Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 108 (2022) 135–140

www.elsevier.com/locate/procedia

6th CIRP Conference on Surface Integrity

Effect of mechanical finishing on residual stresses and application behavior of wire arc additive manufactured aluminum components

Berend Denkena, Marcel Wichmann, Philipp Pillkahn[a]*

[a]*Institute of Production Engineering and Machine Tools, An der Universität 2, 30823 Garbsen, Germany*

* Corresponding author. Tel.: +49-511-762-5389; fax: +49-511-762-5115. *E-mail address:* pillkahn@ifw.uni-hannover.de

---

Abstract

Wire arc additive manufacturing (WAAM) offers great potential for the production of automobile components due to its high material deposition rates, low costs and design freedom. In order to meet the requirements regarding surface integrity and lifetime, the parts must be mechanically finished after WAAM. However, the subsurface properties (e.g. residual stresses) and consequently the application behavior are significantly influenced by the mechanical finishing process. Thus, the effects of deep rolling and heat treatment on the residual stresses and lifetime of AlSi12 and AlSi10Mg parts produced by WAAM are investigated and the results are presented in this paper. Deep rolling was found to induce compressive residual stresses into additive manufactured AlSi12 and AlSi10Mg workpieces. Furthermore, deep rolling increased the lifetime of the WAAM components significantly. With a combination of a heat treatment and subsequent deep rolling AlSi10Mg workpieces were manufactured securely fail-safe.

Keywords: additive manufacturing; residual stresses; application behavior

---

1. Introduction

Additive manufacturing (AM) processes open up new possibilities in production regarding process flexibility and design freedom [1-2]. Hence, especially WAAM becomes interesting for automotive applications because of its high deposition rates in combination with comparably low investment and operating costs [3-4]. Therefore, parts can be manufactured by WAAM economically and without the need for extra tooling [4]. In addition, WAAM offers the potential to meet the requirements of the rising number of variants in automotive sector. This can be achieved by individualization of semifinished mass products with WAAM [4]. WAAM components are near net shaped due to their low geometrical accuracy and high surface roughness. This makes a subsequent mechanical finishing necessary for technical applications [5].

The effects of mechanical finishing on residual stresses and application behavior has been investigated for conventionally manufactured parts [6-9]. Breidenstein et al. investigated the influence of subsurface properties caused by the mechanical finishing on the application behavior of hybrid components. They showed that subsurface properties, such as residual stresses, are influenced by deep rolling (DR) and have a significant effect on the application behavior [6]. Magalhaes et al. created an analytical model for the surface roughness, hardness and residual stresses induced by deep rolling for AISI 1060. They found that deep rolling induces generally compressive residual stresses independent from the chosen heat treatment and deep rolling parameters [7]. The influence of residual stress depth distribution on lifecycle behavior of AISI4140 has been investigated by Meyer et al.. They showed that the deep rolling parameters significantly affect the residual stresses and application behavior. Thus residual stresses and lifecycle behavior can be adapted to the specific requirements [8]. Altenberger pointed the potential of DR for applications in automotive and aerospace industry out. This is due to the

10.1016/j.procir.2022.03.026

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.

characteristic improvement of the surface and the increased mechanical strength of the components because of DR [9].

Furthermore, the effect of mechanical finishing of AM components on the subsurface properties has been investigated. Williams et al. examined interpass rolling in the WAAM process between the deposition of layers. They found out, that interpass rolling can reduce tensile residual stresses in WAAM components or even induce compressive residual stresses [5]. Denkena et al. investigated the effect of mechanical finishing on the subsurface and mechanical properties of WAAM aluminum components. The authors showed the positive effect of deep rolling on surface roughness, hardness and mechanical properties [1]. Köhler et al. examined the WAAM of aluminum components. They showed the direction-dependent manner of mechanical properties in WAAM components [4]. Zhuang et al. investigated the effects of DR on the fatigue life of laser cladded aluminum components. They showed that DR induces compressive residual stresses which lead to an increased fatigue life of the components [10].

