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Investigation of strategies to prevent crack formation in the hybrid-additive manufacturing process of tool components using directed energy deposition

Eike Tim Koopmann[1*] · Giuseppe Zaffino[1] · Christoph Kaminsky[1] · Henning Zeidler[2]

(1) Mercedes-Benz AG, D-71059 Sindelfingen, Germany
(2) Institute for Machine Elements, Design and Manufacturing, TU Bergakademie Freiberg, D-09599 Freiberg, Germany

* eike_tim.koopmann@mercedes-benz.com

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Abstract
The ever-increasing variety of products and variants in the automotive industry requires a high degree of flexibility in production processes. In this context, additive manufacturing processes offer a promising approach. In the area of toolmaking, the directed energy deposition process (DED) is currently used for surface repairs and geometry modifications. Moreover, the hybrid-additive manufacturing of tool components represents a novel approach to a cost-effective and resource efficient production. A major challenge is the heat input into the component, as this impairs the contour accuracy and leads to the formation of cracks in the bonding zone. The aim of this paper is to develop an optimized manufacturing strategy to minimize residual stresses and therefore cracks in the bonding zone. In this context, welding specimens with an adapted laser power are additively manufactured. Furthermore, the geometry of the welding specimens is adjusted to minimize notch stresses in the first layers. The specimens are analyzed metallographically to determine the formation of cracks in the bonding zone. Finally, the results are used to manufacture a hybrid-additive tool component.

Keywords Directed energy deposition · Additive manufacturing · Tool components · Crack formation

1. Introduction and motivation

In the current dynamic market, the demand for customized products is constantly growing. To meet this demand for individuality, car manufacturers must design the product development process as flexible as possible [1]. From today's perspective, this target cannot be achieved by using only conventional manufacturing processes [2]. For this reason, additive manufacturing processes have become more and more established in recent years [3]. Due to the possibility of near net shape production, they offer an almost complete, flexible design of the component geometry and a low consumption of materials [4]. They are also characterized by high cost-effectiveness despite small lot sizes and the flexibility to implement geometry changes in new products [5].
The additive manufacturing processes directed energy deposition (DED) and powder bed fusion (PBF) have also found a wide range of applications in modern toolmaking especially in the area of processing forming dies over the past few years [6,7]. The high forming forces during the production process of automotive sheet metal components in combination with a short cycle time between the individual pressing sequences lead to high material stresses and wear on the tools [8]. The worn tools are not replaced but repaired instead, to achieve higher efficiency through time and cost savings [2]. For this purpose, new material is applied on the worn areas using the DED process and the original geometry is then reproduced by milling [9]. Besides the repair of forming dies, the DED process also offers the possibility of making major geometry changes to the tools [10]. Additionally, the PBF process allows tool components with complex canal designs to be manufactured in a single step without the need of a subsequent drilling process and a small post-processing effort [11]. Furthermore, the use of the PBF process in

combination with a topology optimization reduces the weight of forming tool components by up to 20 % while achieving almost the same mechanical strength [12]. However, the DED process offers several advantages compared to the PBF process, as several different metals can be processed with an almost unlimited component size or functionally graded materials can be created [13]. This allows the required hardness and strength properties to be generated for the desired application [14].

Forming tools as well as their components have a limited weldability due to the high carbon content in the material [15]. With the cold work steel 60CrMoV18-5 (1.2358), 10 layers of a quadratic specimen with a porosity of less than 0.5 % could be welded onto a substrate plate of the material X37CrMoV5-1 (1.2343) using the DED process [16]. In this case, there is a correlation between the particle size range of the powder used and the occurrence of cracks and increased porosity [16]. Furthermore, square structures of the hot-work tool steel X3NiCoMoTi18-9-5 (1.2709) with an edge length of 15 mm have already been welded defect-free onto a substrate of the material 1.2343, which also reaches the strength and hardness requirements of a forging tool [7]. In addition, a hybrid-additively manufactured forming tool with an active forming element made of the hot-work tool steel X37CrMoV5-1 (1.2343) could be used in series production, but cracking occurred in the bonding zone during the DED process [17]. The component had to be replaced after 50 % of its lifetime due to edge deformation and wear on the active element [17]. Another approach to avoid cracking in the manufacturing process of tool components is the carbon-martensitic hot work steel X45CrMnMoNiSi6-3-3-1-1 (X45), which was used as powder feedstock to weld 10 rectangular layers with low porosity and crack density [18]. The required tool hardness was reached with 693 HV30 by quenching and tempering [18].

