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RESEARCH PAPER

Arc-welding based additive manufacturing for body reinforcement in automotive engineering

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Abstract

Arc-welding based additive manufacturing is a cost-efficient, productive technology which has been shown to be capable of producing high-integrity components. It is suggested that in automotive engineering, this manufacturing process can be used to reinforce body components by generating stiffening elements. Benefits of this method could be more flexural rigidity with comparatively lower material volume. In the current study, wire arc additive manufacturing (WAAM) with an advanced short arc welding process with low heat input was chosen. The first objective of the work was to check possibility of generating a gusset plate on zinc-coated car body parts by additive manufacturing, for reinforcing of formed thin steel sheets. The second aim was to increase flexural rigidity of the sheets by depositing weld metal as a grid. Bending tests of the sheets indicated an increased flexural rigidity compared with the parent material. This production method and the results of this study are related to automotive engineering but could be employed for other applications. The aim is to demonstrate how these goals could be approached, what difficulties and limitations exist, and where further research work could be initiated.

Keywords Welding · Additive manufacturing, automotive

1 Introduction—Wire arc additive manufacturing

"Wire arc additive manufacturing (WAAM)" has now been recognized as a relatively rapid, cost-effective alternative for generating metal components [1]. High deposition rates and lower investment and operating costs compared with powder-based additive manufacturing processes are of particular interest for the production of large-volume components [2]. The use of WAAM has been facilitated by the development of energy-reduced digitally controlled short arc processes and the simplified use of industrial robots for torch movement [1]. Additive manufacturing often means generating of complete components by adding layer by layer. There are some processes that can be applied for this purpose. Of particular interest for additive manufacturing are the digitally controlled short arc processes, which can reduce thermally induced residual stresses. In order to achieve this, certain current and voltage curves are imprinted, partly in combination with defined wire movements. This leads to particularly low-energy material transition achieved at relatively high deposition rates (general in literature: 1–4 kg/h). For additive manufacturing, special features of arc-based welding processes are currently subject of intensive research and must be taken into account. High heat input and material input due to the arc lead to thermally induced residual stresses [2].

WAAM seems to be one of the most promising technologies for additive manufacturing. It is known for high productivity, high energy efficiency, and low raw material cost [3]. Compared with other metal additive manufacturing processes with the wire and arc additive manufacturing

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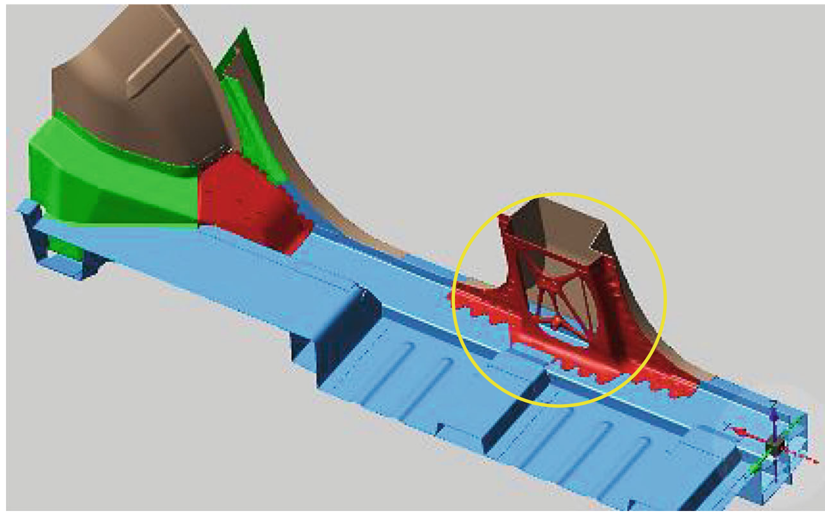


Fig. 1 Laser additive manufactured (LAM) part of the center pillar of a car [5]

(WAAM) process, an easy accessibility of the welding point is given. Further benefits are flexibility in shape and material of the component, material savings compared to forged parts, no necessary forming tools, short-term conversion to other shapes and materials is possible, high material quality due to the heat treatment coupled with the process in multi-layer welding, in particular uniform and isotropic toughness as well as adding material to an already existing workpiece [1].

Despite all the benefits, some drawbacks delay or inhibit the diffusion in the industry. Some issues to be clarified are e.g.: the layer deposition strategy (reduce residual stress and strains), assure a constant height for each layer as well as match the required geometry [3] (and its necessary accuracy), that is often impeded due to "stair stepping" effect [4].

2 Body reinforcement in automotive engineering

For material savings and stiffening, additive manufactured parts can be used, for example, in automotive engineering, as shown in Fig. 1.

But rather than inserting additional parts, material can be added to an existing component by additive manufacturing. In automotive engineering, WAAM could help to reinforce body components just by generating stiffening elements (Fig. 2). In order to stiffen flat areas of car body sheet, it is possible to apply a grid of weld metal. For the stiffening of angles, a gusset plate consisting of weld deposit can be created.

