

Material Characterization of Hybrid Components Manufactured by Laser- Based Directed Energy Deposition on Sheet Metal Substrates

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Abstract. Laser-based directed energy deposition (DED-LB/M) allows the application of a wear-resistant metal coating to the surface of a sheet metal substrate. Subsequent deep drawing of the part enables high material efficiency, significantly shorter production times, and lower unit costs compared to, for example, solely machined production of the entire component. At the same time, energy-intensive global heat treatment strategies can be avoided. For the numerical analysis of such hybrid process chains, both the sheet metal substrate and the additively applied coating are usually characterized individually. However, the low thickness of the coating in combination with a relatively high welding depth, which is required for a good bond to the sheet metal substrate during subsequent forming, lead to a strong gradient of the mechanical properties as well as complex mechanical interactions in the bonding zone. Therefore, appropriate characterization methods are required. In this work, an investigation of different influencing factors, like the rolling, hatch and tensile direction, is carried out with the aid of tensile tests using hybrid specimens. In this way, interactions between the influencing factors are identified. As substrate, 3.5 mm thick 16MnCr5 blanks are used, with an approximately 0.68 mm thick coating of Bainidur[®] AM. In addition, an optical surface roughness measurement and metallographic analysis of the tensile specimen's edge area after laser cutting is performed.

Introduction

In view of increasing ecological and economic constraints, consistent lightweight construction in combination with high-performance and resource-efficient manufacturing processes is becoming a key aspect for securing long-term market competitiveness and reducing CO₂ emissions [1]. Since individual manufacturing technologies often fail to meet these high demands, hybrid manufacturing processes are gaining importance. One example of hybrid manufacturing is the combination of additive manufacturing (AM) and subsequent forming [2]. Numerous possibilities exist for combining AM and forming processes as shown in [3]. For the coating of components, however, DED-LB/M is particularly well suited. In the process, a laser beam melts a supplied powder material to deposit material on the surface of a substrate. High deposition rates as well as filigree three-dimensional structures can be achieved [4]. In addition, curved surfaces can be coated due to the mobility of the processing head, which makes the process suitable for both the process sequence of first forming and then AM as well as vice versa [3]. Regarding the production of wear resistant coatings, an in-situ-alloy formation can be realized by mixing in ceramic [5] or carbon black nanoparticles [6] into the powder prior to processing. In the context of these investigations, however,

the focus lies initially on the mechanical properties and formability of simple single layer coated sheet metal components.

One possible approach for simulating the forming behavior of hybrid AM components is to characterize the materials individually, defining them as separate areas in the model. Due to the thin layer height relative to the substrate thickness for coated sheet metal substrates, there exists a relatively large area with graded mechanical properties, which makes an exact simulative mapping difficult. At this point, the present work aims to characterize the direction-dependent mechanical properties for coated sheets in order to provide a basis to improve the predictive capability of simulations in the future and to better understand the material behavior during the forming process. Tensile tests on hybrid components provide a method for determining the mechanical properties of such hybrid components. The approach of using hybrid manufactured tensile specimens was already utilized in [7] and further adapted in [8]. In both studies, a micro-alloyed, pearlite-reduced fine-grained steel with relatively high yield strength $YS = 630$ MPa and tensile strength $TS = 930$ MPa was used for both the powder and substrate material. Process parameters were adapted to achieve a good bond to the substrate and a nearly defect-free microstructure in the coating. The results show, that the mechanical properties of the coated tensile specimens reach at most those of the base material while the ductility of the coated material reduces [8]. The reduced ductility of such coated components compared to the pure substrate material is also reported by other publications e.g. [9]. With regard to the yield strength and tensile strength of the material after coating, however, higher values have been observed when processing medium Carbon steel C45 which has a much lower yield and tensile strength in the initial state [10]. Because the mechanical properties depend not only on the process parameters but also on the specimen preparation, the process control and the selected materials, these have to be investigated individually. In addition, the influence of the coating direction in combination with the rolling direction has not yet been considered for DED-LB/M coated sheet metal substrates for the material combination used here.

Experimental Set-Up

Material. As substrate, 3.5 mm thick sheets of cold-rolled and subsequently spheroidized (GKZ annealed) 16MnCr5 (1.7131) steel supplied by the Schaeffler AG and a metal powder with a similar chemical composition, Bainidur[®] AM supplied by the Deutsche Edelstahlwerke Specialty Steel GmbH & Co. KG, are used for the investigations. The chemical composition of the two individual materials is listed in Table 1. The powder is manufactured by means of gas atomization ensuring spherical particles with a particle size distribution of 45 - 90 μm .