A high carbon content leads to the formation of martensite in the heat-affected zone, resulting in material hardening and cracking due to stresses that arise during the cooling process [15]. With increasing build-up height and therefore increasing volume, the residual stresses in the component also increase, which is a significant reason for crack formation [19].

In the DED process, there is a correlation between defect formation and the energy density applied during the welding process [20]. Insufficient energy input per area results in an insufficient bonding of the melt and the solid, which favours the formation of cracks [20]. With an increased energy input, the overlap of the tracks as well as the size of the melt pool are also increasing, which leads to a higher dilution and a reduction of cracks in the bonding zone [21]. In higher layers, the heat dissipation decreases, which means that a sufficient temperature in the melting pool and therefore a sufficient dilution can be achieved with less energy input [21].

Cracking in the bonding zone could also be reduced in the DED process when welding 5 layers onto the EN-GJS-HB265 substrate with a carbon content of 3.6 % by using a so-called step, which is a first layer with a larger dimension [22]. By increasing the number of steps in the welding specimen, the stresses could be distributed more equally and the formation of cracks could be reduced further [22].

Another approach for the prevention of cracks is to preheat the substrate, which reduces hardening in the heat-affected zone [23]. By preheating the substrate, slower cooling rates and lower temperature gradients are also achieved, which leads to a reduction of martensite and so to a reduction in crack formation [8]. A post-heat treatment also enables a controlled cooling of the component, so that formation of martensite can be reduced as well as residual stresses can be minimized [24,25].

In this paper, an additive build-up of 45 layers with the feedstock material 3.33 LOWC on the cold work steel 1.2333 is manufactured by using DED. Geometric modifications of the welding specimen and a variation of the laser power are used to improve the bonding quality and solve the problem of crack formation. Based on the results, a defect-free tool component is produced in a hybrid-additive manufacturing process.

2. Experimental procedure

2.1. Material

The cold work steel G59CrMoV18-5 (1.2333) from Dörrenberg Edelstahl with a carbon content of 0.6 % is used as substrate material. Due to its good weldability and hardening properties, this material is used to produce cutting, forming and deep-drawing tools [11]. The powder feedstock 3.33 LOWC from Höganäs is used for the additive build-up. With a carbon content of 0.2 %, a powder particle size of 45 to 150 µm and a nickel content of 16 % the powder material 3.33 LOWC is suitable for a crack-free deposition on materials with a high carbon content. Current applications include geometry modifications and the repair of functional surfaces on tools [22]. The chemical compositions of the powder feedstock and the substrate material are shown in Table 1.

Table 1: Chemical composition of substrate and powder feedstock for the directed energy deposition process

Chemical elements (wt.-%)	Fe	C	Cr	Ni	Mo	Mn	Si	V
1.2333	Bal.	0.6	4.5		0.5	0.8	0.4	0.2
3.33 LOWC	Bal.	0.2	28	16	4.5	0.65	1.2	

2.2. Robotic system set-up

The multifunctional laser beam hardening and cladding system HARD+CLAD, provided by ERLASER, is used for the DED experiments. A continuous wavelength diode laser LDF 4000-40, provided by Laserline GmbH, with an emission wavelength of 900-1100 nm and a maximum output power of 4000 W is used as laser source. The laser head uses a facetted mirror to focus the laser beam with a diameter of 3.5 mm on the surface of the substrate. The collimation and focusing focal lengths are kept constant at 182 mm and 350 mm throughout all experiments. The laser head and the 3-jet powder nozzle 3-Jet-SO12-S, manufactured by Fraunhofer ILT, are attached to a KUKA KR480 R3330 MT 6-axis robot system with a tilt-turn table and linear unit. Argon is used as shielding gas for the melting pool and for powder delivery. For all experiments, the feeding gas volume flow rate of 5 litres per minute and the shielding gas volume flow rate of 5 litres per minute are kept constant throughout all experiments. The powder feed unit PF 4/4, manufactured by the GTV Company, is equipped with 4 different powder pots and ensures a constant powder mass flow.