In theory, the changes in the cross section as well as the heat treatment as a result of welding are intended to

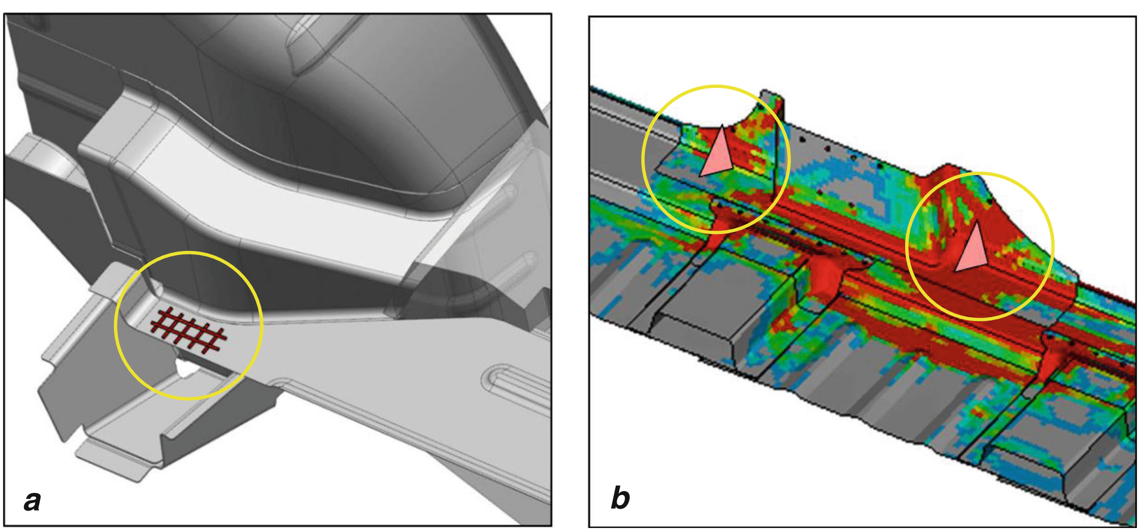


Fig. 2 Possible applications of arc-based additive manufacturing in automotive engineering: welding grid (**a**), gusset plate (**b**)

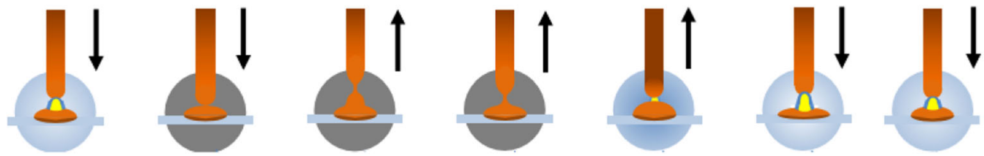


Fig. 3 One cycle of drop transfer in case of the welding process "MoTion Control Weld" [6]

increase stiffness. In addition to the benefits described above, the benefits of this simple and modifiable method could be more flexural rigidity even though comparatively less material volume is used and the possibility to use the system, respectively to modify it quickly, for many other applications.

3 Experimental procedure

3.1 Welding process

In case of manufacturing thin 3D components, a low-energy welding process is needed. Standard processes can be unstable at the low level of welding energy required, and spatter formation may be a problem. In this study, an advanced waveform controlled short arc welding process with low heat input and very stable arc was investigated and chosen. Special feature of this process is the bidirectional wire motion during welding for a better drop separation, almost no formation of spatter and a more stable arc. In each cycle, one drop separation occurs. The wire electrode is fed forward until the voltage almost reaches the value 0 (short circuit). At this moment, the drop passes into the weld pool. The short circuit acts as a trigger to move the wire backwards in a defined way. The droplet is detached cleanly, which results in significantly fewer weld spatters. The wire is fed back further until a certain (set) arc length is reached and the cycle is repeated (Fig. 3).

This is realized by a special powerful motor (Fig. 4, "MoTion Drive," near the welding torch) which provides the small high-frequency movements of the wire. As a result, the arc-on-time and the thermal energy can be reduced to a minimum. The "MoTion Control Unit" (Fig. 4) serves as a wire buffer, from which the motor can pull and push the wire as needed. A "CLOOS Qineo NexT" was used as welding power source (Fig. 4b, Table 1).

