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Reviewed Paper

PROCESS-INTEGRATED ALLOY ADJUSTMENT IN LASER DEPOSITION WELDING WITH TWO WIRES

L.Budde[1], N.Schwarz[1], J.Hermsdorf[1], S.Kaierle[1], L.Overmeyer[1]

[1]Laser Zentrum Hannover e.V., Hannover, Germany

Abstract

For Direct Energy Deposition (DED) with wire as filler material, the material selection is mostly limited to commercially available welding wires. This limits the achievable material properties for cladding and Additive Manufacturing purposes. Using a coaxial deposition welding head, in which two different wires can be fed and controlled individually, the alloy composition can be adjusted in the common process zone in-situ.
In this study, the two wire materials AISI 316L and ER 70S-6 are used in different mixing ratios to fabricate single weld seams. The different mixing ratios are achieved by varying the wire feed rates. The material content in the weld is varied between 0% and 100% in 20% steps. The weld seams are examined with regard to the distribution of alloying elements, hardness and microstructure. Homogeneous mixing of the two materials was achieved at all mixing ratios. At a content of 40% or more of ER 70S-6 in the weld seam, there was a drastic change in the microstructure and a significant increase in hardness. The microstructure changed from austenitic to ferritic-pearlitic, which was accompanied by an increase in hardness from 170 HV0.1 to 428 HV0.1.

Introduction

Laser wire Direct Energy Deposition (LW-DED) is a manufacturing process that can be used for cladding, repair welding or Additive Manufacturing. In this process, the filler material is provided as a wire and melted and bonded to the substrate by means of laser radiation. The process is very material efficient as nearly 100% of the wire is applied.[1] This is an advantage of wire-based processes over powder-based processes, where there is always overspray and handling is much more demanding. However, the choice of materials available with wire is limited, while a wider range of powders is available or can be produced with comparatively little effort by atomization or mixing of different alloys and alloying elements. For many applications, the conventionally available wire materials are sufficient, but in some cases the requirements exceed those of the conventionally available materials. By alloying different materials in-situ, the properties can be specifically adapted to the application or graded transitions between two materials can be realized. In recent years, investigations have been carried out into the combination of several powders or the combination of wire and powder in a common process zone and the development of processing heads for those processes. In addition to a targeted adjustment of the alloy composition, the formation of a graded transition between two materials is also possible with this technology. [2], [3]

State of the Art

The use of a homogeneous material is sufficient for many applications to meet the requirements, but some components have requirements that go beyond the capabilities of conventionally available materials or that require local adaptation of the material properties in the component. For these applications, the use of process-integrated alloyed materials is required and, in some cases, a graded material transition with adapted alloy compositions. The process-integrated alloying of metallic materials has been considered in a number of studies. Ostolaza et al. used the stainless steel AISI 316L and the hot-work tool steel AISI H13 powder in a L-DED process to manufacture functionally graded parts. The mixing ratio of the powders was adjusted layerwise with 20% composition intervals. The hardness in the graded sample showed a nonlinear course. The addition of even small amounts of AISI 316L led to a drop in hardness from around 60 HRC to 30 to 35 HRC. This is due to differences in the microstructure.[4] A combination of a coaxial powder feeding with a lateral wire feeding was investigated for L-DED investigated by Teli et al.. A wire of H11 steel and Niobium powder was used. A homogenous distribution of the alloying elements was observed. The hardness of the samples manufactured with additional Niobium powder presented a reduced hardness compared to samples manufactured without it and a refinement of the microstructure was achieved. [5] An important aspect of in-situ alloying of multiple materials is the homogeneous mixing of these materials. In a study on transport phenomena in laser hot-wire cladding, Wei et al. observed that the Marangoni effect leads to strong currents in the melt pool. [6] This can contribute to a good mixing of the materials. In the previously mentioned investigations, powder was added for alloy fabrication. Compared to powder, wire is easier to handle and the risk potential for the machine operator is lower. Therefore, the adjustment of the alloy with two or more wire materials has some advantages over a powder-based process.