In order to meet the requirements of automotive components lifecycle behavior of WAAM components and the effects of mechanical finishing processes need to be known. This leads to the aim of this paper: **Knowledge about the effect of deep rolling process parameters on residual stresses and lifecycle behavior of WAAM aluminum parts.**

Nomenclature

AM	Additive Manufacturing
AlSi12	Aluminum-Silicon12 (Al-4047)
AlSi10Mg	Aluminum-Silicon10-Magnesium (Al-4046)
d	Diameter
d_b	Ball diameter (Deep rolling)
DOE	Design of experiment
DR	Deep Rolling
f	Feed
HT	Heat Treatment
I_a	Anode current
k	Factor thousand
kV	Kilovolt
m	Meter
mA	Milliampere
mm	Millimeter
M_b	Bending Moment
min	Minutes
MPa	Megapascal
n	Number
Nm	Newtonmeter
p_w	Deep rolling pressure
U_a	Acceleration voltage
Rz	Arithmetic average roughness
v_f	Feed rate (WAAM)
v_{wire}	Wire velocity (WAAM)
WAAM	Wire Arc Additive Manufacturing
σ	Stress
σ_b	Bending stress
θ	Bragg angle

2. Materials and Methods

For the investigations of Al-4047 (AlSi12) WAAM components, welding wire by the Metal Technology Canterbo GmbH with a diameter $d = 1.2$ mm was used as filler material. The chemical composition of the AlSi12 welding wire is shown in Table 1.

Table 1. Chemical composition (weight %) welding wire AlSi12 (Al-4047).

Material	Al	Si	Fe	Cu	Mg	Mn	Zn
Al-4047	>88.5	11.2	0.2	0.001	0.001	0.001	0.001

The Al-4046 (AlSi10Mg) workpieces were manufactured using a welding wire from Drahtwerk Elisental W. Erdmann GmbH & Co. with a diameter $d = 1.2$ mm. The chemical composition of the welding wire is shown in Table 2.

Table 2. Chemical composition (weight %) welding wire AlSi10Mg (Al-4046).

Material	Al	Si	Fe	Cu	Mg	Mn	Zn	Ti
Al-4046	>89.4	10.0	0.2	0.001	0.31	0.01	0.003	0.02

A EWM Alpha Q 352 puls welding power source is used for the WAAM of the workpieces. The WAAM system contains a Manutec 6-axis robotic handling system and is shown in Fig. 1. A reduction of heat input by the WAAM process in the workpieces is achieved by using the coldArc puls process by EWM. As a shielding gas Argon 4.6 was utilized. A standard welding program for AlSi welding wire with a diameter $d = 1.2$ mm was used for the manufacturing of the workpieces.

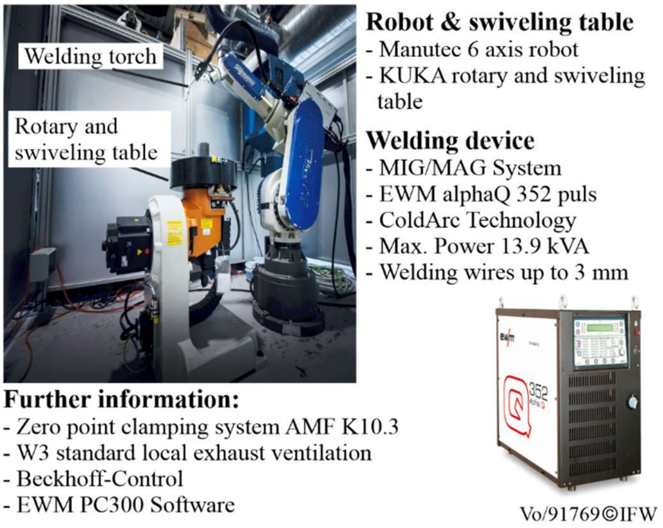


Fig. 1. WAAM System

In Order to investigate the application behavior, rotating bending test samples were manufactured. The process chain consist of WAAM, pre-turning, an optional heat treatment, turning and optional deep rolling. In Fig. 2 (a) the dimensions of the test samples are shown. Fig. 2 (b) shows the deep rolling process schematically. The experimental setup for the mentioned processes is introduced subsequently.

First, the semifinished workpieces were manufactured layerwise from AlSi12 and AlSi10Mg by WAAM. To examine the influence of the building direction on the application behavior, workpieces were manufactured in vertical and horizontal building direction for AlSi12. This is shown in Fig. 2 (c). In order to ensure cost-efficient investigations the AlSi10Mg samples were only manufactured in the vertical building direction. All samples were manufactured with a constant WAAM process parameter set consisting of a feed rate $v_f = 600$ mm/min and a wire velocity $v_{wire} = 8$ m/min. For each experimental series of workpieces with vertical building

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.

direction, five samples and for workpieces built horizontally, four samples were manufactured and investigated.