These experimental welding trials were subdivided into two fundamental topics. The first was to check the feasibility in principle of generating a gusset plate by additive manufacturing for reinforcing a right angle of formed thin steel sheets on car body areas. The second topic was to increase flexural rigidity of the sheets by depositing weld metal

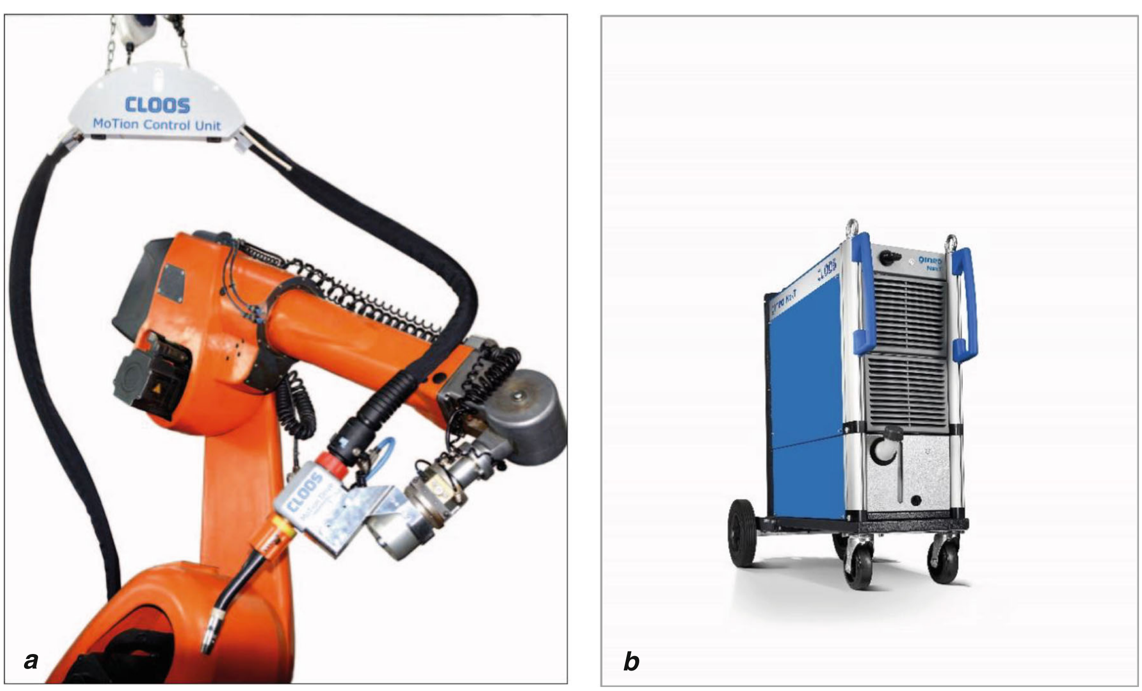


Fig. 4 Main components of the welding system with bidirectional wire movement: "MoTion Control Unit" and "Motion Drive" (**a**) welding power source "Qineo NexT" (**b**)

Table 1 Welding machine details

Type	Serial No.	Welding range	Open-circuit voltage
Qineo NexT 452	101	25 A/15 V–450 A/36.5 V	80 V
Duty cycle	40%	60%	100%
	450 A	450 A/36.5 V	350 A/31.5 V

in the shape of a grid. A subsequent bending test was used to show whether and how much increase in strength could be achieved.

3.2 Gusset plate

Preliminary welding trials (Fig. 5a, b) on uncoated and zinc-coated steel sheets of 2 mm thickness showed that alternating welding in flat position with a break of about 2 s after each weld seam seems to achieve the best results. In these experimental tests, it was found that reversing the weld direction of subsequent beads resulted in a lower warpage. Simulations of temperature profile show that in multilayer welding, the same weld direction of the subsequent beads leads to much greater distortion than the opposite direction [7]. This was therefore applied to the body parts.

The minimum achievable thickness depends mainly on the diameter of the filler metal used. The wire diameter was 1.0 mm, and the thickness of the gusset plate was about 2.8 mm. The welding current was reduced with increasing number of layers, so that the cooling time could remain the same. This procedure was then tested on car body parts (Table 2). These were electrolytically or hot-dip galvanized and 0.7 mm thick.

3.3 Grid

3.3.1 Welding trials on uncoated steel sheets

Preliminary tests on steel sheets of 2 mm thickness showed that alternating welding in flat position with a break of about 2 s after each weld seam lead to less deflection compared with same direction welding.

According to a study of A. Nickel [8], the deflection is also significantly influenced by the orientation of the weld seams on the sheet metal. Depositing a long raster pattern leads to more deflection (Fig. 6) than a short raster pattern.

A bending test according to VDA-238 was used. In order to be able to evaluate the direction of the grid in comparison to the bending axis, additional diagonal grids were welded. Three samples were investigated (Fig. 7): base material, orthogonal grid, and diagonal grid. The distance between each weld seams was kept equal. To achieve excellent penetration at the intersection points, the welding power was chosen to be higher for the second layers. The welding parameters are listed in Table 3.

3.3.2 Welding trials on zinc-coated steel sheets

In order to be able to evaluate the applicability on zinc-coated steel sheets, welding was also tried on these materials (Fig. 8). The short patterns were welded first.