Two approaches exist for feeding the wire into the process zone for DED. With lateral wire feeding, the wire is fed laterally into the process zone and the laser beam vertically. As a result, the welding result depends on the angle of the wire feed, the positioning of the wire in the melt pool and the welding direction. A change in the welding direction strongly influences the process, up to process abortion. [7], [8]

Due to the directional dependence of the lateral process, various coaxial deposition heads have been developed in recent years. With these, the wire is fed vertically, and the laser radiation envelops the wire providing the necessary energy input to melt the wire material. The arrangement of the laser radiation is achieved by using several laser beams [9], the use of ring-shaped laser beams [10] or by smart beam splitting and merging [11]. In this way, deposition welding heads that are capable of omnidirectional welding can be realized.

In the aforementioned processing heads, one wire is conveyed into the process zone. Tyralla et al. used a lateral laser hot-wire deposition welding head with three wires with a diameter of 1.2 mm, that were feed into one common melt pool. An additively manufactured torch was used for guiding the wires towards the process zone. An oscillated laser beam with a laser power of more than 4 kW was used to ensure sufficient melting of all wires. A deposition rate of 7 kg/h and a degree of dilution of 8.2% were achieved with a nickel-based alloy as material for the wires. [12] Leyens et al. developed a high power coaxial deposition welding head for feeding four wires and, if necessary, powder into one common melt pool. [13] Schwarz et al. have developed a coaxial processing head in which two wires are fed into a common process zone. The wire feed rates at which the two wire materials are conveyed can be adjusted separately, and the mixing ratio of the two materials in the weld can thus be adjusted. In this way, different alloys can be manufactured. With the developed setup, homogenous intermixing of elements was achieved using two different welding wires. [14]–[16]

Aims and Perspectives

The aim of the study is to investigate whether process-integrated alloying with the wire materials ER 70S-6 and AISI 316L can be used to selectively adjust the properties of the weld seam. For this purpose, weld seams are produced with different mixing ratios of the two wire materials and investigated with regards to the following properties:

- Distribution of the alloying elements
- Hardness
- Microstructure

The two materials selected are commonly used materials that are easily available on the market as wires. They differ significantly in chemical composition, microstructure and hardness. Austenitic stainless steel has a high content of chromium and nickel elements, which do not occur in mild steel. Therefore, these two elements can be used to assess the mixing of the two materials in the process zone. The two materials differ greatly in their thermal expansion coefficients. By intermixing the two materials, graded transitions can be created between the two materials, thus avoiding stress peaks. Likewise, the coefficient of thermal expansion can be specifically adapted to the application.

Materials and Methods

Unalloyed flat steel made of S355J2 was used as substrate for the tests. The corrosion-resistant austenitic welding wire AISI 316L and the unalloyed mild steel ER 70S-6 were used as welding wires. An overview of the chemical composition of the materials used is given in Table 1.

Table 1: Chemical composition of the investigated materials in wt.-% [17]

	C	**Si**	**Mn**	**P**	**S**	**Cr**	**Ni**	**Mo**	**Fe**
S355J2	0.23	0.60	1.70	0.035	0.035				Bal.
ER 70S-6	0.08-0.12	0.9-1.1	1.6-1.8						Bal.
AISI 316L	0.02	0.8	1.7	<0.02	<0.01	19	12	2.7	Bal.

The DiCoLas (Diode Coaxial Laser) processing head, which was specially developed at the Laser Zentrum Hannover e.V. for omnidirectional deposition welding with two wires in one process zone, is used to perform the deposition welding tests. The laser radiation is guided to the processing head via fibers by three individually controllable laser diodes. The three laser beams are arranged in a ring around the welding nozzle and converge in a common spot. The two wires are fed into the process zone through a specially made welding nozzle at an angle of 3.5° to the substrate surface. The experimental setup is shown in Figure 1.

