to other deposition methods e.g. laser deposition welding, the geometrical precision of PTA is lower. But there are also process settings existing that allow energy and cost efficient coating for small size deposition. Jhavar et al. developed a µ-PTA process that makes it possible to remanufacture or repair defects on molds and dies [4]. For a 90MnCrV8 steel that was coated with powders of aluminium oxide and chromium oxide Ulutan et al. evaluated the effects of surface melting on the hardness, wear behaviour and microstructure caused by PTA [5]. Motallebzadeh et al. made investigations with a hypo-eutectic cobalt-based hardfacing alloy that was deposited on a steel substrate using PTA. High temperature tribological performance and the microstructure was examined [6]. Stellite 6 alloys that have been coated on stainless steel were studied under the regard of wear resistance by Ferozhkhan et al. [7].

Cross wedge rolling. CWR can be described as a preforming process that produces rotationally symmetrical workpieces out of circular cylindrical billets. The process is using two oppositely moving wedge-shaped tools and creates parts with variable diameters in axial direction. A illustration can be seen in Figure 2.

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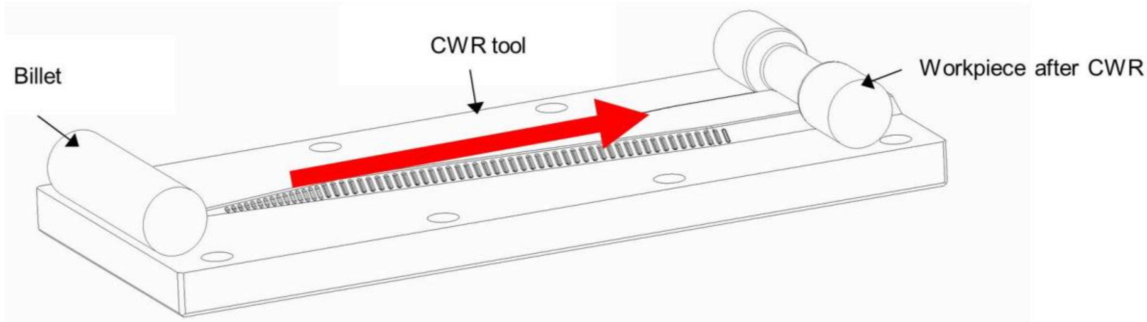

Fig. 2: Scheme of the CWR process

Because of the wedges, the mass of the workpiece is displaced during the process, which leads to an uneven distribution along the main axis [8]. CWR has a high material utilization and is therefore the first choice for preforming. [9]. For the work with monolithic materials the most important process parameters for common CWR are the forming velocity and the temperatures of billet and tool. First basic studies on the process combination of deposition welding and subsequent hot bulk forming were performed using laser-stabilized gas metal arc deposition welding [10].

For a long time, CWR was not widely taken into account throughout the forming industry, even when the process has many advantages. The complexity of the process design and tool manufacturing are the main reasons for this. However, through latest researches a simulation tool has been developed [11], which makes it possible to automatically generate the geometry of a part [12,13]. Also a new method was found to downscale the effort of experimental trials [14].

IV. Semi-Finished Workpieces: Parameters And Results Of Production Process Steps

Deposition welding by plasma transferred arc— The PTA deposition process is performed with the power supply STELLITE STARWELD PTA 302 CONTROL and the plasma torch KENNAMETAL STELLITE HPM 302.

The torch is equipped to a six-axis industrial robot (REIS RV30-16). To ensure a constant width and thickness of the coating, as well as the flatness, are the main challenges. For the base material the unalloyed steel 1.0402 (C22) was used in form of cylindrical billets with a diameter of 30 mm. 1.0402 is a typical bulk material that is used to produce e.g. low cost shafts. As the coating material the quenched and tempered low alloyed steel 1.7035 (41Cr4) was chosen.