Table 1: Chemical composition of 16MnCr5 and Bainidur[®] AM

16MnCr5 (1.7131)										
WT%	C	Si	Mn	P	S	Cr	Cu	Ni	Al	N
From	0.14		1.00			0.85			0.020	0.0036
To	0.18	0.10	1.20	0.020	0.008	1.05	0.10	0.10	0.050	0.0080
Bainidur [®] AM										
WT%	C	Si	Mn	P	S	Cr	Mo			
	0.23	0.7	1.2	<0.020	<0.020	1.0	0.9			

Directed energy deposition (DED-LB/M). In DED-LB/M, material is applied to the surface of a substrate by a laser beam melting a supplied powder material. The powder is provided by a powder hopper and is transported into the processing zone using a carrier gas stream and focused by a powder nozzle mounted on the processing head. The energy of a high-power laser passing through the processing head causes the surface of the component and the powder introduced to melt and bond together. As the processing head moves relative to the surface of the component, a welding bead is formed. [11]. Process parameters include the feed rate v_L , spot size d_L , laser power P_L , powder mass flow M_L , overlap O , shielding gas flow V_{Shield} , carrier gas flow V_{Carrier} , and initial component temperature T_{in} . All experiments are performed on a ERLAS UNIVERSAL 50349 machine (ERLAS

GmbH) which is equipped with an integrated five-axis DED-LB/M cell and a 4 kW Laserline LDF 4000-4 diode laser (Laserline GmbH) with a characteristic wavelength of 900 - 1,080 nm. The processing head has an adjustable telescope lens system, which enables the laser spot size to be varied from 1.0 mm to 3.4 mm. Argon of type 4.6 is used for both shielding and carrier gas. A parameter set as shown in Table 2 was used for all specimens. The parameters are based on preliminary investigations of the same material combination and DED-LB/M system and ensure a defect-free processing of these alloys [12].

Table 2: Parameters used for DED-LB/M coating of Bainidur® AM [12]

DED-LB/M Parameters							
P_L	d_L	v_L	M_L	O	V_{Shield}	V_{Carrier}	T_{in}
600 [W]	1.5 [mm]	400 [mm/min]	2.61 [g/min]	50 [%]	20 [L/min]	4 [L/min]	RT

Tensile tests with optical strain measurement. The aim of the material characterization is to determine relevant mechanical parameters, such as yield strength YS, tensile strength TS, uniform elongation El_u , and anisotropy r . This knowledge about the material behavior represents the basis for a subsequent numerical process simulation and design, which will be developed in the future as part of the HyConnect research project. In the context of this project, the steel under investigation will be processed by deep drawing for the final application. Due to the prevailing stress conditions, tensile tests are particularly suitable for characterization. The tensile tests performed according to DIN EN ISO 6892-1 [13] ensure up to El_u uniaxial stress conditions and are performed on a universal testing machine Z100 (ZwickRoell GmbH & Co. KG) equipped with hydraulic jaws and an optical strain measurement system ARAMIS (GOM GmbH). This allows the evaluation range to be flexibly adjusted around the area of necking, is independent of machine springing and can reliably measure even small specimens with very high resolution. The tensile specimens used have an initial parallel length $l_0 = 30$ mm according to [13], and must be primed white and covered with a stochastic pattern before the test is carried out, so that the specimen strain can be measured optically. For this purpose, two CCD cameras are stereoscopically arranged and record the displacement of the applied grid at 5 Hz during the test. From the test results, the stress-strain curves and yield curves can be determined and the mechanical properties can be derived.

Manufacturing of hybrid tensile specimens. As substrate, 200 x 200 x 3.5 mm sheets of 16MnCr5 are laser cut with holes in the corners for clamping and reducing distortion during AM. These are then coated with five (0.680 ± 0.074) mm thick 15 x 160 mm patches using Bainidur® AM in DED-LB/M. Between the patches a spacing of 15 mm is left to reduce thermal influences of neighboring patches as shown in Fig. 1.