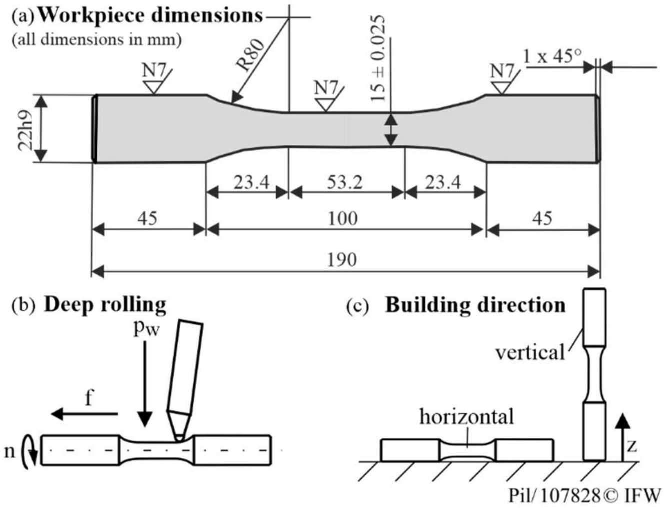


Fig. 2. (a) Workpiece dimensions, (b) Deep rolling (c) Building direction

Since the influence of the turning process on residual stresses and application behavior is not investigated in this paper, turning is considered as an auxiliary process. The rotating bending test samples were manufactured with constant turning process parameters according to DIN 50113 [11].

To investigate the effect of heat treatment on the residual stresses and the application behavior, especially for the AlSi10Mg workpiece samples, experiments with heat treated samples were conducted. Therefore, a T6 - heat treatment solution annealing and quenching was performed after preturning of the samples. Solution annealing was conducted for 3 to 6 hours at 525 °C. An artificial aging step was provided for 6 – 8 h at 165 °C according to the T6 standard.

Deep rolling investigations were carried out in order to examine its influence on the residual stress state of the additive manufacturing workpieces and the application behavior. Therefore, the deep rolling process parameters deep rolling pressure $p_w = 2 - 5$ MPa and feed $f = 0.05 - 0.1$ mm were varied. A standard HG6 deep rolling tool of the Fa. Ecoroll AG with a ball diameter of $d_b = 6.35$ mm was used. The pressure was provided by an external compressor system HGP 6.0 of the Fa. Ecoroll AG with an operation window of $p_w = 2 - 60$ MPa.

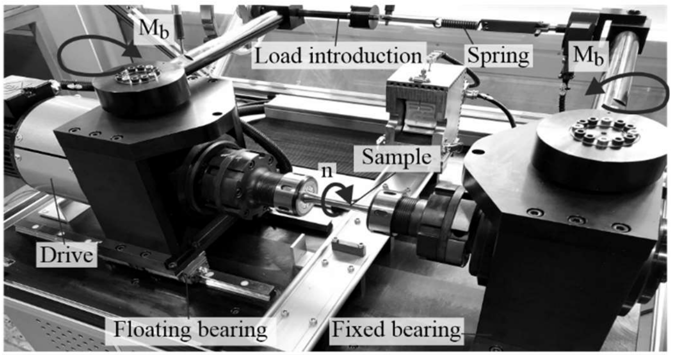
A summary of the DOE and the investigated process parameters in this paper is shown in Table 3.

Table 3. DOE and investigated process parameters

Material	Heat Treatment	Building direction	Deep Rolling pressure p_w	Deep Rolling Feed f
Al-4046	Yes	Horizontal	-	-
Al-4047	No	Vertical	2 MPa	0.05 mm
			5 MPa	0.01 mm

The residual stresses were determined via X-ray diffraction using the $\sin^2\psi$-method. The measurements were conducted on a Seifert XRD 3003 ETA diffractometer with white radiation from a tungsten anode. The non-destructive energy dispersive method was used. The acceleration voltage U_a was set to 50 kV and the anode current was set to $I_a = 58$ mA. Measuring spot size was 2 mm in diameter and the measurement direction was transverse and parallel to the machining direction with a constant Bragg angle θ of 11°. Reference measurements were conducted on 3 samples, and showed the comparability of the residual stress measurements. The accuracy and reproducibility of the energy dispersive residual stress measurement via X-ray diffraction is shown by Breidenstein et al. [12,13]. Due to this for each parameter set one sample was investigated via X-ray diffraction.