The material was atomized under argon-atmosphere to make it usable as a powder filler material for the PTA-process. 1.7035 is used often for driving elements like steering components, front vehicle axles and crankshafts. In purchase it is more expensive than 1.0402. The chemical composition is shown in table 1. The materials were selected due to their similar forming behaviour at the typical forging temperature of 1250 °C, which is for 1.0402 35 to 140 MPa and for 1.7035 30 to 75 MPa.

The process parameters shown in table 1 have been used for the deposition process. The workpiece rotates 11 times while one rotation lasts 48 seconds, resulting in a total process time of 8 minutes and 48 seconds. During welding the robot oscillates the PTA-torch with a frequency of 3 Hz and a deviation of 3 mm to create seams with a higher width. The welding current is dynamically controlled and reduced from 150 A to 120 A in regard to a strong raising workpiece temperature.

TABLE I
Process Parameters For The PTA Deposition Process

Parameter	Value
Welding velocity	2 mm/s
Working Distance	10 mm
Grit size of powder particles	0.063 to 0.160 mm
Powder quantity	10 g/min
Voltage	25 Volt
Shielding gas flow (Argon)	10 l/min
Plasma gas flow	1 l/min
Transport gas flow	4 l/min
Current	150– to 120 A

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Evaluation— The coating thickness after welding is an important evaluation parameter. Figure 3 shows a cross section of a deposition welded semi-finished workpiece along its axis. The coating geometry shows a wavelike contour at the inner and outer diameter, which can be attributed to the helical welding process. The mixing between base material and coating material due to high process temperatures is the reason for this characteristic look of the weld.

The geometry of the weld seam prevents that an overall coating thickness can easily be determined because of the coatings inhomogeneousity along its axis. To evaluate the flatness, the deviations of the outer and inner diameter are taken into account. 0.71 mm is the difference between the smallest and biggest outer diameter. In regard to an average coating thickness of 4.02 mm, the deviation can be calculated to 17.5 %. The inner diameter differs more in its geometry than the outer diameter. The distance between the smallest and largest inner diameter is 1.71 mm, which follows a deviation of 42.3 %.

In order to be able to refer the deviation of the layer thickness to an overall deviation of the semi-finished workpiece, the measured inaccuracies of the coating and the size of the base material have to be taken into account. The flatness on the inside is lower than on the outside (Fig. 3). While the deviation of the outer diameter is calculated to just 2 %, the deviation of the outer diameter is 5.4 %.

The microstructure of the coating of the welded billets shows different crystal formations, as it is common for low alloyed steel (Fig. 5). Because of much heat transfer into the workpiece during the deposition process, the billet is red heated. After deposition it rapidly cools down in air. However, the exact temperatures and cooling conditions after the deposition process are not known.

Many areas of the microstructure consist of Widmanstaetten ferrite, which is present in a needle-like formation in the grey-shaped regions. The brighter areas are of common ferrite, the black islands consist of bainit.

Cross wedge rolling of PTA deposition welded billet— The flat wedge tools are mounted to a hydraulic press from the manufacturer NEFF, which is able to produce a maximum force of 6300 kN. The tools can be moved by a force of maximum 100 kN by two hydraulic cylinders. The adjustable forming speeds are between 60 and 360 mm/s.

The parameters in table 2 have been used to perform the following investigations. For standard steels like 1.0402, 1250 °C is a common temperature to carry out forging processes.

Kache et al. showed that an area reduction of 54 % as well as the angles α = 30° and β = 7° are feasible parameters for a CWR-process that shall be free from defects [14]. For the flat wedges a medium forming speed of 120 mm/s was chosen.

TABLE II
PROCESS PARAMETERS OF THE CWR-PROCESS

Parameter	Value
Workpiece temperature	1250°C
Tool temperature	20°C
Tool geometry	α = 30°, β = 7°
Cross section reduction	54%
Forming speed	120 mm/s
Materials	1.0402 + 1.7035
Average coating thickness	≈ 4 mm

Evaluation— The deformation zone resulting from the CWR-process affects the whole length of the applied coating on the semi-finished workpiece, as can be seen in figure 4.