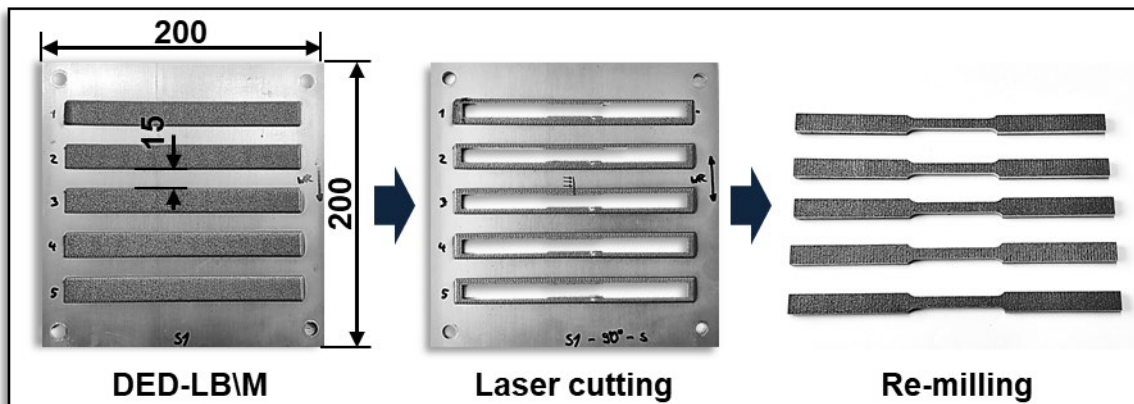


Fig. 1: Manufacturing of hybrid tensile specimens on sheet metal substrates

The tensile specimens are laser-cut from the patches with oversize, taking care to remove them centrally, i.e. not from the edge area of the patches. For this purpose, a laser cutting system TruLaser Cell 7020 (TRUMPF GmbH & Co. KG), with a 4 kW CO₂ laser is used. Due to higher cooling rates

and other interfering factors during AM, the mechanical properties of the edge areas may differ considerably from those of the central area of the patches. This influence is to be excluded for the investigations in this work. Active height control is required for laser cutting due to the thermal deformation of the substrates after coating. Finally, the tensile specimens are re-milled to nominal dimensions on the cut sides to remove the heat-affected zone (HAZ) from laser cutting and then cleaned in acetone in order to remove any remaining powder or grease. An oversize of 1 mm was chosen. Based on etched cross-sections after laser cutting, it was possible to determine that the maximum width of the HAZ is about 0.2 mm, well below the re-milled area as shown in Fig. 2.

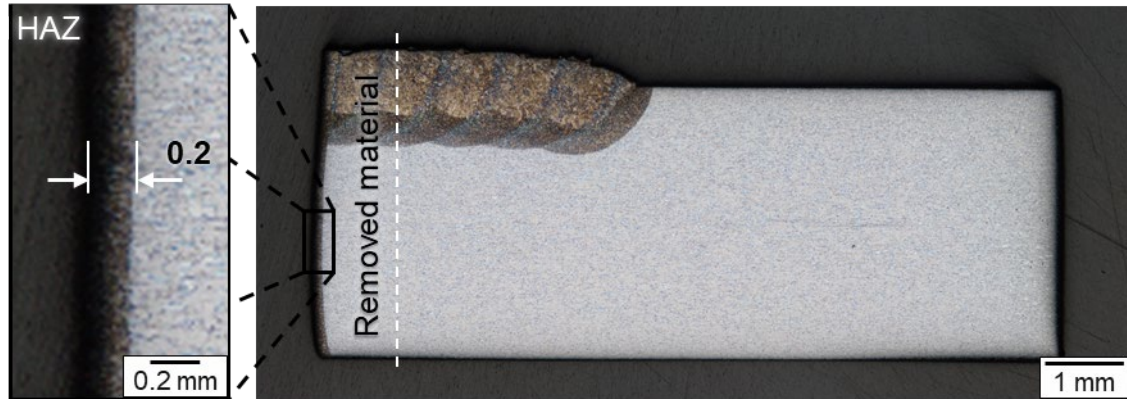


Fig. 2: Etched cross-sections after laser cutting indicating the HAZ and re-milled area

To characterize the direction-dependent properties, both the rolling direction (RD) with 0° and 90° to the tensile direction and the coating direction vertical (V) and parallel (P) to the tensile direction are varied. Five replicate tests are performed for each parameter combination, resulting in 20 samples. Of these five replicate tests, three are used for optical strain measurements on the coated front face (FF) and two for optical strain measurements on the uncoated back face (BF). In Table 2 an overview of the investigated parameter combinations is given.

Table 3: Overview of the parameter combinations tested

Rolling direction (RD)	Hatch strategy	Strain measurement position
0°	Vertical (V)	Front Face (FF)
		Back Face (BF)
	Parallel (P)	Front Face (FF)
		Back Face (BF)
90°	Vertical (V)	Front Face (FF)
		Back Face (BF)
	Parallel (P)	Front Face (FF)
		Back Face (BF)
No. of repetitions n = 5 (n _{FF} = 2 and n _{BF} = 3)		

Since the tensile tests are carried out in the as-built condition and the surface roughness is expected to have a strong influence on the mechanical properties of the material, the surface of one specimen coated in the V and one in P direction is measured optically by laser scanning microscopy on a topography measuring station VK-X 200 (Keyence) before laser cutting. A 3-jet nozzle is used in the AM process; therefore there may also be directional dependencies with regard to the surface topography of the specimens. The measurement is carried out in accordance with DIN EN ISO 25178 [14] and serves to gain an estimate of resulting surface properties after DED-LB/M.