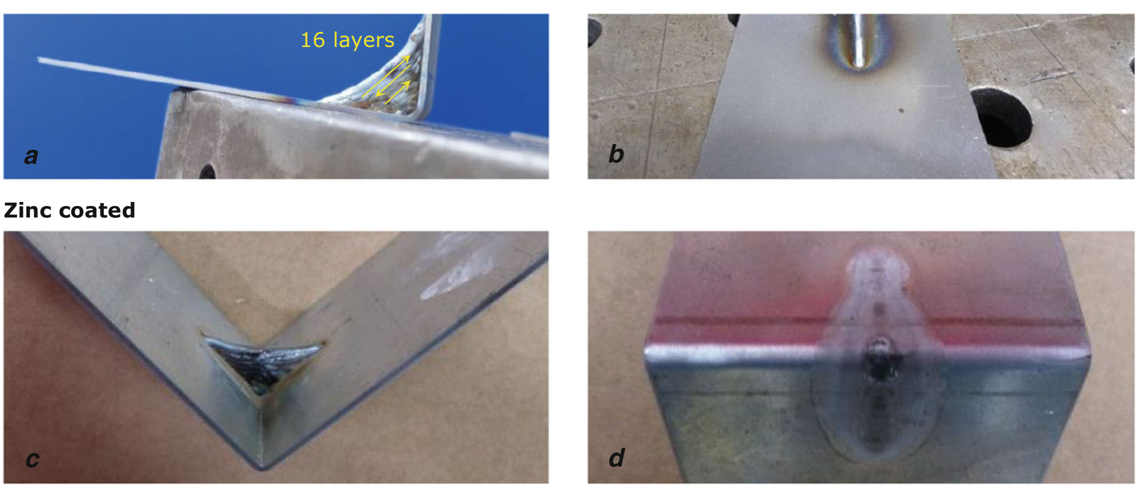


Fig. 5 Welding results of additive manufacturing of a gusset plate on steel sheets of 2 mm thickness: uncoated (**a** and **b**), zinc coated (**c** and **d**)

Table 2 Experimental assembly and parameters for welding a gusset plate on car body parts

Layer No.	1-3	4-9
Welding current	73 A	52 A
Voltage	12,1 V	11,6 V
Welding speed	80 cm/min	
Heat input	53 J/mm	36 J/mm
Wire feed speed	1,2 m/min	1,5 m/min
Shielding gas	92 % Ar + 8 % CO_2	
Filler material	G3Si1, Ø 1,0 mm	
Base material	Steel, electrolytically galvanized	
Thermal efficiency	0,8	

3.3.3 Welding trials on zinc-coated car body parts

The slicing of the models as known from large components is not necessary, but rather the welding sequence is important, so that the thin body panels do not deform too much. Furthermore, there was no complicated programming needed. Simple lines were sufficient. On the car body parts, the long patterns were welded first. The parameters in Table 4 were set for welding to the body parts (assembly the same as above).

3.4 Bending test

The uncoated steel sheets were examined in a three-point bending test according to VDA 238-100. The experimental assembly is shown in Fig. 9. A flat sheet is bent to an angled sheet until a certain bending angle is reached and the bending force decreased after the maximum. The maximum applied force represents the bending stiffness.

4 Results

4.1 Gusset plate

The gusset plate was tested on zinc-coated car body parts (Fig. 10). These 0.7 mm thick areas were both hot-dip galvanized or electrolytically galvanized.

In principle, it is possible to generate a gusset plate. The welds are visually appealing. At the rear side of the

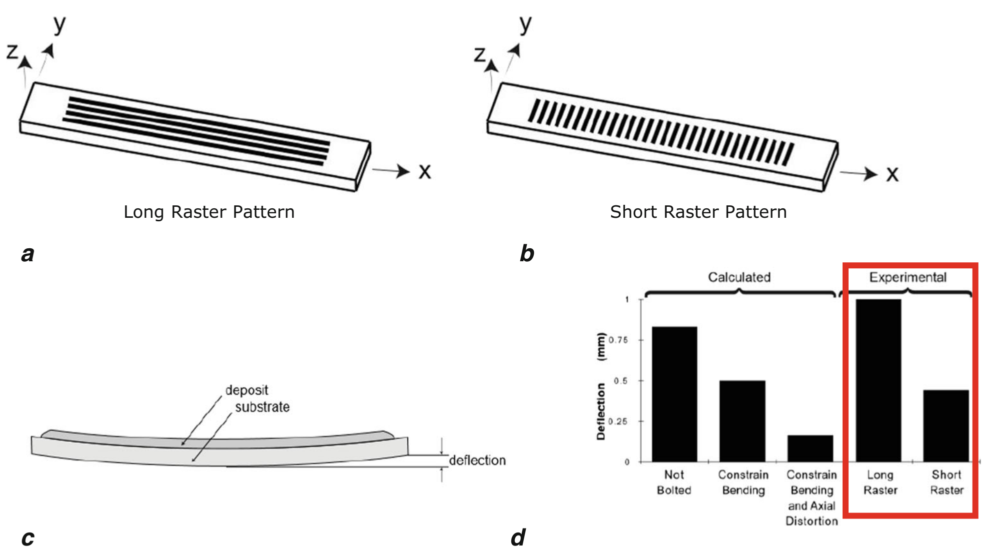


Fig. 6 Results of a study of shape deposition depending on welding direction [8]: long raster pattern (**a**), short raster pattern (**b**), illustration of deflection (**c**), exp. deflection of long and short raster pattern (**d**)