The surface is still inhomogeneous after cross wedge rolling. As can be seen in figure 5, the deviation of the outer coating diameter is taken into account in order to re-evaluate the flatness. Between the smallest and largest outer diameter a difference of 0.71 mm is measured. The deviation is calculated to 33.8 % with an average coating thickness of 2.1 mm. The deviation of the coating on the outside is higher than on the inside. The inner diameter differs just about 0.54 mm, which results in a deviation of 25.69 %. For the flatness of the coating on the outside as well as on the inside, the maximum deviations referred to the diameter are taken into account. The coating on the inside has a lower flatness than on the outside. While the deviation of the outer diameter is 2.55 %, it is just 2.47 % for the inner diameter. Caused by the uneven surface geometry, the diameter of the workpiece in the reduced area differs between 23.27 mm and 24 mm. This deviation of the diameter results of the spreading velocity during forming operation, which is defined by the wedge angles of the tool. For a shorter process time, a large wedge angle can be used. However, this increases the risk of forming deviations in the reduced area (e.g. necking).

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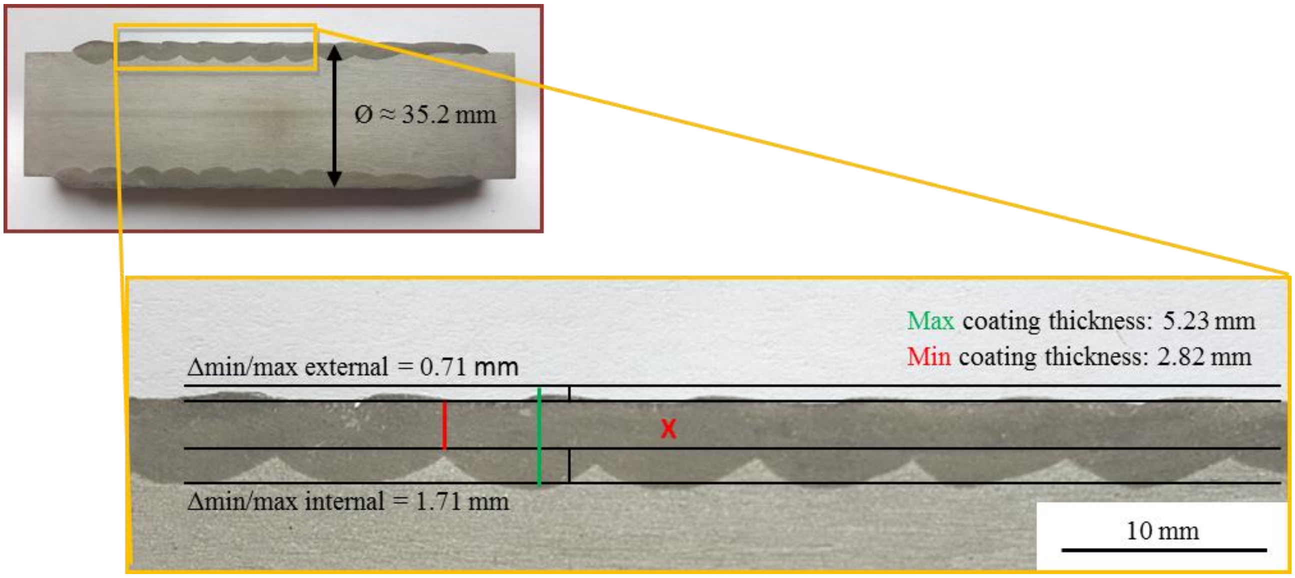