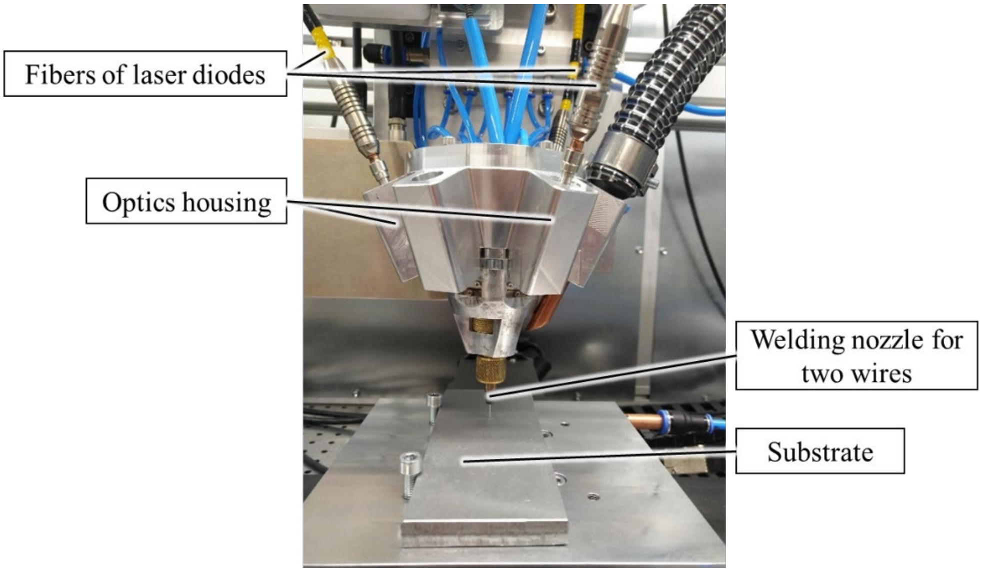

Figure 1: Experimental setup for laser deposition welding with two wires

Single seams with a length of 40 mm are welded onto the substrate. The wire feed rates of the two wires are varied to achieve mixing ratios of the materials between 0%/100% to 100%/0% in 20% increments. The sum of the wire feed rates is 550 mm/min for all tests and the welding speed is a constant 210 mm/min. In this way, a constant weld cross-sectional area is obtained for all weld seams. Three weld seams are applied per parameter set. An overview of the process parameters is given in Table 2.

Table 2: Parameters for the LD-DED process

Parameter	**Unit**	**Value**
Laser power P_L	W	540W – 630 W
Combined wire feed rate v_w	mm/min	550
Welding speed v_s	mm/min	210
Wire diameter d_w	mm	0.8
Stickout l_w	mm	7
Shielding gas flow $\dot{V}$ (Argon)	l/min	5
Laser beam source	-	Fiber-coupled laser diodes
Wavelength	nm	970 ± 7
Spot diameter in focus	mm	1.6

The weld seams are analyzed with a laser-scanning microscope to determine the dimensions of the weld seams. Three transverse sections are made for each seam, in which the element distribution and the microstructure are examined. The cross-sections are etched with V2A for the analysis of the microstructure. In addition to the transverse sections, a longitudinal section is also made parallel to the substrate surface. The section is positioned at half the seam height. The element distribution along the weld seam and the hardness are investigated.

Results and Discussion

The welds with the different mixing ratios are shown in Figure 2. A stable process was present in all weld seams. The weld seams have a height of 0.8 mm and a width of 2.3 mm.