gusset plate (where the root is), the zinc coating is damaged due to the high heat input in relation to this small area. Warping of the sheet angles during welding can only be prevented by a convenient clamping device. For implementation in automotive industry, the aspects of the damaged zinc coating and possible warpage must be investigated further.

4.2 Grid: uncoated steel sheets

At the beginning of the experimental tests, welding trials on bright steel sheets of 2.0 mm thickness were carried out in order to find out if it is possible to weld across weld seams and achieve full penetration at the intersection points. The welds were 2.5 mm wide and narrow at the intersection points at about 0.8 mm (Fig. 11).

Transverse macrosection examinations (Fig. 12) show generally good penetration and layer structure. In addition, it can be seen at the intersection points that the first layer is remelted very deeply and that there is no particularly large seam height. A tempering effect, found in multilayer welds, is not clearly visible at the intersection points. The welding power of the second layer was deliberately chosen to be higher so that the intersection points are correctly fused. The Heat Affection Zone (HAZ) clearly extends to the underside of the sheet, which is also the case for the 0.7 mm thick body panels. Finally, the welds are visually appealing.

Table 3 Parameters for welding a grid on uncoated steel sheets

	Long patterns	Short patterns
Welding current	120 A	104 A
Voltage	13 V	16 V
Wire feed speed	4,1 m/min	3,4 m/min
Welding speed	150 cm/min	120 cm/min
Heat input	50 J/mm	67 J/mm
Shielding gas	92 % Ar + 8 % CO_2	
Filler material	G3Si1, Ø 1.0 mm	
Base material	Steel	
Thermal efficiency	0,8	

4.3 Bending test

As shown in Table 5, in total, 7 different examination points were defined. The base material without weld seams is

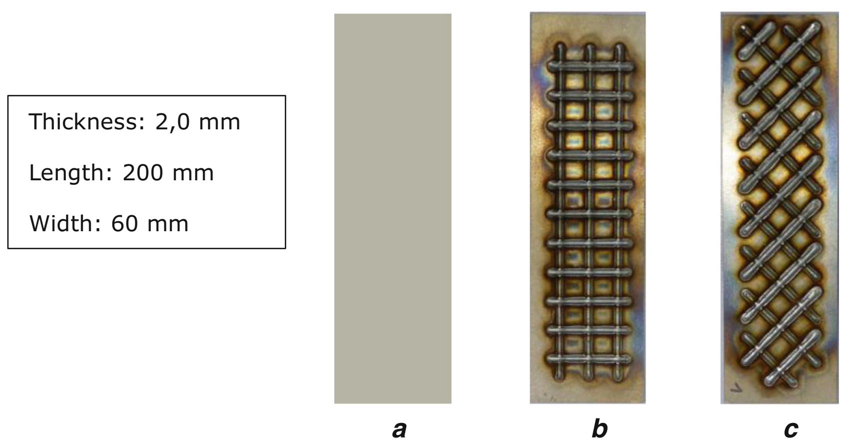


Fig. 7 Three types of samples for bending test: without grid (**a**), orthogonal grid (**b**), diagonal grid (**c**)

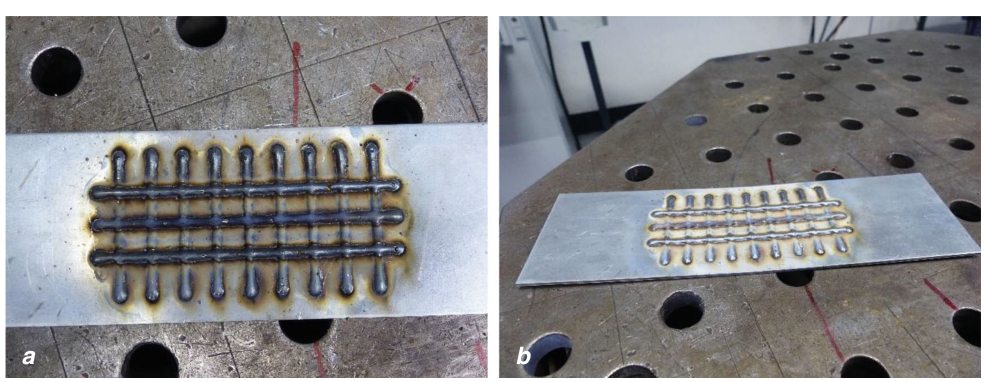


Fig. 8 **a**, **b** Welding results of additive manufacturing a grid on zinc-coated steel sheets of 2 mm thickness

