Investigation of the composite strength of hybrid steel-steel semi-finished products manufactured by laser beam welding and friction welding

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Abstract. An ever-increasing demand for more effective products with lower weight, more compact design and extended functionality has led to the use of material combinations with locally adapted properties instead of mono-materials. The Collaborative Research Centre (CRC) 1153 "Tailored Forming" at LUH addresses this topic with the aim to develop hybrid bulk-metal components on the basis of a new, tailored production process using joined semi-finished products. In contrast to existing manufacturing processes for hybrid bulk-metal components where the joining takes place during the forming process or at the end of the production chain, CRC 1153 uses tailor-made semi-finished products which are joined before the forming process. This contribution focuses on the production of hybrid semi-finished products from a steel-steel (C22.8 and 41Cr4) material combination by means of laser beam as well as friction welding. The effects of additional ultrasonic coupling into the weld-pool are presented for laser beam joining and a positive effect on the weld pool was observed. Furthermore, the resulting properties of the joining zone are investigated by uniaxial tensile tests at room temperature and metallographic analyses of the respective manufacturing processes. The friction welding proved to be a very robust process for the production of semi-finished steel-steel products.

1 Introduction and motivation

The desire for a reduced resource usage and an increased component as well as production process efficiency gives rise to an enhanced demand for adapted components and adjusted processes. These components need to offer locally customized areas for different stresses and load conditions. The use of more expensive, more difficult to process and higher alloyed steels can be reduced in combination with lower grade steels. For this approach, a joining process for the two similar materials has to take place. High material thicknesses, inconvenient component geometries and materials which are difficult to weld represent a challenge for the joining process. High carbon contents of the hardenable steel lead to hot cracking susceptibility for thermal welding of these steels. The use of ultrasound during welding is an approach to reduce this behavior due to the vibrations impact on the melt. The impact of the ultrasound amplitude on the shape of the weld reinforcement, the crack area and the hardness peak value in the weld was shown before [1]. This indicates the ultrasound assisted laser beam welding as an appropriate method for joining hot cracking susceptible steel grades in dissimilar joints. This procedure is compared with the manufacturing process friction welding in this research contribution.

1.1 Laser beam welding

Laser beam welding offers some advantages compared to other fusion welding processes. There are, for example, the localized heat input, the resulting narrow weld and heat affected zone, low thermal distortion and the good automation capability. High material thicknesses can be joined. Regarding sheet metal, stainless steels up to 20 mm with 16 kW laser power were welded. For round bars, the heat conduction and distribution is significantly different, so a transfer and comparison of the sheet metal process is not simple. The effects of ultrasound or vibration in common for welding processes were shown before for different materials as example steel [1], aluminum alloys [2-4] or nickel base alloys [5]. The results are grain refinement [2], reduced hot cracking [2] and an increase of the mechanical characteristics. Large dendrites are fewer [5], the grains are orientated more randomized and hardness levels are lower, furthermore there is an effect on the residual stress level [5]. The methods of generation of vibration are the direct introduction with tungsten plunger [6] or electrodynamic shaker [3] or indirect introduction (sonotrode [6] or piezoelectric transducer [2]).The frequencies investigated reach from low frequencies (48 Hz [5]) to ultrasound (20-40 kHz [6]). For EN AW-6082, there was shown an influence depending on the position in the waveform and amplitude of the ultrasonic with the system used [4]. The grain refinement is depending on the seam depth [3].

1.2 Friction welding

The friction welding process, which has gained much importance in recent years, is one of the press welding processes. In this process, the materials are joined together by plastic deformation. The heat required for the formation of welded joint is generated by the friction arising as a result of the rotation of one workpiece against the firmly fixed joining partner as well as due to the pressing force acting on the workpieces. Thus, this process is of particular advantage not only for the application of similar materials but also for the welding of material combinations, which cannot be joined by the application of other welding processes. Due to the temperatures just below the liquidus limit, the resulting recrystallization, the high compressive stresses as well as the resulting intensive material deformation, a very fine-grained microstructure with particularly good static and dynamic mechanical properties can be achieved. In contrast to fusion welding, almost pore free joints can be produced by this process. The relatively shorter heating time, as compared to the fusion welding, leads to a very small expansion of the heat affected zone and limits the thermally induced, undesirable structural changes of the base material only to a narrow area around the joining zone. [7]