Results

Optical surface roughness measurement. Fig. 3 shows the positions of the two optical surface measurements. Each measurement represents a 5 x 5 mm area on the top of the coated patches in V and P orientation. The enlarged illustrations show the surface topography once with and once without color scaling. The color scaling provides an improved visibility of the height differences. Hereby the red areas represent the peaks and the blue areas the valleys. What can be deduced from the measurements is that the coating shows a characteristic waviness in V and P direction resulting from the overlap of individual weld beads. The coating direction however has hardly any influence on the resulting surface roughness. The values for the mean arithmetic height $S_a = 25.76 \mu\text{m}$, the mean square height $S_q = 32.57 \mu\text{m}$ and the maximum height $S_z = 218.93 \mu\text{m}$ for the V coated sample are very close to the values of the P coated sample with $S_a = 23.20 \mu\text{m}$, $S_q = 29.52 \mu\text{m}$ and $S_z = 233.69 \mu\text{m}$. While S_a and S_q seem slightly lower for P, S_z is slightly higher, which would have to be checked in the future for a significant distinction using a larger replicate set. In summary, it must be assumed that the rough surface and waviness in the as built condition can cause an influence due to notch effects. The similar roughness values for the V and P samples however indicate that the 3-jet nozzle used provides a uniform powder distribution independent of the laser buildup direction. Therefore, the influence of the roughness on the mechanical properties can be neglected in the comparison of the different coating directions and only the waviness remains to be considered.

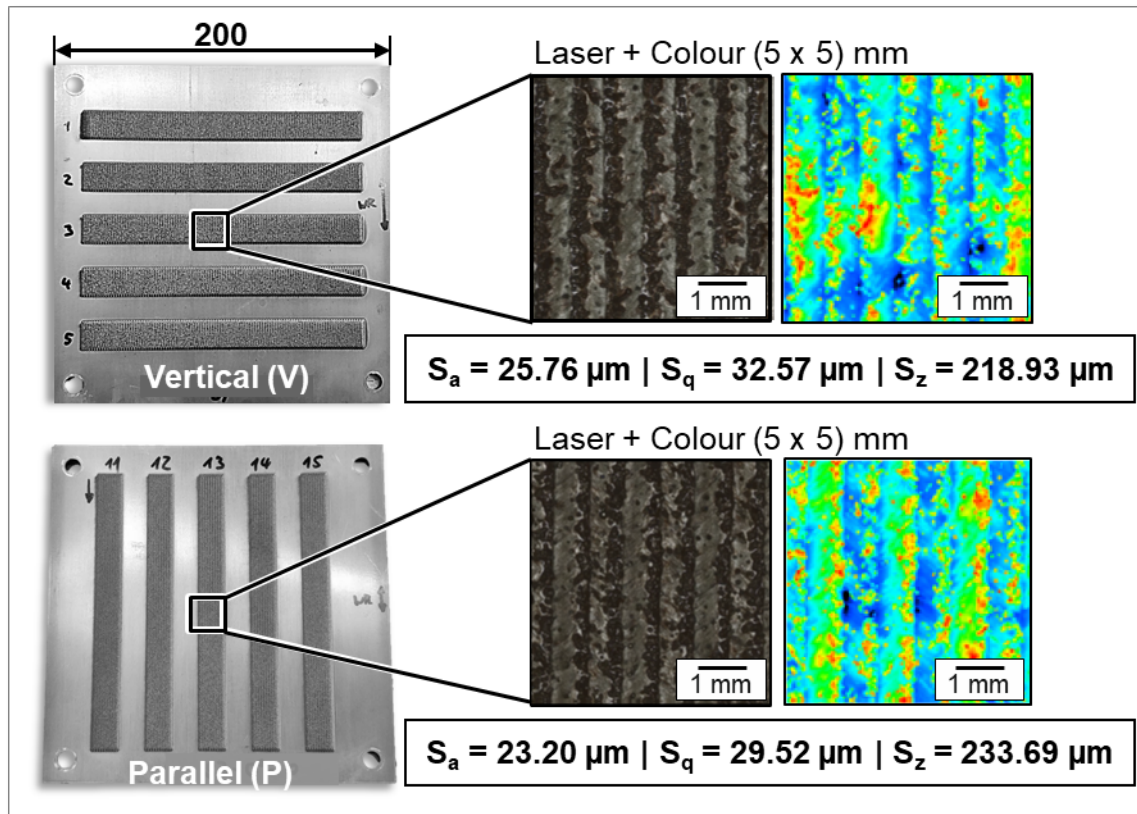


Fig. 3: Optical roughness measurement of the coating in V (top) and P (bottom) direction