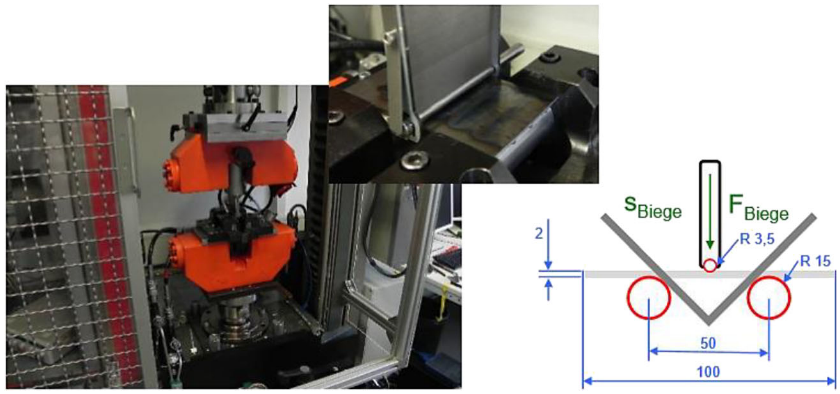


Fig. 9 Experimental assembly for bending test according to VDA-238 [9]

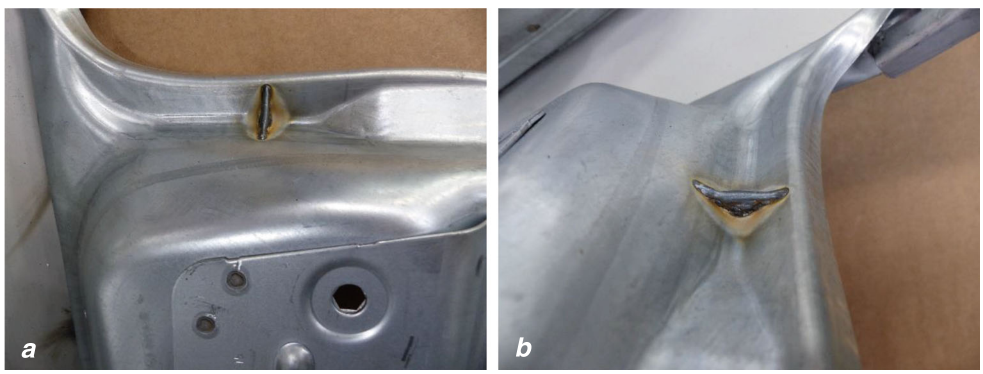


Fig. 10 **a**, **b** Welding results of additive manufacturing of a gusset plate on car body area of 0.7 mm thickness

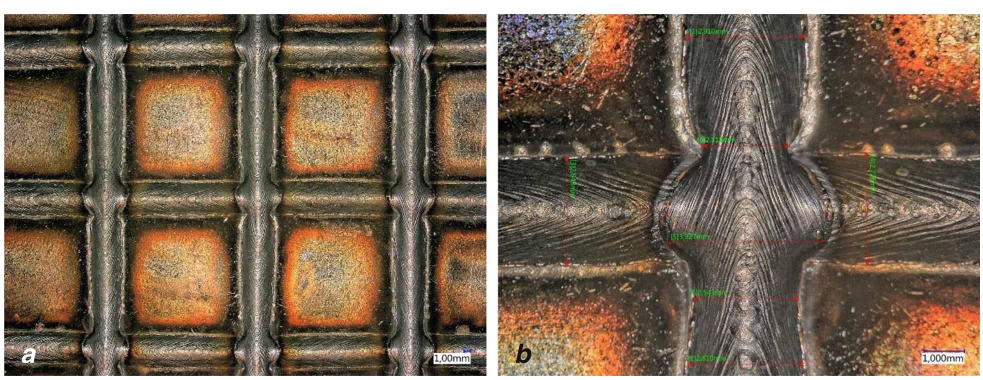


Fig. 11 Welding results of additive manufacturing of a grid on uncoated steel sheets: close-up of a weld grid (**a**), close-up of an intersection point (**b**)

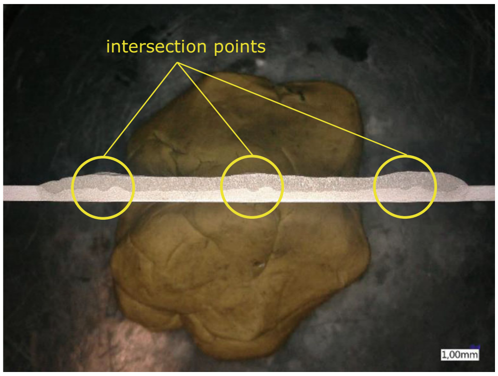


Fig. 12 Macrosection of welding results of additive manufacturing of a grid on uncoated steel sheets

indicated as orange. The orthogonal grids were examined between and on the intersection points (black and blue). The small-area diagonal grids were examined on one or two intersection points (green and yellow), and the large-scale diagonal grids were examined on two or three intersection points (red and gray).