Figure 3: Coating geometry after deposition welding

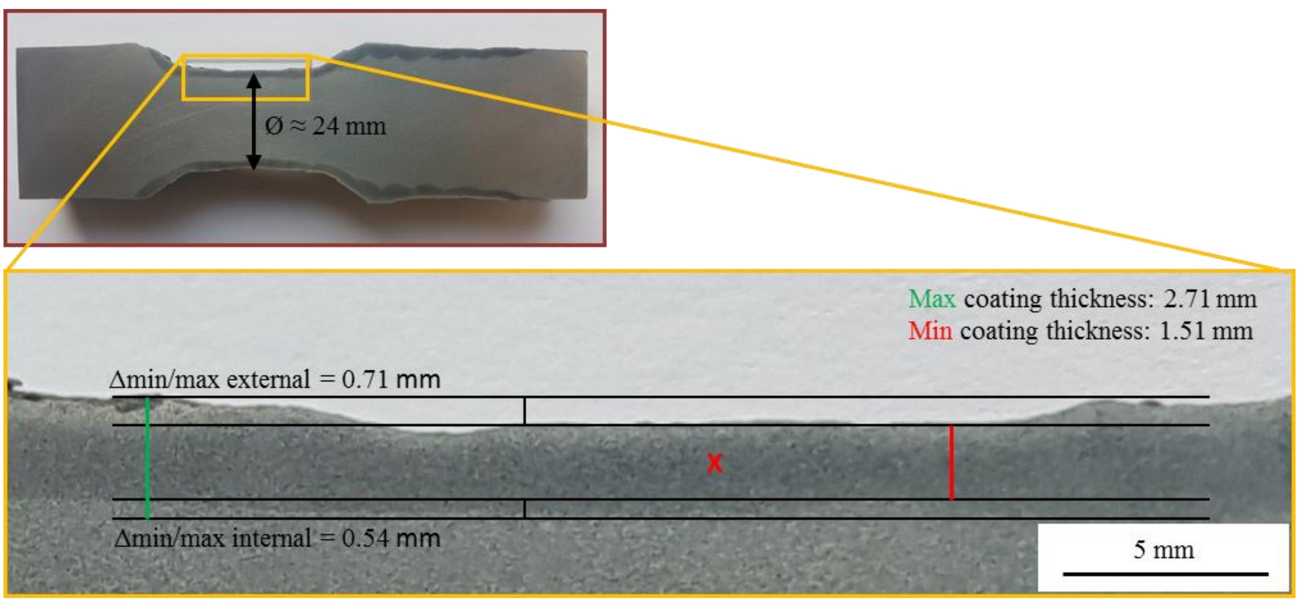

Figure 4: Coating geometry after CWR

The coating flatness on the outside is therefore strongly dependent on the tool angles and the resulting CWR process defect.The structure completely recrystallizes after hot forming. It now consists of uniform round grains of ferrite and bainite (figure 6), which can be described as a classical forming structure.

A lower brittleness and higher ductility compared to the previous weld structure is expected, because of the better distribution and higher homogeneity of the different structural parts.

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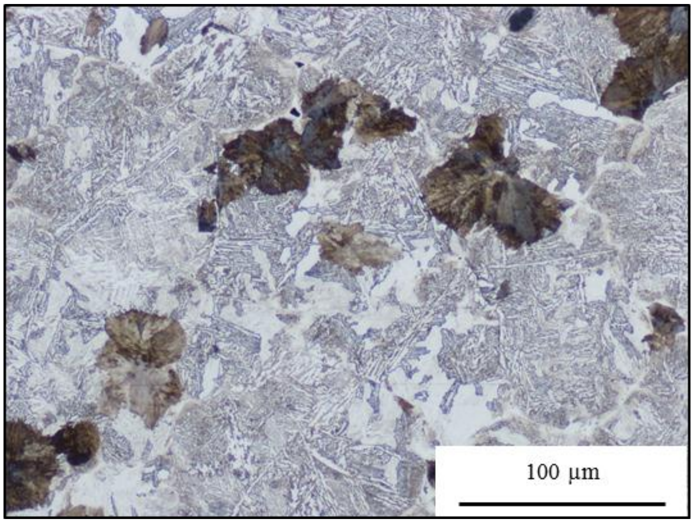