2.3. Methodology

Avoiding the formation of cracks in welding specimens by adjusting the laser power and the specimen geometry is the main focus in this work. The initial geometry is shown in Figure 1a, where the dimensions of the welding specimens are given as 32.5 x 32.5 x 45 mm^3. A layer is generated with a meandering fill pattern and a single-track offset of 1.6 mm, which corresponds to 50 % of the single-track width. In addition, an outer contour track is used to increase the contour accuracy. The laser power of 2000 W, the scanning speed for the experiments of 19 mm/s, the powder mass flow of 17.9 g/min and the powder focus distance between the laser head and substrate of 12 mm are kept constant. A z-offset of 1.00 mm is used for the multilayer build-up, whereby each layer is rotated by 90 degrees around the z-axis in comparison to the previous layer to increase the contour accuracy of the additive build-up. In the first step, the constant laser power of 2000 W is adjusted as shown in Figure 1b. The laser power P_{Start} in the first three layers is varied in the range from 2200 W to 3000 W to achieve a higher dilution in the bonding zone between substrate material and additive build-up. For the remaining 42 layers, the laser power is kept constant at 2000 W to reduce the thermal load on the welding specimen. Based on this, a geometric modification is made on the first layer (Figure 1c) aiming to distribute occurring stresses in the welding process more equally. The first layer is enlarged up to a base area of 35.7 x 35.7 mm^2, whereby the laser power P_{Start} in the first three layers is varied from 2200 W to 3000 W in different experiments. One more step is added to the specimen geometry in Figure 1d) to further reduce the occurring stresses in the welding process. By adding this modification, the first layer is enlarged to a base area of 40.5 x 40.5 mm^2, while the second layer is scaled up to an area of 35.7 x 35.7 mm^2. The dimensions of the following layers are not adjusted and correspond to the initial geometry. In preliminary experiments it is shown that pre- and post-heating the substrate reduced the temperature gradient between the substrate and the additive build-up, which has a positive effect on the prevention of crack formation in the bonding zone. The substrate is therefore pre-heated at 280 °C. After the manufacturing process, the entire component is post-heated at 280 °C for 2 hours. The results of the preliminary experiments are shown in Figure A1 and A2 in the appendix.

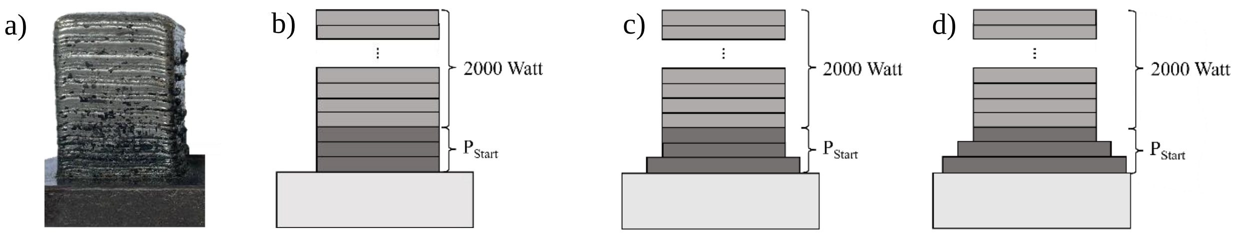

Figure 1: Geometry of the welding specimens (a, b) without steps, (c) one step and (d) two steps

The results are used to produce a hybrid-additive manufactured tool component. Figure 2a shows a punch that is used as cutting segment in a forming tool for the production of automotive body parts. The tool component has a base area of approximate 60 x 60 mm^2 and a maximum height of 47 mm. The process parameters from Figure 1 are used for the additive manufacturing process of the component, where the substrate is pre- and post-heated for 2 hours at 280 °C. It is also possible to apply a harder material in the area of the cutting edge to increase the wear resistance [14]. Figure 2b shows the tool component after the manufacturing process without modifications, where a crack formation in the bonding zone can be observed. A crack formation can also be observed in three additional manufactured tool components.

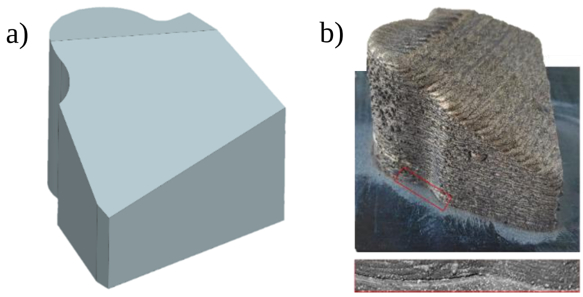

Figure 2: Tool component for shear cutting operations (a) CAD geometry and (b) hybrid-additively manufactured before milling with crack formation in the bonding zone

2.4. Characterization

Using wire eroding and cut-off grinding, the welding specimens are prepared for the metallographic analysis. After warm embedding, the specimens are ground in a multi-stage process and polished in a three-stage process with a diamond suspension of grain sizes of 9, 3 and 1 µm. Etching with a 3 % Nital solution is then conducted to determine the heat-affected zone. The procedure of the metallographic analysis is shown schematically in Figure 3.