The bending tests of the grid sheets indicated a clearly increased flexural rigidity compared with the base material (Fig. 13).

The bending force could be increased by at least approx. 50% (yellow). The maximum increase in bending stiffness was about 90% (blue). In general, more intersection points seem to lead to more bending stiffness, but a larger grid does not necessarily achieve the same stiffness. The blue curve indicates that the stiffness depends considerably on the load direction relative to the grid. This should be considered when designing the component. No cracks were found in these bend specimens.

Table 4 Parameters for welding a grid on car body parts

	Long patterns	Short patterns
Number of welds per grid	3	6
Welding current	45 A	35 A
Voltage	15.3 V	14.6 V
Wire feed speed	1.0 m/min	0.7 m/min
Welding speed	100 cm/min	60 cm/min
Heat input	33 J/mm	41 J/mm
Shielding gas	92% Ar + 8% CO_2	
Filler material	G3Si1, Ø 1.0 mm	
Base material	Steel, galvanized	
Thermal efficiency	0.8	

4.4 Grid: zinc-coated car body parts

Creating grids consisting of weld deposit were tested on car body parts (Fig. 14). These 0.7 mm thick areas were hot-dip galvanized.

Instead of the zinc-coated sheets, it is possible to weld a grid on the car body parts. At this status of development, the welds were visually not appealing unlike the deposits on bright steel sheets. At the rear side of the parts, the zinc coating is damaged due to the high heat input (in relation to the thin parts) needed for good penetration. Warping of the parts during welding can only be prevented by a convenient clamping device or perfectly matched welding sequence, weld length, and parameters. For implementation in automotive industry, the aspects of the damaged zinc coating and possible warpage must be investigated and prevented, although this was not the object of these experiments. Furthermore, it is difficult to put in enough energy to break through the zinc coating at the front side and achieve good penetration while keeping the zinc coating at the rear side undamaged.

5 Conclusions and outlook

The WAAM process is an upcoming technology for generating 3D parts. Adding material to an existing component is often used as a repair technique but may also be used to enhance performance of an existing design. There are many fields of application which could use the employment of this technology as an advantage. In the automotive industry, for example, engineering methods could be reviewed. As one application, WAAM could be used for creating local stiffening elements to reinforce critical body parts. On the one hand, targeted flat surfaces and also complex dimensioned components could be locally stiffened by welding on one-layer welding (in shape of a grid, lettering, etc.), or, on the other hand, small, effective stiffening ribs can be welded into the body contour using local WAAM multilayer seams. The advantage of this solution is its high flexibility. In robot-guided welding, the stiffening elements for surface stiffening or for complex structures can be freely programmed in terms of shape and dimensions and can be adapted to the defined load situation. It is possible to weld on individual beads or complex grid structures. This method is intended to increase the flexural rigidity of a component in a simple way and with a slight increase in weight or respectively with comparatively lower material volume (and weight) in case of reduced base material volume in cause of stiffening elements.

Compared with conventional welding processes, the special WAAM process offers enormous advantages concerning heat management. The special control ensures that the

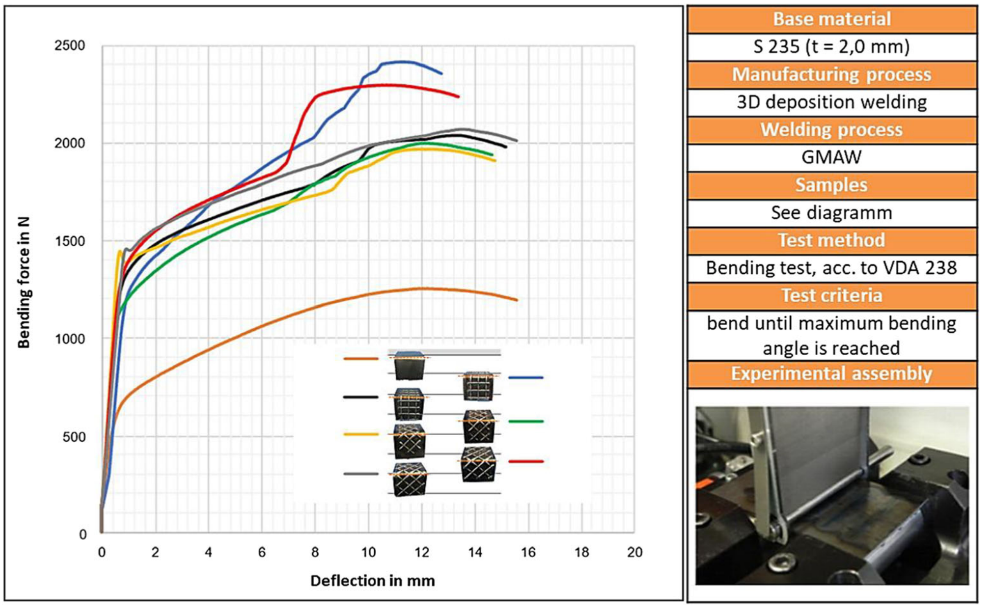


Fig. 13 Bending results of the uncoated grid sheets [9]