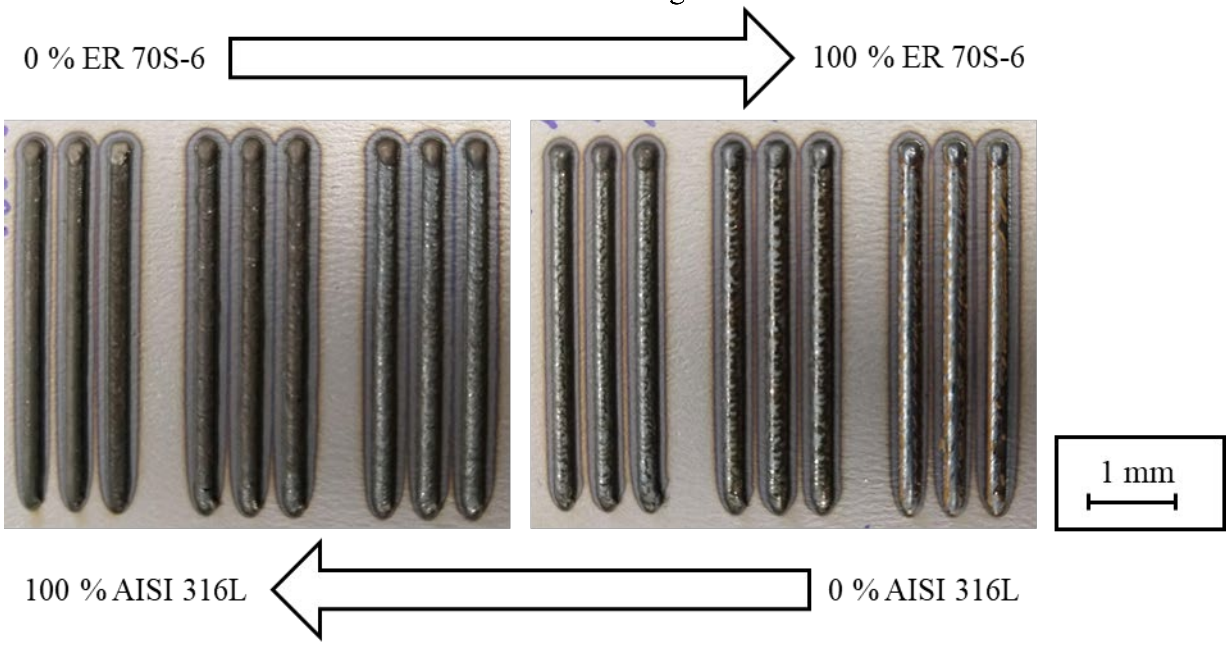

Figure 2: Top View of the single weld seams with different mixing ratios

Cross-sectional and longitudinal EDX analyses are performed to assess the intermixing of the two wire materials in the weld seam. The element distribution in cross-section is shown as an example in Figure 3. The wire material AISI 316L has a high chromium content as alloying element while the substrate and the base material have no chromium. It can be seen that the chromium elements are evenly distributed over the weld cross-section. In the case of molybdenum, uniform intermixing is also achieved. Silicon and manganese are present in all three materials to a similar extent. Regardless of the mixing ratio of the materials, silicon and manganese are present in form of a local enrichment on the weld seam surface. Silicon and manganese react with oxygen from the environment and form oxides on the seam surface. By improving the shielding gas coverage of the melt pool, this effect can likely be suppressed, and the local enrichments can be avoided. Oxide formation is a well-known problem in welding technology and mechanical post-treatment is usually carried out to remove the oxides in order to avoid inclusions or, in the case of arc-based processes, process instabilities [18]. The distribution of elements does not vary along the length of the seam. It can therefore be concluded that good mixing of the two materials was achieved over the entire weld length.