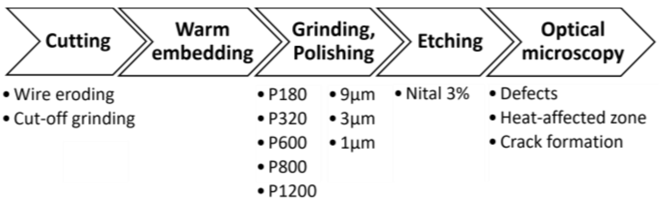

Figure 3: Metallographic analysis procedure of the welding specimens

The cross-sections of the specimens are examined using optical microscopy in combination with the software Stream Enterprise from Olympus to identify geometric quantities, defects and crack formation.

3. Results and discussion

A defect-free additive manufacturing process is an important requirement for series production. Two key factors are a low porosity and a crack-free component [20]. In this work, a maximum limit of 0.1 % is set for porosity. In the welding specimen with a constant laser power of 2000 W, a porosity of 0.033 % is measured. Figure 4 also shows the bonding zone of the additively manufactured specimen with a constant power of 2000 W. Along the transition zone of the substrate 1.2333 and the feedstock material 3.33 LOWC, an almost horizontal, continuous cold crack is detected, which indicates an insufficient bonding quality of the materials. The same result is observed in three additional welded specimens.

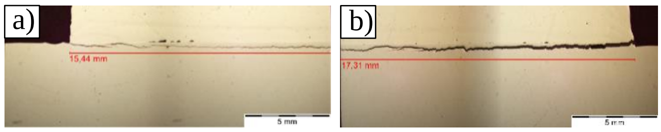

Figure 4: Cross-section of the bonding zone of a welding specimen with P_{Start} 2000 W (a) left side and (b) right side

To analyse the bonding, individual tracks are welded with a laser power between 2000 W and 3000 W. Furthermore, each track is welded four times to achieve a reliable result. A higher laser power in combination with a constant scanning speed leads to a greater dilution of the substrate and the additive build-up, so crack formation can be inhibited [21]. The limit for dilution recommended by Fahrenwaldt et al., which is defined as the ratio of melted substrate and welded material, is given as 30 [26]. The results are shown in Figure 5 using cross-sections of the welding tracks with 2000 W, 2400 W and 3000 W laser power. For a laser power of 2000 W, the dilution ratio varies from 19.26 to 19.92. An increase of the laser power to 2400 W leads to an increased dilution ratio between 29.22 and 29.89. The critical limit is exceeded at 2600 W while the highest dilution ratio of 34.46 to 35.22 is measured at 3000 W.

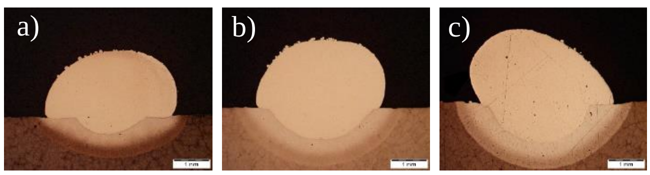

Figure 5: Cross-sections of the welding tracks with a laser power of (a) 2000 W, (b) 2400 W and (c) 3000 W

The effect of increasing the laser power P_{Start} for the welding specimen in Figure 1b is shown in Figure 6. The initial crack length of 32.75 mm is reduced to 17.56 mm on average by the increased laser power of 2200 W and a higher dilution. A further improvement in crack formation is not achieved by a higher laser power P_{Start} of 2400 W and 2600 W, as crack lengths of 17.53 mm and 17.77 mm are measured. The shortest crack length of 9.85 mm on average is measured at the laser power P_{Start} of 2800 W. For 3000 W, a crack with a length of 15.27 mm is observed, so the crack issue in these experiments cannot be solved by only adjusting the laser power.