welding process requires a minimum of heat input. On the one hand, the heat input is required to melt the material on the arc side and to create a connection to the weld seam. The challenge is to put in as little heat as possible in order to avoid damaging the zinc layer and to avoid generating visible residues at the rear side of the weld seam that would result in undesirable efforts for subsequent processing. In addition, the process is not only suitable for galvanized materials but especially for thin steel sheets. It is possible to weld these grids not only on galvanized sheets but also on thin body parts. At this stage of development, these welds are visually not appealing, unlike the results achieved on uncoated steel sheets. For implementation in automotive industry, the aspects of the damaged zinc coating and possible warpage must be investigated further.

Bending tests on uncoated grid sheets carried out in this study indicate a clearly increased flexural rigidity up to 90% more bending force compared with the base material. In general, more intersection points seem to lead to more bending stiffness, but not necessarily a larger grid size. The stiffness seems to depend on the load direction relative to the grid. This should be considered when designing the component. At this time, no cracks were found on the bend specimens. More arc power leads to increased deposition rate, and higher welding speed leads to decreased HAZ size. Although a higher deposition rate can be achieved with more arc power and higher welding speed, this considerably increases the penetration depth [10], which can be counterproductive in the case of very thin car body sheets if the penetration depth is greater than the thickness of the sheet.

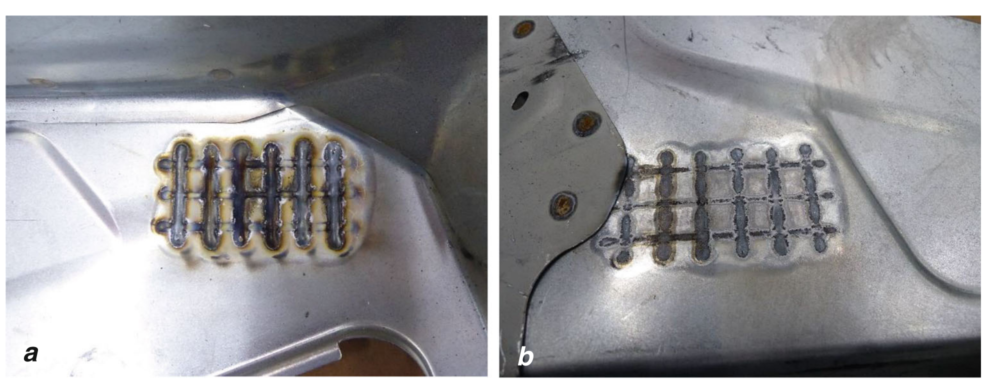
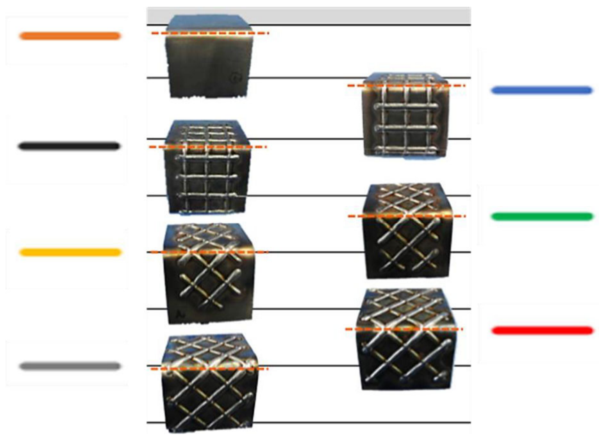


Fig. 14 Welding results of additive manufacturing of a grid on car body area of 0.7 mm thickness: weld side (**a**), rear side (**b**)

Table 5 Bending test samples [9]

Color of curve	Samples	Color of curve



But there are still some aspects that should be examined in more detail, especially to clarify to what extent the influence of changed heat input or the influence of the grid shapes has an effect on deformation and the failure behavior in the component test, e.g., due to different proportions of coarse grain in the microstructure, particularly high-strength steels for automotive. This is not yet sufficiently known. Instead of the described benefits, further research is needed to realize actual applications. The aspect of residual stresses must also be investigated to evaluate the safety of welded products. At present, it is assumed that the combination of structural change and changes in cross section leads to optimum utilization. This means that neither the application of a grid solely nor structural change alone would lead to these results. Mesh size could also be important. The knowledge gained from the applicability of this production technology can already be taken into account in the design and development of complex components and incorporated into the methods.

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