Mechanical properties from the tensile test. In this section, the results of the mechanical properties as a function of rolling, hatch, and tensile direction are discussed. The graph in Fig. 4 shows the yield and tensile strength for the respective parameter combinations. The results of the hybrid tensile specimens are represented by bars and those of the pure sheet metal by dashed reference lines. The yield strengths and tensile strengths of the hybrid tensile specimens show a significant increase compared to the pure sheet material, despite the relatively thin Bainidur® AM coating of 0.68 mm. The $YS = (413.0 \pm 46.2) \text{ MPa}$ is on average 54 % higher and the $TS = (576.0 \pm 22.8) \text{ MPa}$ is on average 36 % higher, compared to the pure substrate material with $YS = (267.9 \pm 4.8) \text{ MPa}$ and $TS = (424.5 \pm 1.5) \text{ MPa}$.

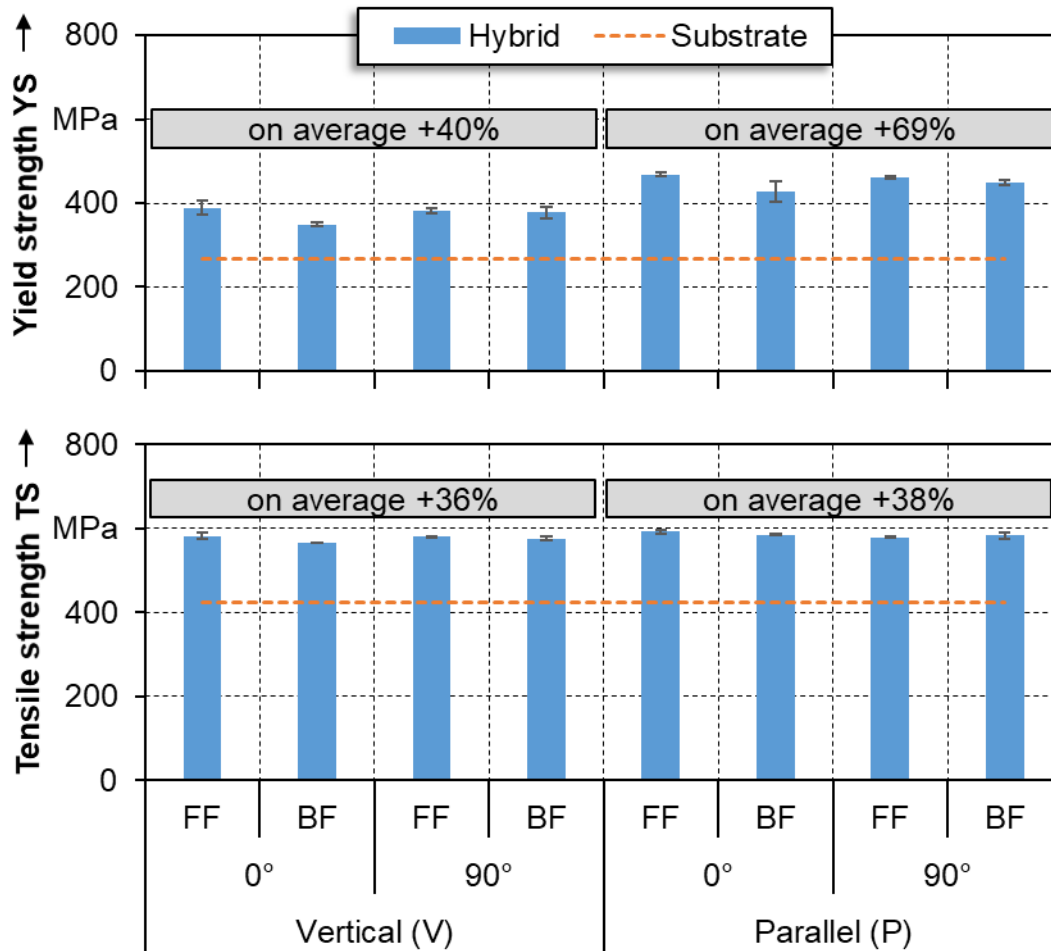


Fig. 4: Yield and tensile strength as a function of rolling, hatch and tensile direction