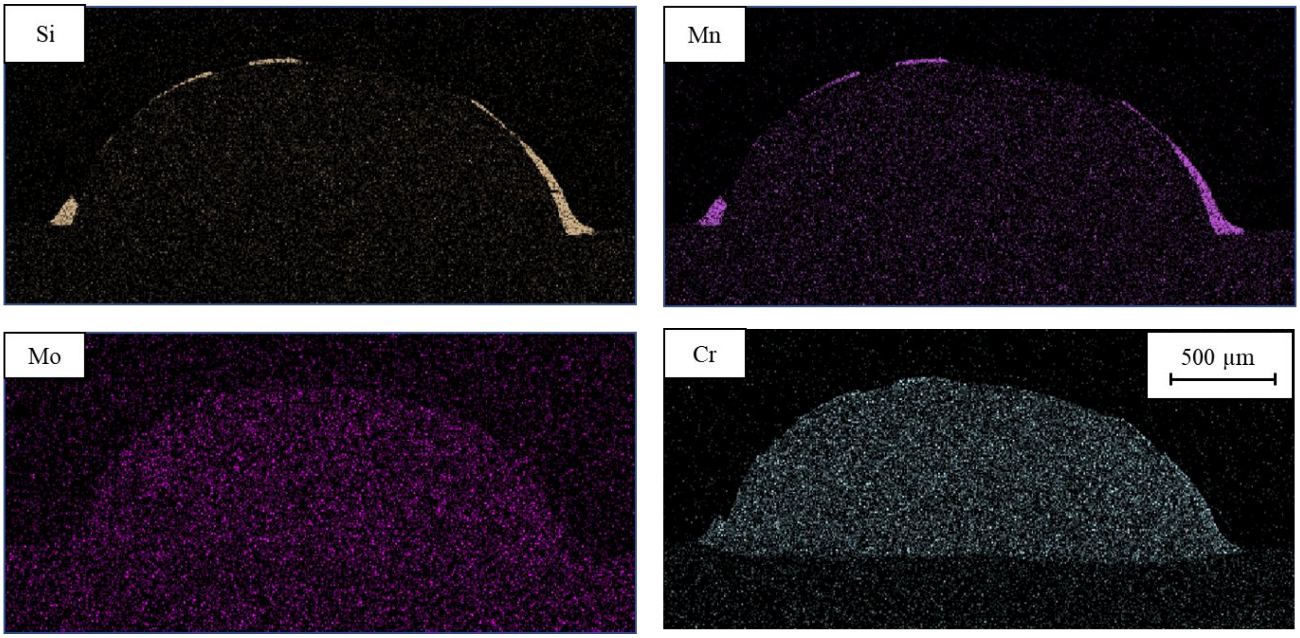

Figure 3: Distribution of the alloying elements in a weld seam with a mixing ratio of 80% AISI 316L and 20% ER 70S-6

The proportion of alloying elements in the weld seams is shown in Figure 4. For comparison, the values from the weld material data sheets are also listed. The wire material AISI 316L has a high chromium content of around 19% and a high nickel content of around 12%. In the weld seams made of 100% AISI 316L, a chromium content of 16.7% and a nickel content of 11.4% are measured. As expected, the chromium and nickel content decreases with increasing admixture of ER 70S-6 and is 0.1% and 0.2%, respectively, in the weld seam with 100% ER 70S-6. The proportions of silicon, manganese and molybdenum are approximately constant, as both materials have a comparable alloying element content.

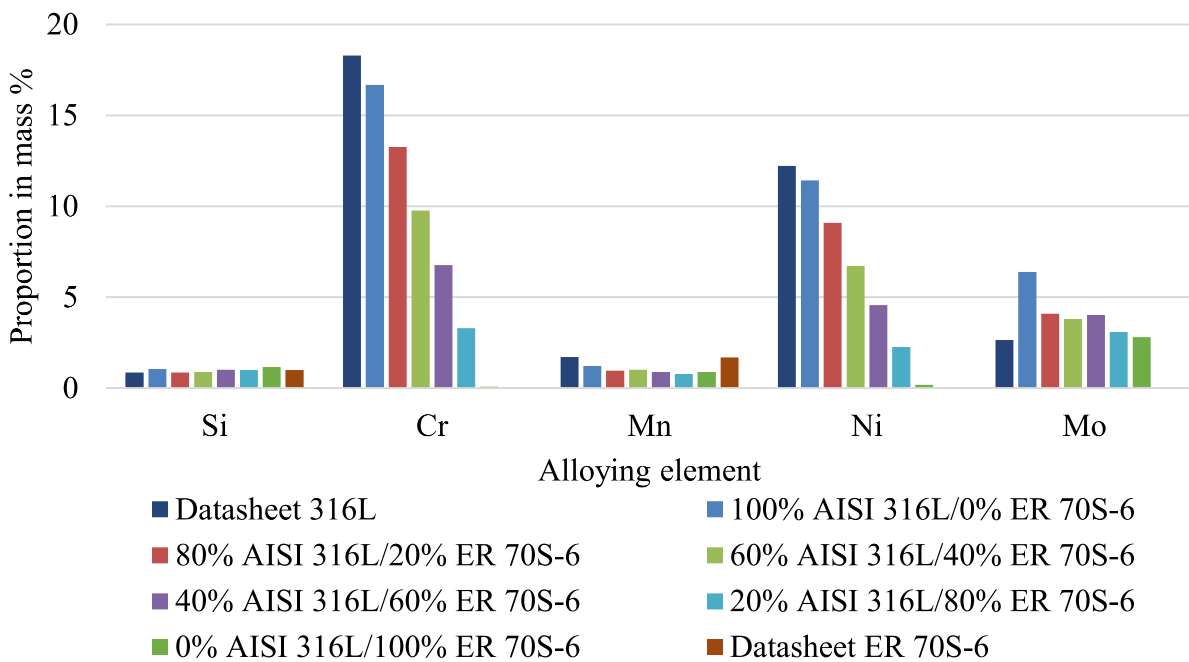

Figure 4: Chemical composition of weld seams with different mixing ratios

In the plain AISI 316L weld seam, a hardness of 177 HV0.1 is present while in the plain ER 70S-6 weld seam, a significantly higher hardness of 392 HV0.1 is obtained. Up to an admixture of 20% ER 70S-6, the hardness is below 200 HV0.1. With further admixture of ER 70S-6, the hardness increases abruptly and lies between 380 HV0.1 and 428 HV0.1 for all weld seams with a higher ER 70S-6 content.