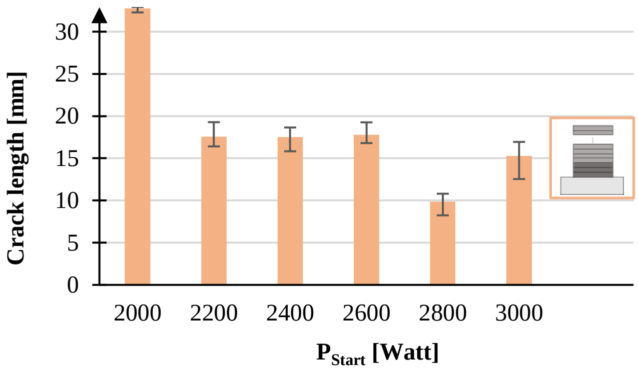

Figure 6: Crack length of the specimens without step depending on the laser power

Despite the reduction of crack formation in the bonding zone, a defect-free build-up is a basic requirement for the hybrid-additive manufacturing process of tool components [14]. To reduce the notch stresses between the additive build-up and the substrate, the welding specimens are geometrically modified. While the number of layers is kept constant, the first layer of the welding specimens is modified to reach an equal distribution of stresses (Figure 1c). The effect of a step in combination with a higher laser power P_{Start} on the formation of cracks is shown in Figure 7.

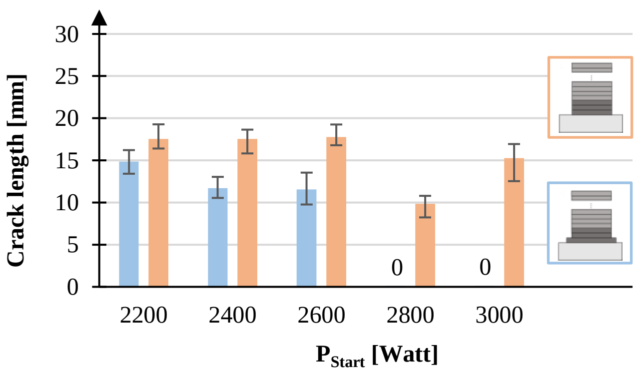

Figure 7: Comparison of the crack length of the specimens with one and without a step depending on the laser power

A reduction in crack formation is observed for both welding specimens at a laser power P_{Start} of 2200 W. In comparison, the crack length is reduced by 2.69 mm on average up to 14.87 mm for the welding specimen with one step. A positive effect of the added step can also be detected for the laser powers P_{Start} of 2400 W and 2600 W, even if cracks with a length of 11.57 mm and 11.72 mm on average cannot be prevented. A crack-free build-up of the welding specimen is achieved at a laser power P_{Start} of 2800 W in combination with one step. Furthermore, no cracks are visible in the bonding zone at a laser power P_{Start} of 3000 W. With the aim of using the laser power as efficient as possible, the geometry of the welding specimen with one step and the laser power P_{Start} of 2800 W is defined as reference for further experiments.

There are two additional key factors in additive manufacturing processes, namely economic efficiency and production time [20]. Productivity is primarily reduced by pre- and post-heating times of the substrate, which prevents residual stresses in the component [8,25]. The substrates are preheated at 280 °C for 2 hours in all experiments to minimize the temperature gradient between the welding material and the substrate. The addition of a second step (Figure 1d) is used to examine if preheating remains a necessary factor. No cracking is detected in the bonding zone of the four welded specimens after the metallographic analysis, as the cross-section in Figure 8 shows for example.

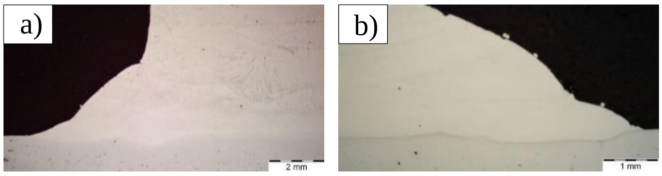

Figure 8: Cross-section of the bonding zone of the welding specimen with P_{Start} 2800 W and 2 steps without preheating (a) left side and (b) right side

The results are used to produce a complex, hybrid-additive manufactured tool component. A laser power of 2800 W is used for the first three layers, while the higher layers are welded with 2000 W. The tool component from Figure 2 is geometrically modified by using one step. As investigated in previous experiments, the substrate is pre-heated at 280 °C, while the welded tool component is post-heated for 2 hours at 280 °C. The manufacturing result before milling is shown in Figure 9a, where a crack can be observed between the first, larger layer and the unmodified additive build-up. The same result is also observed in three additional welded tool components. In general, there is a higher potential for cracking, particularly at edges and corner areas, due to the increased stress concentration [25].