The application behavior was tested by using a rotating bending test. The experiments were conducted at a SyncoTec Power Rotabend 4-point rotating bending test machine. This device is shown in Fig. 3 and has a nominal load of 400 Nm. The preload at the beginning of the tests was set to $M_b = 10 – 20$ Nm at a rotating speed of 600 min^{-1}. The speed is increased to 6,000 min^{-1} after the target load is adjusted. For better comparison, all tests were carried out with a bending moment of $M_b = 25$ Nm. This results in a bending stress amplitude of $\sigma_{max} = 75$ MPa and a mean stress of $\sigma_{mean} = 0$ MPa. In order to minimize the influence of the surface roughness on the application behavior of the workpieces, it was ensured, that all workpieces samples exhibit an arithmetic average roughness of Rz < 6 µm. For workpieces with vertical building direction, five samples and for workpieces built horizontally, four samples were investigated.



Rotating bending test stand:
SincoTec Power Rotabend
4-Point Rotating bending test

Test conditions:
Bending moment: $M_b = 25$ Nm
Bending stress: $\sigma_b = 75$ MPa

Pil/107827© IFW

Fig. 3. Experimental setup of the rotating bending test machine

3. Results

3.1 Residual stresses

Since the residual stresses transvers to the deep rolling direction are higher than parallel to the deep rolling direction, these measurements were evaluated in this paper. The effect of heat treatment (HT) and deep rolling on the residual stresses development in WAAM AlSi12 components has been investigated. Therefore, the residual stress depth profiles along the process chain are shown in Fig. 4. In this figure, the residual stress state after turning, heat treatment and deep rolling of the samples is shown. The initial residual stress state after turning exhibits tensile residual stresses close to the surface. This is due to the thermal heat input in the turning process. In a depth of about 250 µm compressive residual stresses occur. In comparison, the heat treatment induces compressive residual stresses over the entire measurement range.

This can be attributed to the quenching process in the heat treatment. Since the chosen heat treatment is not ideal for casting alloys such as AlSi12, the quenching might lead to the

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.

compressive residual stress through inner tension. Nevertheless the heat treatment was conducted on the AlSi12 samples, because a future application in automotive industry is the printing of part features onto semifinished casting parts made of AlSi10Mg. Afterwards the T6 heat treatment is a standard process. By deep rolling even more compressive residual stresses are induced into the workpiece. The chosen deep rolling parameters lead to maximum compressive residual stress of about -180 MPa. The induction of compressive residual stresses into the workpiece by deep rolling is a well-known effect for conventionally manufactured components and is stated to have a positive effect on their lifetime [7-9].

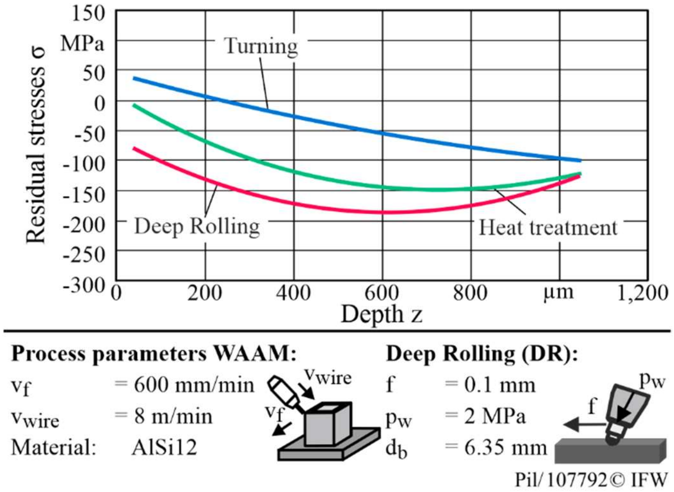


Fig 4. Residual stress depth profiles along the process chain AlSi12

The influence of DR parameters on residual stresses of AM AlSi12 samples was investigated. The residual stress depth profiles for not heat treated samples fabricated with different deep rolling parameters are shown in Fig. 5.