2 Experimental setup

2.1 Materials

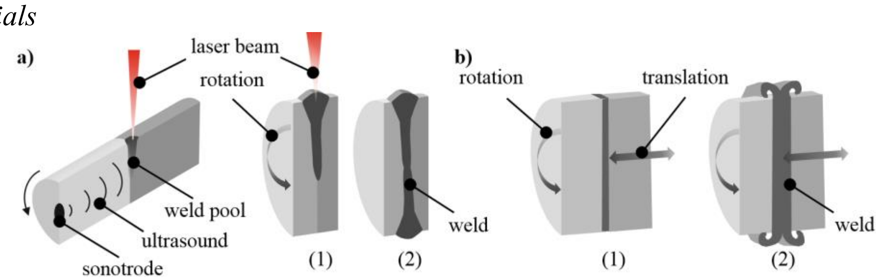

Figure 1. Schematic drawing of the specimen geometries in cross section during (1) and after (2) welding: a) laser beam welding; b) friction welding

Two steels are examined in this contribution. C22.8 (1.0460) is an unalloyed steel, the second steel 41Cr4 (1.7035) has an maximum equivalent carbon content of 0.840. 41Cr4 has a higher tensile and yield strength and is hardenable as compared to C22.8. Specimens are used in the form of round bars

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with a diameter of 30 mm. The joint shape is a butt weld. Figure 1 shows a schematic drawing of the sample geometries cross sections during and after welding for both processes.

2.2 Manufacturing of semi-finished hybrid components by ultrasound assisted laser beam welding and friction welding

2.2.1 Ultrasound system. The ultrasonic assisted welding system was developed to enable an ultrasonic assisted laser beam welding process. To ensure the desired vibration distribution, which is a longitudinal vibration at 20 kHz, sonotrodes for the specimens used are designed. The combination of the sonotrodes and the specimens lead to a longitudinal vibration resonance frequency of 20 kHz, where the connection of the specimens is located in the vibration maximum. To validate the vibration behaviour, the amplitude along the specimens is measured utilizing a laser-doppler-vibrometer with an in-plane setup. Additionally, the dependency between the vibration amplitude in the vibration maximum and the current at a second short circuited measurement transducer at the end of the vibration system is measured. The measured current at this transducer is used to control the vibration amplitude to the desired value. In addition, the vibration amplitude at the driving transducer is measured during the welding process to monitor the vibration amplitude behaviour during the process.

2.2.2 Laser beam welding system. The laser beam source used is a diode-pumped, solid-state disk laser with a maximum power output of 16 kW. The diameter of the optical is with 200 µm, the focal length of the collimation lense is 150 mm, focal length of the focusing lense is 300 mm) and the resulting focal diameter is 400 µm. The beam is not positioned on the vertex of the sample to avoid the formation of droplets by extending the time for solidification in order to realize a full penetration weld. The position of impact of the laser beam is moved rotationally by 6 mm, corresponding to the circumference of the sample, there is an angel of 20° to realize a still perpendicular angel of incident of the laser beam. Argon is used as process gas via two gas nozzles to shield the surface and to blow away the metal vapor. The samples were welded with ultrasonic vibration amplitudes of 0 µm and 3 µm. Laser power is 8.0 kW, welding speed 0.95 m/min.

2.2.3 Friction welding system. For the production of the steel-steel semi-finished products, the "Genius Plus" friction welding machine of the company Kuka, which is available at the IFUM, was used. The semi-finished products to be joined were placed in the friction welding machine in a slide and spindle clamp. A rotational movement of the spindle and a translational displacement of the slide caused both metallic semi-finished products to glow at the end faces due to the frictional heat. Both components were thus welded together by breaking the rotating semi-finished product and pressing under an increased force of the stationary semi-finished product.