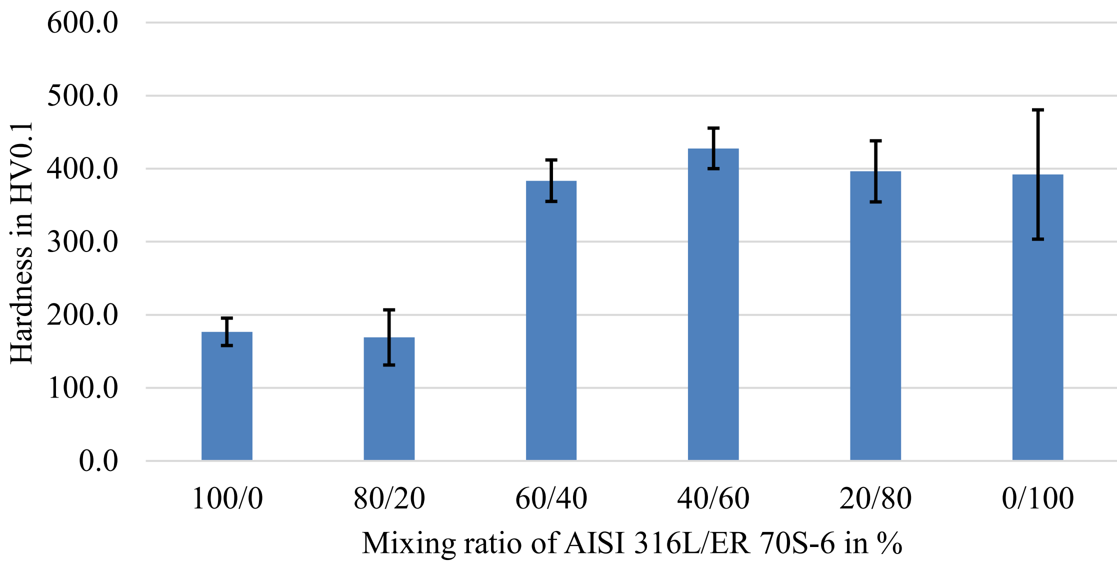

Figure 5: Hardness of the weld seams with different mixing ratios

The microstructure of the weld seams are shown in Figure 6. An austenitic microstructure is present in the weld seam made of AISI 316L, and a ferritic-pearlitic microstructure is present in the weld seam made of ER 70S-6. The mixing of the weld seam with the base material is very low and can therefore be ignored. At a mixing ratio of 80% of austenitic stainless steel and 20% of mild steel, an austenitic microstructure is also obtained. From an admixture of 40% mild steel, the microstructure becomes ferritic-pearlitic, which also explains the increase in hardness from this mixing ratio.