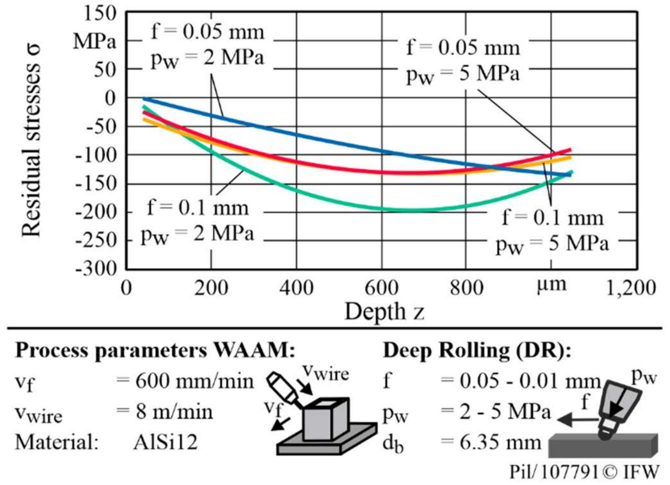


Fig. 5. Effect of deep rolling parameters on residual stresses AlSi12

It can be seen that deep rolling induces compressive residual stresses into the workpiece. A deep rolling parameter set of feed $f = 0.1$ mm and a deep rolling pressure $p_w = 2$ MPa induces the highest compressive residual stresses into the workpiece. Usually the highest compressive residual stresses are induced by the deep rolling parameter set with the lowest feed f and the highest pressure. In this case prior investigations showed for a deep rolling pressure $p_w = 5$ MPa a negative influence on the surface roughness. This effect indicates a significant deformation of the components [1]. This deformation leads to a relief of the residual stresses. Furthermore, the effect of the building direction as shown in Fig. 2 (c) on the residual stresses in the AlSi12 workpieces was investigated. No significant deviations in the residual stress state of horizontal and vertical samples were found.

The effect of Heat Treatment (HT) and Deep Rolling (DR) on the residual stress state for AlSi10Mg workpieces manufactured by WAAM has been investigated. The results of the depth resolved residual stress measurements are shown in Fig. 6. The residual stress depth profiles for AlSi10Mg without heat treatment and deep rolling (Turning), for heat treated samples and for heat treated and deep rolled samples are shown.

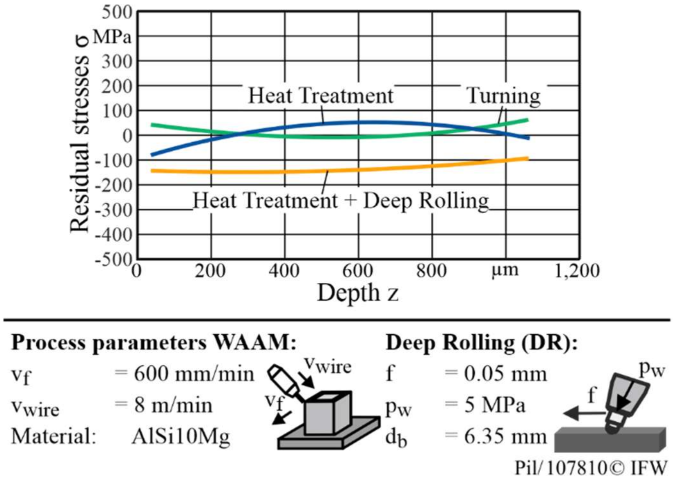


Fig. 6. Influence of HT and DR on residual stresses AlSi10Mg

The initial manufacturing state (Turning) without HT and DR can be seen as almost stressless. The heat treatment induces little tensile stresses compared to the initial manufacturing. However, there are no significant deviations between the residual stress states of the heat treated and not heat treated samples. This leads to the conclusion, that the heat treatment does not significantly affect the residual stress state of the workpieces. The heat treatment consists of solution annealing and quenching, which leads to a homogeneous microstructure for wrought alloys such as AlSi10Mg with little residual stresses. In combination with deep rolling, it leads to compressive residual stresses throughout the whole measurement range. This effect can be attributed to the deep rolling process [7]. Deep rolling induces compressive stresses into the workpieces by using the chosen process parameters. This is a result of the work hardening of the surface zone because of the deep rolling process. Furthermore, the effect of residual stress relief due to load over the lifecycle is investigated for AlSi10Mg. Therefore, residual stress measurements were conducted after turning, after deep rolling and after 10,000 load cycles in the rotating bending test machine. The results are presented in Fig. 7. DR induces compressive residual stresses into the workpieces. These compressive residual stresses do not tend to relieve early in the lifetime of the workpiece sample. The residual stress depth profile of the sample after 10,000 load cycles shows the same development from the surface up to a depth of about 500 µm as the unloaded sample before. In greater depths the compressive residual stresses tend to be minimized after the rotating bending test. This results in an almost stressless state at a depth of about 1,000 µm. However the surface residual stresses tend to have a higher impact on the lifetime in rotating bending tests, than

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.

residual stresses in higher depths. This is because the main load in rotating bending tests occurs in the surface.