Figure 5: Microstructure of the coating as welded, pointed in figure 3 as X

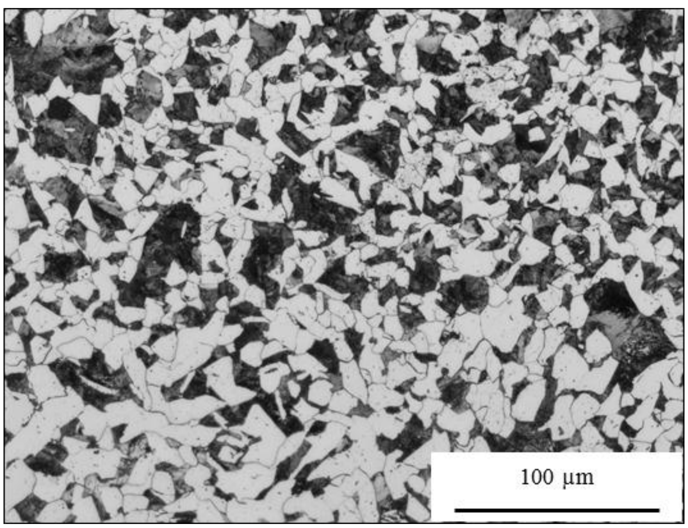

Figure 6: Microstructure of the coating after CWR, pointed in figure 4 as X

V. Hardness

The hardness was measured in Vickers HV 10 with the WOLPERT TESTOR 930/250 hardness tester. The hardness of the coating and the base material were examined after welding and after CWR. The arithmetic mean of ten individual measurements was calculated for one value in table 3.

A hardness drop of 32 % is observed in the coating layer after CWR, while the hardness of the base material does not change significantly.

This can be explained by the strong heat treatment caused by the forming temperature of 1250 °C and due to the structural transformation of the CWR-process. This result lets the forming structure appear to be much better suited for subsequent mechanical processing than the just welded structure. Considering a later tribological application, the formed layer of 41Cr4 seems to allow higher degrees of performance than exclusively welded layers.

TABLE III
Hardness in Vickers HV 10

Condition	Coating	Base material
As welded	324 HV	148 HV
After CWR	218 HV	151 HV

VI. Conclusion And Outlook

The presented work in this paper explains the production of coaxial hybrid parts and subsequent CWR. 1.0402 was used as base material and 1.7035 as coating material. PTA deposition welding was used to apply the coating. Deposition welding creates an inhomogeneous coating along the length of the semi-finished workpiece. An average coating thickness of 4.02 mm was applied which varied from 2.82 mm to 5.23 mm. The flatness in the contact area of the coating material is more fluctuant than on the outside. While the coating diameter on the outside varies about 0.71 mm (2 %), the inner diameter varies about 1.71 mm (5 %).

A welded coaxial semi-finished part was then used for the CWR process. After CWR the coating was optically analysed. The coating thickness varies from 1.51 mm to 2.71 mm after the rolling process. The coating surface on the inside shows a variation of 2.6 % and 2.5 % on the outside. Due to the CWR process, the homogeneity of the coating surface increases and therefore flatness is improved. The coating in the reduced area was smoothed by the forming process so that the coating thickness after CWR only varies by 0.6 mm. It was also shown, that a classical forming structure can be achieved in the deposited layer of 1.7035 after CWR.

For later studies, investigations to improve the individual process steps will be performed. Targets are higher deposition rates during the welding process, higher degrees of deformation in CWR or different material combinations. This could be e.g. hybrid components made of steels with higher carbon equivalents (CEV>0.5), but also dissimilar material combinations as steel and nickel-based alloys.

Acknowledgement

The results presented in this paper were obtained within the Collaborative Research Centre 1153 ‘‘Process chain to produce hybrid high performance components by Tailored Forming’’ in the subprojects A4 and B1. The authors would like to thank the German Research Foundation (DFG) for the financial and organisational support of this project. The authors declare that they have no conflict of interest.

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