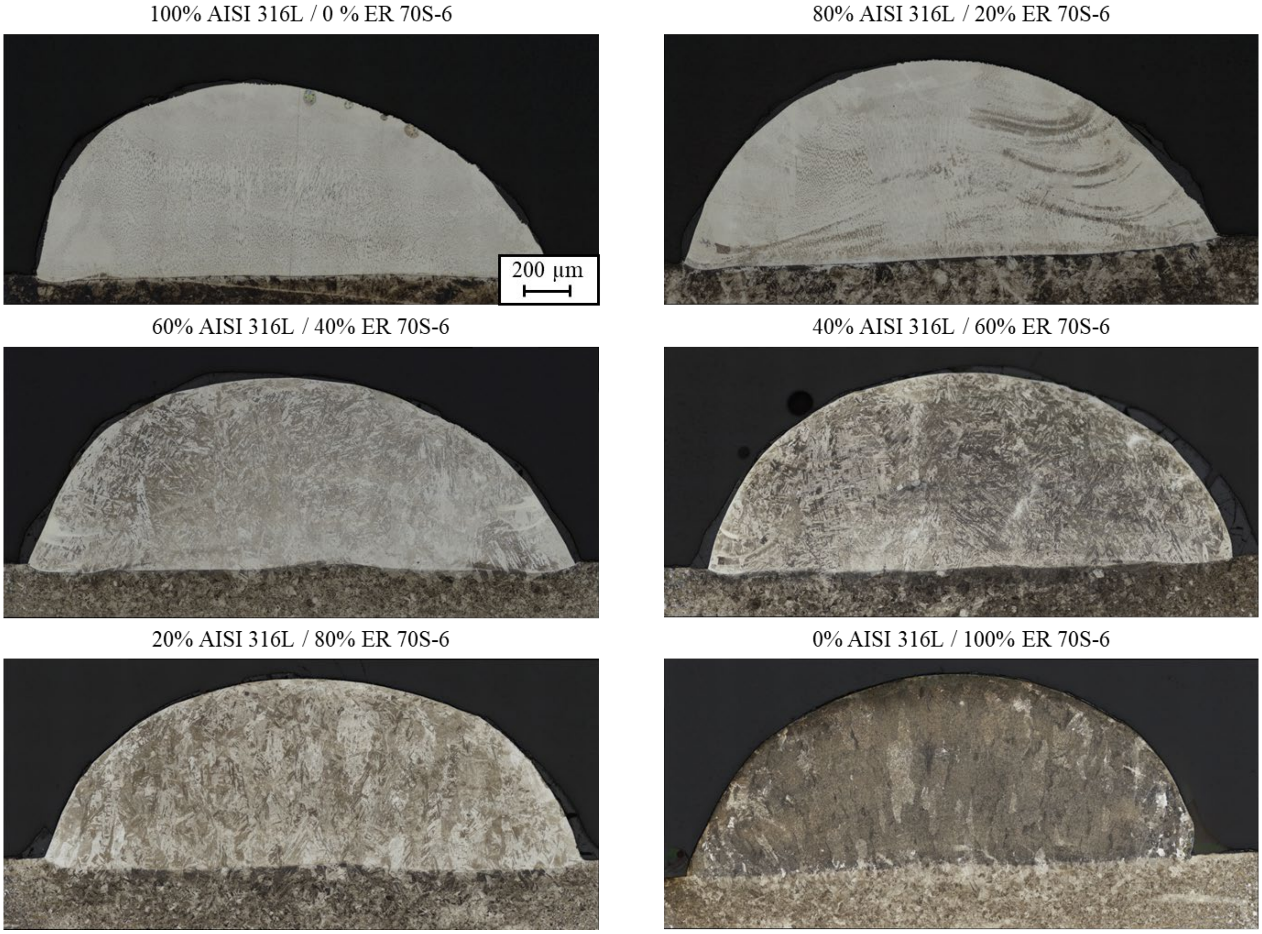

Figure 6: Cross-section of weld seams with different mixing ratios

Conclusion and Outlook

Weld seams with different mixing ratios of the two wire materials AISI 316L and ER 70S-6 were applied by means of a coaxial laser double-wire deposition welding head and investigated with regard to their properties. The following conclusions can be drawn from the investigations:

- ➔ A stable welding process was present at all mixture ratios investigated.
- ➔ Homogeneous mixing of the two wire materials in the process zone is achieved. Regardless of the mixing ratio, the elements molybdenum and silicon are more frequently deposited on the weld surface.
- ➔ The hardness of the weld depends on the mixing ratio and is less than 200HV0.1 for pure AISI 316L weld seams and with an admixture of 20% of ER 70S-6. With larger proportions of ER 70S-6, the hardness is significantly higher at 380 HV0.1 to 430 HV0.1.
- ➔ The stainless steel AISI 316L has an austenitic structure, and the structural steel ER 70S-6 has a ferritic-pearlitic structure. From an admixture of 40% ER 70S-6, the microstructure becomes predominantly ferritic-pearlitic.
- ➔ A linear increase in the proportions of alloying elements does not lead to a linear increase in hardness values.

Due to the different mixing ratios, different hardness and microstructural properties could be adjusted. In the next step, cuboid specimens are to be produced from several weld seams lying next to and on top of each other. From these, samples can be taken for the determination of the coefficient of thermal expansion. It will be investigated whether the coefficient of thermal expansion can be specifically adjusted by changing the alloy composition. The knowledge gained can be used for the design of graded material transitions to avoid stress peaks during the manufacturing process or under thermal load. On the other hand, strongly deviating coefficients of thermal expansion can be set in a controlled way in order to achieve beneficial residual stresses in stressed component areas by means of thermomechanical post-treatment.

Acknowledgments

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