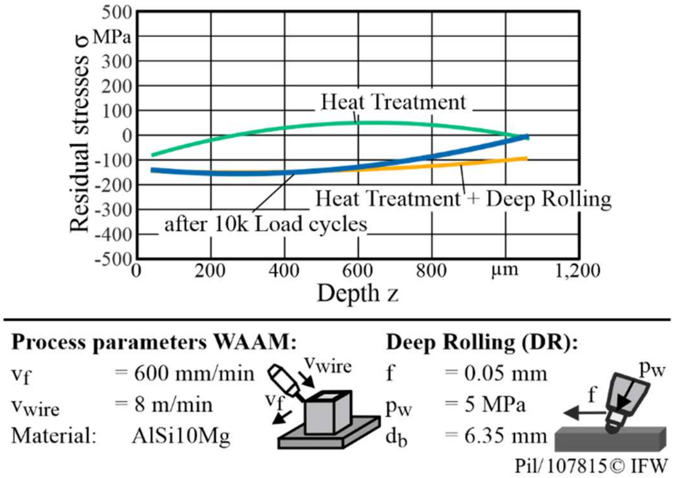


Fig. 7. Residual stress relief in AlSi10Mg after 10,000 load cycles

3.2 Rotating bending tests

The application behavior of additive manufactured workpieces has been also examined by rotating bending tests. The results for AlSi12 are presented in the following. Fig. 8 shows the influence of the building direction on the lifetime. It can be seen that vertical samples tend to exhibit a significant higher number of load cycles than horizontal samples. This effect can be attributed to the load direction, which is parallel to the building direction of the horizontal samples and consequently transverses to the layer direction in WAAM components (see Fig. 2 (c)). Thus, horizontal samples in a rotating bending test represent a more critical kind of loading.

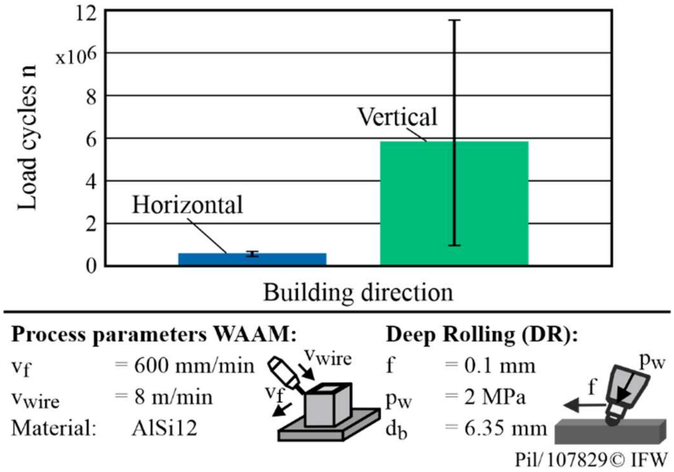


Fig. 8. Influence of the building direction on the application behavior AlSi12

The effect of deep rolling and heat treatment on the application behavior of WAAM AlSi12 has been examined. The results are shown in Fig. 9. The number of load cycles until the fracture in rotating bending tests for different post-processing methods and parameters can be seen here.

On the left side the results for heat treated samples are shown and on the right side the rotating bending test results for workpieces without heat treatment are shown. Samples which have not been deep rolled show the lowest lifetime of all. Regardless of the chosen deep rolling parameters, an increased average lifetime is achieved by deep rolling.

For AlSi12 the heat treatment shows no positive effect on the lifetime. Because of the high standard deviations no optimal DR parameter set was found. Further investigations on the optimal WAAM and DR parameters for AlSi12 are suggested.

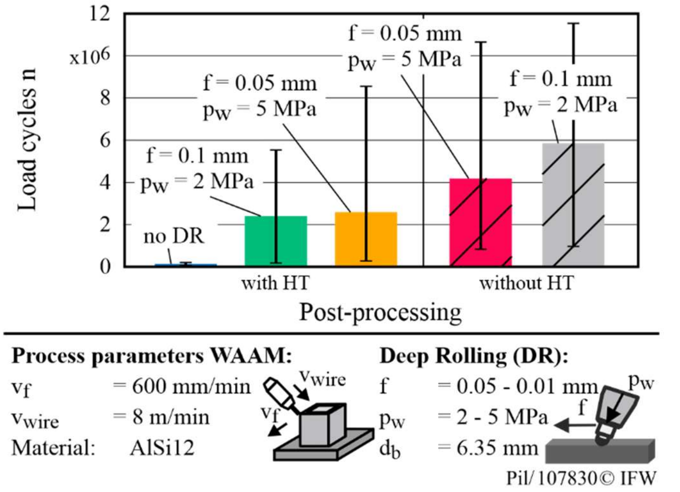


Fig. 9. Influence of HT and DR on application behavior AlSi12

Nevertheless, for the WAAM AlSi12 samples high deviations regarding lifetime occur. This can be attributed to the porosity in the components. When porosity occurs near the surface the pore can operate as a crack initiation point and lead to an early fracture. A picture of the fracture zone of the samples after the rotating bending test is shown in Fig. 10.