High cooling rates may lead to the formation of a fine-grained, mostly dendritic microstructure of the coating applied in DED-LB/M [12]. For the selected alloys and process parameters, this coating exhibits a bainitic-martensitic microstructure, with about three times the hardness of the soft-annealed base material and a transition zone in between [12]. Thus, it can be assumed that the increase in strength is primarily caused by the coating and not by a thermally induced microstructural transformation in the substrate material observed for higher laser powers of 800 W [12]. The higher strength of the coating also increases that of the material composite. The coating therefore has a stiffening effect, which can be beneficial with regard to the mechanical properties of the finished component [7], but disadvantageous for the planned forming operation. The increase in yield and tensile strength of the composite lead to an increased springback [1], higher process forces and must therefore be taken into account in the part design. When examining the differences between the V and P coated specimens, it can be observed that the P coating along the tensile direction achieves much higher YS of +69 % and slightly higher TS of +38 % on average. With the V coated specimens reaching +40 % and +36 % correspondingly. One possible reason is that the weld beads form individual force channels when oriented P to the tensile direction. These force channels are less disturbed by notch effects than with the V specimens. A similar behavior is observed in fiber-reinforced composite materials [15] which may represent a comparable mechanism of action. Another possible reason for the deviating YS and TS of the V and P specimens might lie in their different effective cross-sectional areas. Due to the waviness of the coating resulting from the overlap of individual weld beads it can be assumed that the effective cross-sectional area of the P specimens is greater than that of the V specimens considering the uniaxial stress state in the tensile direction. Because the thickness of the specimens is measured with a micrometer at the highest point before the tests, this can also lead to deviations. Notch effects may further amplify this effect, however, in order

to draw definite conclusions, further investigations with different surface topographies will have to be carried out in the future and specimen thicknesses need to be measured optically for a reference. The results of the specimens coated 0° and 90° to the RD hardly differ. This can presumably be attributed to the metallographic alignment of the grains of the cold-rolled sheet metal substrates, which is largely lost during soft annealing. Nevertheless, it can be assumed that a more pronounced grain orientation will lead to stronger directional dependencies, since the shape change is favored in one direction. The resulting interactions with the coating will be investigated in future studies. Lastly, the differences in mechanical properties measured on the FF and BF are examined. The values for YS and TS on the coated FF tend to be slightly higher. The average difference between FF and BF is about (24.5 ± 10.6) MPa for the YS and (5.4 ± 4.9) MPa for TS. This observation can be explained by the different material properties of the coating compared to the substrate material. Although both areas experience the same overall force, the coated FF deforms less during the tensile test and reaches relative to the BF slightly higher values. Due to the high standard deviations relative to the values, however, only tendencies can be identified at this point. For a more precise differentiation of the forming behavior between FF and BF, the deformations must be recorded simultaneously on both sides by an additional ARAMIS system.

The uniform elongation El_u is shown in Fig. 5 As reported by [8] among others, a general reduction of ductility is to be expected. This behavior can also be confirmed for the coating of soft-annealed 16MnCr5 with Bainidur[®] AM. The hybrid tensile specimens show an average uniform elongation of $El_u = (8.3 \pm 0.7) \%$ which is about 47 % lower than that of the pure substrate material with $El_u = (15.7 \pm 0.34) \%$. The effect most likely results from the lower ductility of the pure AM coating which is specified with an elongation at break of $A_{5.65} = 10 \%$. However, the ductility of single-layer coatings is assumed to be even lower due to higher cooling rates at the surface and the reduced heat input due to the absence of overlying layers resulting in higher residual stresses. This behavior can be assumed on the basis of the hardness values in [12], and must be investigated by further tensile tests with pure AM material.