3 Results and discussion

3.1 Ultrasonic system evaluation

To ensure that the position of the connection is at a vibration maximum, the vibration distribution along the workpieces is measured. Figure 2 a) depicts the vibration amplitude $\hat{x}$ along the workpieces. The distribution verifies that the designed sonotrodes lead to a vibration maximum in the joining zone of the two workpieces. In a further investigation, the dependency between the measured current at the sensor transducer and the vibration amplitude in the vibration maximum is measured for the pre welding condition. The results are shown in Figure 2 b). The dependency is approximately linear in the range up to 7 µm at 400 mA. The measured current used to control the vibration amplitude during the welding process. In addition, the vibration amplitude is monitored during the welding process and depicted in Figure 2 c) for an exemplary weld. It shows a nearly constant behavior, so the influence of the vibration is expected to be constant throughout the welding duration.

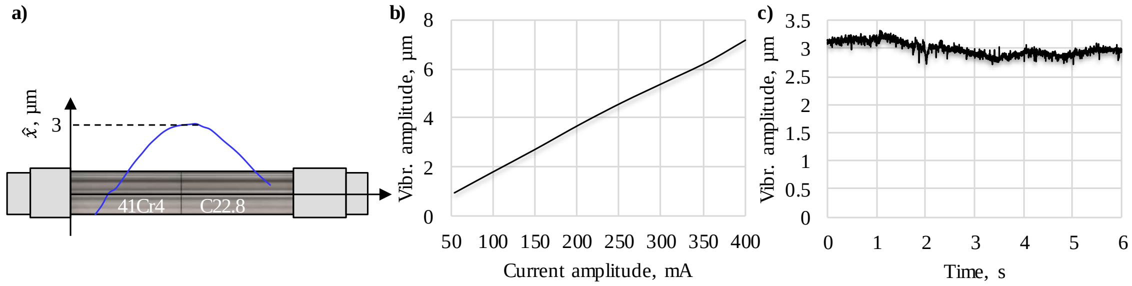

Figure 2. a) Measured vibration distribution along the workpieces b) dependency between vibration amplitude and measured current amplitude at measurement converter c) measured vibration amplitude during welding process

3.2 Metallographic analyses

Before a metallographic analysis of the three finished hybrid semi-finished products could be carried out, corresponding longitudinal sections of the respective samples were prepared. After the specimens had been set in place and then ground as well as polished, the specimens were etched in order to visualize and identify the grain boundaries as well as all microstructural constituents of the samples. Three longitudinal sections are shown in the figure 3: a) laser welding without the ultrasound system (LWwoUS); b) laser welding with the ultrasound system (LWwUS) and c) friction welding (FW).

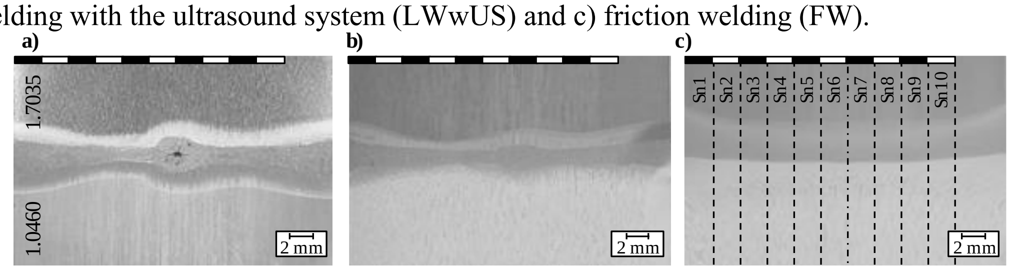

Figure 3. Longitudinal grinding of hybrid semi-finished products according to: a) LWwoUS; b) LWwUS; c) FW