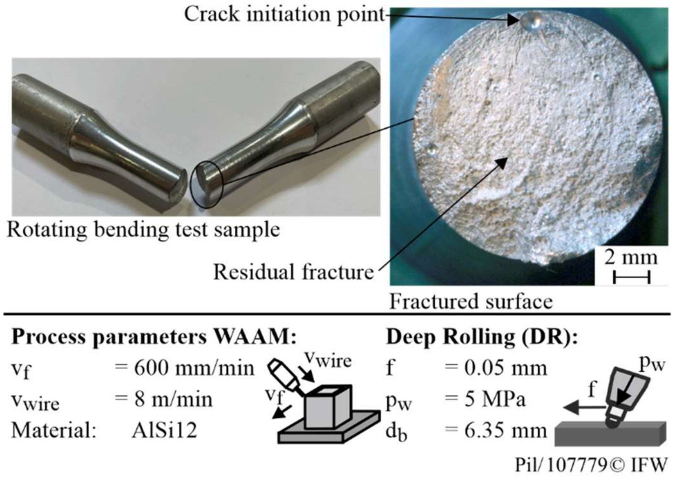


Fig. 10. Failure Analysis AlSi12

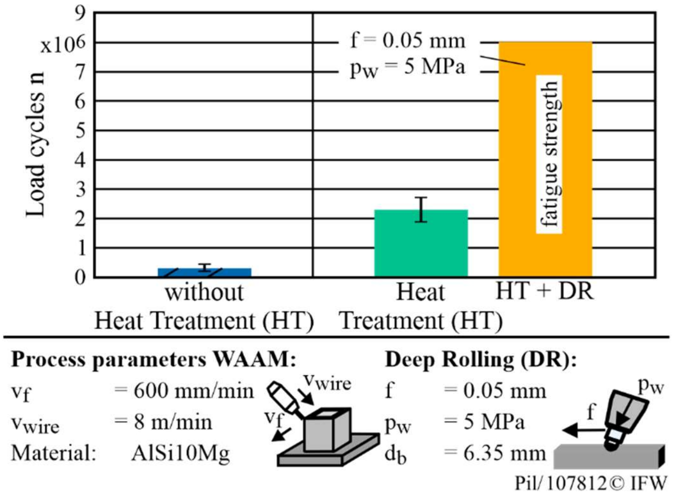


Fig. 11. Influence of post-processing on the application behavior AlSi10Mg

For the AlSi10Mg samples, the effects of heat treatment and deep rolling on the application behavior have been

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.

investigated. The results are shown in Fig. 11. It can be seen that a heat treatment significantly increases the lifetime of the workpieces. This is due to the solution annealing which leads to a homogenous microstructure for wrought alloys such as AlSi10Mg. In comparison to that, WAAM components exhibit areas with different microstructures, because of the repetitive heating and cooling cycles in the WAAM process [3]. Furthermore, fatigue strength of the samples is obtained by additional deep rolling. In this process chain, samples were produced securely fail-safe by a combination of HT and DR.

4. Conclusion and Outlook

In this paper, the effects of mechanical finishing on the residual stresses and the application behavior of WAAM aluminum components are discussed. Since WAAM components are only near net shaped, a mechanical finishing process is necessary to achieve the desired geometry and subsurface properties. To investigate the effect of DR on the residual stresses and application behavior of AM components, two experimental stages were performed for the materials AlSi12 and AlSi10Mg. First, rotating bending test samples were manufactured by WAAM and subsequently machined by a turning process. Afterwards, the effect of deep rolling on the residual stresses is investigated by X-ray diffraction under variation of the deep rolling parameters feed f and pressure p_w. Additionally the influence of building direction and heat treatment were taken into account. The second stage contained the investigation of the influence of mechanical finishing on the application behavior of aluminum AM components. Therefore, rotating bending tests were conducted. Here, the influence of DR parameters, building direction and HT on the lifetime of the workpieces was examined.