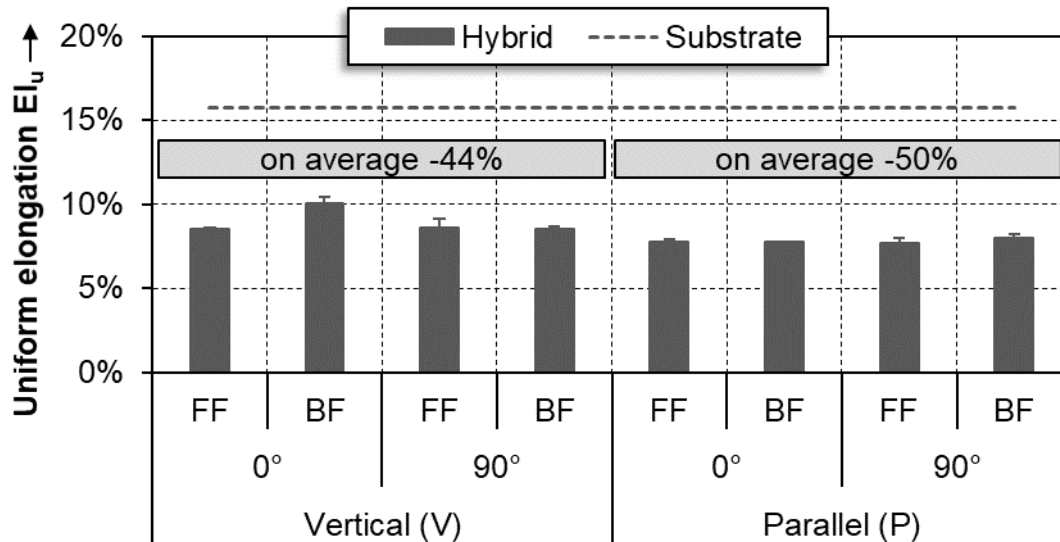


Fig. 5: Uniform elongation as a function of rolling, hatch and tensile direction

The V specimens with $El_u = (8.9 \pm 0.6) \%$ show on average slightly higher values than the P specimens with $El_u = (7.8 \pm 0.5) \%$; respectively -44 % and -50 %, compared to the substrate. This can be explained by a higher stiffening effect of the V coating in the width direction of the specimen. As a result, the necking is counteracted slightly, allowing higher uniform strains to be achieved. In addition, the V arrangement of the weld beads favors the deformation of the coating due to a lower yield strength, which in turn also leads to higher uniform elongations. No obvious differences can be observed between 0° and 90° as well as between FF and BF. An exception is the result of the specimens with V coating at 0° measured on the BF. Here, the uniform elongation is slightly higher

reaching $El_u = (10.0 \pm 0.4) \%$. In summary, due to the lower uniform elongation compared to the sheet substrate, necking and a reduction in sheet thickness are more likely to occur, which can lead to failure in subsequent forming operations. This must be taken into account when determining the process parameters, thickness and position of the coating prior to forming.

Finally, the anisotropy values determined from the measured shape changes in thickness and width directions are discussed. These are shown in Fig. 6 together with an image of the tensile specimens after testing.