A second manufacturing process is conducted with the same set of parameters and two steps due to the larger welding mass of the tool component compared to the specimens from Figure 1. The result is shown in Figure 9b, where no cracks are visible in the bonding zone of both materials and in the rest of the component. Based on this result, it can be demonstrated for three additional welded tool components that increasing the number of steps leads to a reduced stress concentration in the component, so crack formation can be avoided entirely.

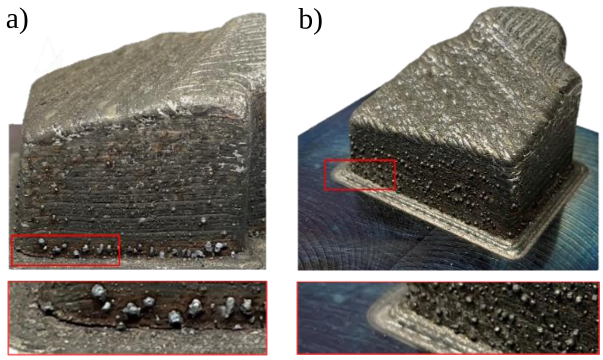

Figure 9: Hybrid-additively manufactured tool component before milling with (a) one step and (b) two steps

4. Conclusion and outlook

The aim of this paper is to develop strategies to prevent cracking in the hybrid-additive manufacturing process of tool components using DED. In that context, welding specimens are additively manufactured onto the cold work steel 1.2333 and the bonding zone is examined metallographically. The crack formation is reduced by increasing the laser power in the first three layers due to the greater dilution ratio. The best possible result in these experiments is achieved at a laser power P_{Start} of 2800 W with a crack length of 9.85 mm. By geometrically modifying the first layer of the welding specimens, residual stresses are decreased and crack formation is reduced. In combination with a laser power of 2800 W in the first three layers, cracking is completely prevented and the requirement of a defect-free additive build-up is achieved. Furthermore, using a second step ensures a crack-free production of the welding specimen without preheating the substrate. The process parameters of the welding specimens are used as reference for the hybrid-additive manufacturing process of a tool component. Pre- and post-heating the substrate is also conducted due to the larger mass of the geometry. When using an initial power P_{Start} of 2800 W and one step, cracking is observed on edges with a small radius. The usage of two steps results in a defect-free additive build-up of the tool component.

In further investigations, the production of a larger tool component by using DED with a base area of 100 x 100 mm^2 and a height of 90 mm will be examined to expand the area of applications for toolmaking. By systematically modifying the geometry in the first layers and adjusting the laser power, the residual stresses in the component are going to be reduced and a crack-free additive build-up is going to be ensured. In addition, the effect of the pre-heating and post-heating process on the crack formation will be analysed to further minimize residual stresses in the component.

5. Appendix

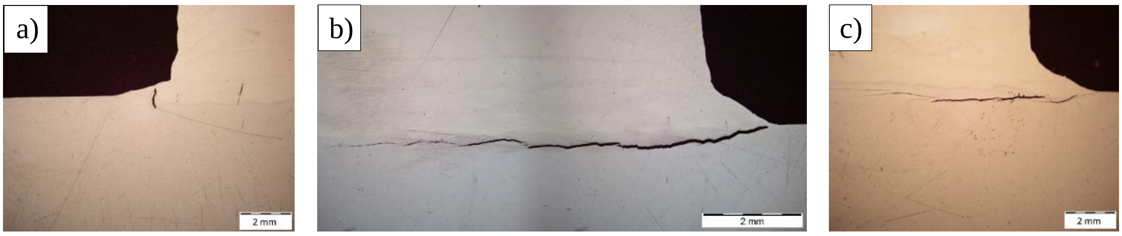

Figure A1: Cross-sections of welding specimens with crack formation and a laser power P_{Start} of 2800 W with (a) only pre-heating, (b) no pre- and post-heating and (c) only post-heating

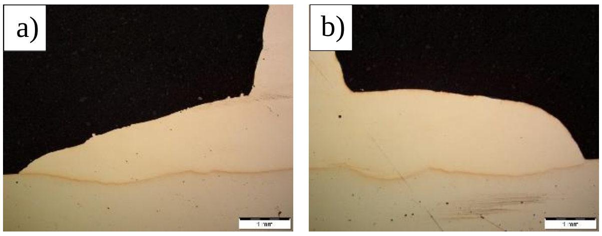

Figure A2: Cross-section of a defect-free welding specimen with a laser power P_{Start} of 2800 W and pre- and post-heating (a) left side and (b) right side

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