The micrographs in the figure 3 show the influences of the respective manufacturing processes. The advantage of ultrasound during the welding process can be seen in micro-sections shown in figure 3 a) and b). Figure 3 a) shows clear defects, such as pores and micro cracks, in the center of the sample. With the help of ultrasound, as already described in the state of the art, the weld pool is positively influenced. This leads to an improved mixing of the weld pool, thus resulting in a significant reduction in the formation of flaws and micro cracks. After the manufacturing process, very similar heat-affected zones exist in both the methods. Due to the profile of the laser beam, these vary significantly across the cross-section of the sample. In the outer area as well as in the center of the sample, the materials are subjected to very high thermal stress. The friction welding process (Figure 3 c), on the contrary, has a very homogeneous heat-affected zone across the cross-section. This is also quite low due to the very short heating time of a few seconds. As a result, the undesirable structural change of the base materials takes place within a few millimeters around the joining zone. Micro hardness measurement is used to determine the condition of a material and its microstructure components. The hardness measurement was carried out based on the Vickers test with a four-sided diamond pyramid indent. The hardness of the three samples was respectively measured at 26 points at the edge as well as in the middle of the sample. Figure 4 shows the hardness profile depths of the three samples a) - c). The metallographic analyses can be confirmed on the basis of the hardness depth gradients. On the one hand, due to defects and micro-cracks in the center of the semi-finished product a), lower hardness values were determined. On the other hand, the undesirable structural changes of the heat-influenced zones are significantly more pronounced in semi-finished products a) and b) than in semi-finished product c). This expansion extends to 4-5 mm for laser-welded semi-finished products, whereas in the case of friction-welded semi-finished products, it is limited to 2-3 mm. The hardness values for all three processes are at a very similar level.

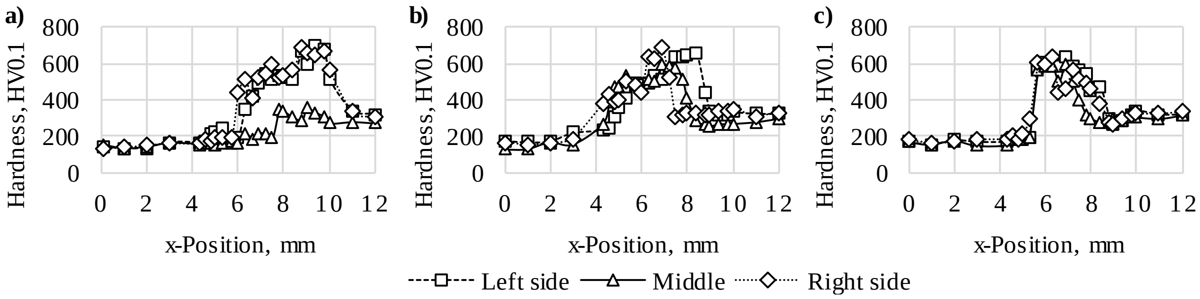

Figure 4. Hardness gradients of the hybrid semi-finished products: a) LWwoUS ; b) LWwUS; c) FW

3.3 Mechanical characteristics

In order to determine the critical thermomechanical stresses that lead to failure of the joining zone, the resulting joining zones were characterized analogous to Behrens et al. [8] and uniaxial tensile tests were performed. The determination of the bond strength of the hybrid components was initially carried out globally, i.e. the largest possible cross-section of the joining zone surface was tested by means of tensile tests. For this purpose, the global tensile specimens were prepared from the semi-finished products by machining. Due to the fact that the joining zone varies depending on the manufacturing process, local joining zone investigations were subsequently carried out. Therefore, ten small flat tensile specimens (Specimen number (Sn) 1 to 10), at every 2 mm along the cross-section of the hybrid semi-finished products, see Figure 3 c), were prepared analogous to the method described in [8] by wire erosion. With the help of the smaller test specimens, it was possible to evaluate the entire joining zone area locally. These tests were repeated thrice for each of the hybrid components. Figure 5 a) shows the results of the global bond strength. The determined composite strengths of the three different hybrid semi-finished products are on a similar level after a repetition of 5 tests. However, the friction welded semi-finished products exhibit the lowest values of scatter during the tests (Figure 5 a)).