It is shown that deep rolling is an effective mechanical finishing process for WAAM in order to induce compressive residual stresses into the workpieces. Here, a comparably low pressure p_w of 2 MPa and a feed of 0.1 mm induced the highest compressive residual stresses in AlSi12 components. Furthermore, no significant effect of the building direction in WAAM process on the residual stresses was found for AlSi12. For AlSi10Mg components, no significant effect of the heat treatment on the residual stresses was found. However, deep rolling induces compressive residual stress into AlSi10Mg components, which remain in a depth of about up to 500 µm constantly under load. The resulting positive effect of deep rolling on the application behavior of additive manufactured components was found for AlSi12 as well as for AlSi10Mg. Furthermore, the building direction was found to have a substantial influence on the lifetime of WAAM components. Vertical built samples have a higher lifetime than horizontal ones, because horizontal samples in a rotating bending test represent a more critical kind of loading. In addition deep rolling increases the lifetime of the components significantly. Especially for AlSi10Mg fatigue strength was achieved by deep rolling in combination with a heat treatment. Here the combination of a homogenous microstructure, because of the HT and the compressive residual stresses at the surface as a result of DR, are beneficial for the application behavior.

The investigations prove the positive effect of deep rolling on the residual stresses and application behavior of WAAM aluminum components. In this context, deep rolling ensures and increases the performance of AM components significantly. Further investigations on the optimized deep rolling parameters for AlSi10Mg should be conducted. In addition, further research is required regarding the influence of the building direction on the application behavior of workpieces out of AlSi10Mg. The influence of the WAAM process parameters on the application behavior of AlSi12 components should be investigated. For a reliable prognosis of the lifetime of AlSi12 components optimal WAAM parameters must be known. Targeted goals in terms of residual stress state and application behavior should be determined. DR process parameters which meet the targeted goals can be identified afterwards. This should be executed by taking the field of tension defined by productivity, cost and resource efficiency and quality into account. A detailed knowledge about the choice of deep rolling process parameters would be beneficial to the users and for the market breaktrough of WAAM.

Acknowledgements

The results were obtained within the project “Powertrain 2025”. The authors want to thank the Federal Ministry for Economic Affairs and Climate Action (BMWK) for funding this project.

References

[1] Denkena B, Krödel A, Pillkahn P. Mechanical finishing of wire arc additive manufactured aluminum parts. In 20th Machining Innovations Conference for Aerospace Industry, MIC 2020, Garbsen

[2] Gibson I, Rosen D, Stucker B. Additive Manufacturing Technologies. 2nd ed. New York: Springer; 2015

[3] Denkena B, Grove T, Vogel N, Stamm S. Additives Potenzial für die subtraktive Prozesskette. In MM – Maschinenmarkt, Das Industriemagazin 2018; 15: p. 32 - 36.

[4] Köhler M, Fiebig S, Hensel J, Dilger K. Wire and Arc Additive Manufacturing of Aluminum Components. Metals 2019; 9 (5): p. 608.

[5] Williams SW, Martina F, Addison AC, Ding J, Pardal G, Colegrove P. Wire + Arc Additive Manufacturing. Materials Science and Technology 2016; 32 (7): p. 641 - 647.

[6] Breidenstein B, Denkena B, Meyer K, Prasanthan V. Influence of subsurface properties on the application behavior of hybrid components. In 5th CIRP Conference on Surface Integrity (CSI) 2020; 1st e-conference; Procedia CIRP 87: p. 302 - 308.

[7] Magalhaes FC, Abrao AM, Denkena B, Breidenstein B, Mörke T. Analytical Modeling of Surface Roughness, Hardness and Residual Stress Induced by Deep Rolling. J. of Materi Eng and Perform 2017, 26: p. 876 – 884

[8] Meyer K, Denkena B, Breidenstein B, Abrao AM. Influence of residual stress depth distribution on lifecycle behaviour of AISI4140. In 5th CIRP Conference on Surface Integrity (CSI) 2020; 1st e-conference; Procedia CIRP 87: p. 450 – 455

[9] Altenberger I. Deep Rolling – The past, the present and the future. In Conf Proc: ICSP 2005, 9: p. 144-155.

[10] Zhuang W, Liu Q, Djugum R, Sharp PK, Paradowska A. Deep surface rolling for fatigue life enhancement of laser clad aircraftaluminium alloy. Applied Surface Science 2014, 320: p. 558 – 562

[11] DIN 50113. Testing of metallic materials - Rotating bar bending fatigue test. 2018

[12] Breidenstein B., Denkena B., Prasanthan V. Energy dispersive residual stress determination. Euro Hybrid Materials and Structures 2016, p. 211-215.

[13] Breidenstein, B., Denkena, B., Mörke, T., Prasanthan, V. Non-destructive determination of residual stress depth profiles of hybrid components by energy dispersive residual stress measurement. Key Engineering Materials 2017, 742: p. 613-620.

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.