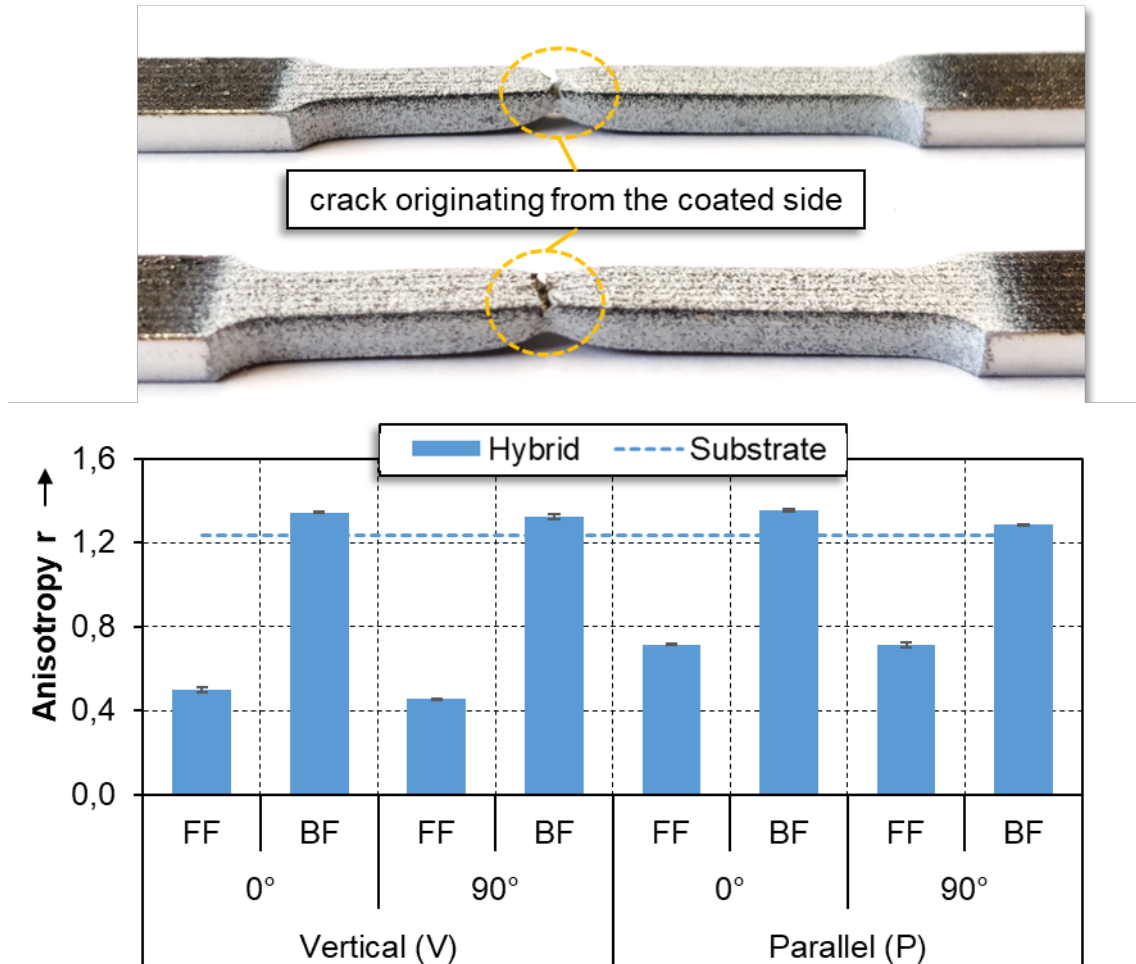


Fig. 6: Fracture behavior and anisotropy of AM-coated tensile specimens

A 90 % drop from the maximum force was selected as the break-off criterion, therefore the specimens still hold together after the tensile tests. The crack starts from the coated side due to the rough surface acting as a notches and a higher hardness of the AM material further amplifying the tension peaks. The image shows that the coating deforms much less than the sheet metal substrate. The relationship is particularly clear in the area of necking. The hybrid manufactured material thins out predominantly from the substrate. This explains why such different anisotropic values are measured for the FF and BF. When looking at the r -values of the FF, they are clearly below $r = 1.0$. The material therefore seems to flow more out of the thickness than out of the width. The reason for this is the stiffening effect of the coating. Since the anisotropy is calculated from the ratio of deformation degrees in width $\phi(w)$ and thickness $\phi(t)$ direction, and the material changes little in width on the FF due to the stiffening coating, but thins out strongly in the area of the substrate, this leads to r -values below 1.0. For local consideration, the coating thins out only slightly on the FF. This also shows that the V coating has a greater stiffening effect in the width direction, which was assumed before. The FF r -values for the V specimens are on average again 33 % lower than the P specimens. Here too, the force transmission most likely plays the decisive role. Since hardly any longitudinal forces flow through the weld beads in the V specimens, and the preferred direction is vertical to the tension

direction, greater forces can be absorbed here and the material is additionally stiffened. At the same time, however, due to the effectively smaller cross-sectional area of the V specimens, an increased force flow takes place in the area of the substrate material, causing it to expand more strongly. Thus, it remains to be investigated how strongly the respective effects are distributed and how this behavior will show up in larger structures. Between 0° and 90° , again only minor differences can be detected.

Summary

The aim of this work was to investigate the direction-dependent mechanical properties of DED-LB/M coated metal sheets made from cold-rolled and subsequently soft-annealed 16MnCr5 substrates with a coating of Bainidur[®] AM. The investigations were carried out in order to derive conclusions about the forming behavior of such hybrid components and to provide a basis for further characterization tests to be used for future simulative hybrid component design. For this purpose, a practical procedure for the manufacturing and execution of hybrid tensile tests was presented. Optical roughness measurements were used to record the as built surface of the specimens coated vertically and parallel to the tensile direction. No direction-dependent roughness differences were seen. However, the macroscopic waviness of the tensile specimens coated in the V and P directions must be taken into account. Next, the mechanical properties of such hybrid structures were presented for different combinations of hatching, rolling and tensile directions. Various factors influencing the forming behavior and mechanical properties could be derived and a significant increase in yield strength by up to +69 % and tensile strength by up to +38 % could be demonstrated. In combination with the relatively thin coating of only 0.68 mm, this represents a potential application for highly stressed components, but at the same time makes the forming of these structures more difficult. Higher yield and tensile strengths lead to increased springback and higher forces required during forming. The greatest differences were found between specimens coated in the vertical and parallel directions. According to the results, the following recommendations can therefore be made. A coating parallel to the direction of deformation leads to better properties of the final product, i.e. higher stiffness and strength. In turn, a coating perpendicular to the deformation reduces the thinning of the sheet and leads to reduced force requirements due to a lower yield strength. Compared with the pure sheets, the hybrid tensile specimens exhibit significantly lower uniform elongations of up to -50 %, which in turn must be taken into account when designing such hybrid components for subsequent forming.

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