In order to assess the bond strengths of the respective semi-finished products in further detail, the results of the local bond strengths at room temperature (exemplarily for one hybrid component) as well as those of the two mono-materials are shown below (Figure 5 b - c). To determine the mechanical properties of the joined hybrid semi-finished products, tensile specimens were prepared by wire erosion from the respective semi-finished products, as shown in Figure 3 c). Thus, it is possible to clearly describe the influence of specimen on the cross-section of the respective semi-finished products. The center of the respective semi-finished products lies between specimen numbers 6 and 7.

The results of the composite strengths of the laser-welded semi-finished products (with as well as without ultrasound) show a very similar course. Both are characterized by a strong decrease of the bond strengths in the center. In the case of LWwoUS, the bond strength decreases to 330 MPa. Whereas, with ultrasonic coupling, bond strengths of 505 MPa can be determined. The bonding strengths of hybrid components are higher than the tensile strength of the mono-material 1.0460 (see Figure 5 c). The decrease in the bond strength can be attributed to defects and micro-cracks. As described above, ultrasound is used to better mix the weld pool, thus minimizing the formation of flaws. The wave-like course of the bond strength can also be attributed to the formation of the weld seam: The thicker the weld, the greater is the bond strength. The results of the bond strength of friction-welded semi-finished products can confirm the positive properties described in section *3.2*. The very homogeneous heat-affected zone is reflected in the very uniform results of the bond strength. In this manufacturing process, there is no reduction in bond strength due to defects. In all tensile tests, with the exception of tensile tests with specimens 6 and 7, the specimens for the mono-material 1.0460 have experienced a failure. The joining zones have withstood the tests. On the contrary, the failure occurred in the joining zone for the case of the laser beam welded semi-finished products with and without ultrasonic coupling (specimens 6 and 7) due to the defects in the center. Disregarding these samples, the maximum strength of the laser welded samples is a little higher than the strength of the friction welded samples.

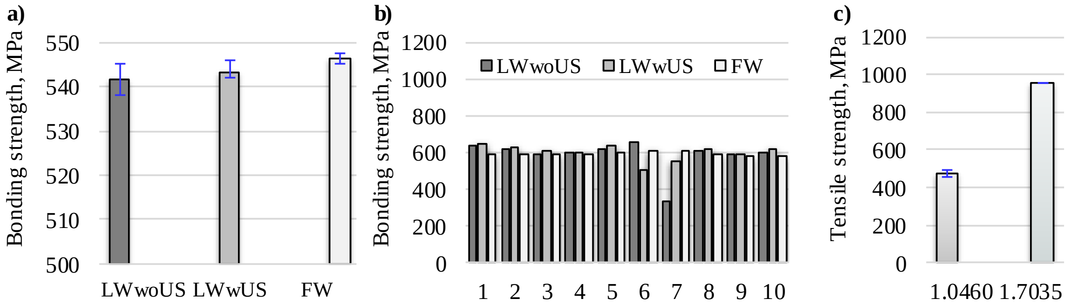

Figure 5. a) Determination of the global bond strengths; b) The bond strengths of the hybrid semi-finished products; c) tensile strengths of the mono materials according to the literature [8]

4 Summary and Outlook

In this contribution, the hybrid semi-finished products used in the CRC 1153 for the production of a hybrid shaft were characterized. The production is carried out by two different forming processes, a cross wedge rolling and a full forward extrusion and will be presented in a future contribution. With these forming processes, it is of utmost importance that the semi-finished products are not damaged or have internal defects in advance. Based on the metallographic analyses and the results of the tensile tests to determine the bond strength, various manufacturing processes have been compared with each other. The additional coupling of an ultrasound during laser beam welding had a positive effect on the weld pool, so that the previous internal flaws and micro-cracks were significantly reduced. The friction welding process proved to be a very robust process for the production of semi-finished steel-steel products. The local bond strength was very uniform and the failure always occurred in the base material of the 1.0460. Further investigations aim to the reduction of the defects in the laser welded samples with refined ultrasound usage to homogenize the strength.

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