Fatigue improvement of aluminium welds by means of deep rolling and diamond burnishing

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Abstract

Deep rolling is an industrially widely established mechanical surface treatment process for the modification of roughness and fatigue resistance. However, the process has not been considered as a potential method for the mechanical post welded treatment of welded joints yet. Even, the potential of deep rolling for increasing the fatigue strength is comparably well-known in the case of non-welded components. Therefore, the effect of deep rolling (hydrostatic mounted tool) and diamond burnishing (mechanical mounted tool) to increase the fatigue strength of butt joints was approved in this work for aluminium alloy AlMg4,5Mn0,7 (EN AW 5083). For this purpose, fatigue tests under full tensile loading were performed in as-welded and deep rolled, burnished and ultrasonic impact treated conditions. Different residual stress states as well as work hardening states are determined in deep rolled and burnished condition. However, similar and significant fatigue life improvement was determined for both processes.

Keywords Deep rolling · Post weld treatment · Fatigue · Residual stress · Work hardening

1 Introduction

In general, the fatigue resistance of steel and aluminium welded joints is lower compared to the base material. The reasons are the notch effect caused by the weld bead, the change of the microstructure (metallogical notch) and the possible presence of tensile residual stresses at the weld toe. For this, multiple methods for the post weld treatment have been developed and approved in the last decades with the aim of increasing the fatigue resistance of welded joints, for example, the high-frequency mechanical impact (HFMI) treatment [1].

However, the main focus in the previous works in this field was the application of post weld treatment for welded joints made of construction steel (typically steel grades

range from S235 to S960 [1]). For welded joints made of aluminium alloys, the recommendation of Haagensen and Maddox [2] covers the effect of burr grinding, TIG-dressing and hammer- and needle-peening also for welded joints made of 5000 and 6000 aluminium alloys. Still, relatively less literature data is available for the mechanical posttreatment of these aluminium alloys. However, some previous investigations focus on the application of shot peening for the posttreatment of aluminium welds made of 5000 alloys [3–5].

Deep rolling and burnishing are a widely industrially applied mechanical surface treatment process with a high degree of automatisisation for the modification of hardness, roughness and residual stress state as well as for the structuring of surfaces. Industrial applications are pivots, crankshafts, steering knuckles, engine valves, spindles, thread bolts, bearings and gear wheels in the automotive, airplane and rail vehicle industry [6]. Extensive investigations about the fatigue performance of deep rolled specimens made of 5000 and 6000 alloys were performed by Juijerm and others [7–9]. These investigations show that the work hardening (increase of dislocation density) can inhibit or retard surface fatigue crack initiation as well as fatigue crack growth under condition that the near-surface work hardening state is stable during cyclic loading.

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The process of deep rolling itself is defined as enforced plastic deformation of surface layers caused by single or multiple rolling by rolls with a determined geometry under constant contact pressure [10]. Several experimental studies are available with the aim of increasing the fatigue resistance of treated components, even if nearly all available studies deal with non-welded parts [8, 11–14].

Previous studies for the application of hydrostatic deep rolling of welded round bar specimen made of S355J2 + N, S690QL and EN AW 5083 showed a significant fatigue life improvement. However, the fatigue life improvement of conventional shot peening was even higher in this case. Furthermore, higher hardness at the weld toe was determined after shot peening. That led to the conclusion that the positive effect of deep rolling could be higher if the process parameters (contact force and tool diameter) are optimized to reach a maximum degree of work hardening at the fatigue critical location of the weld toe. Compared to high-frequency mechanical impact process with contact forces of > 3 kN [15], the contact forces at deep rolling are significantly lower. An application for low strength materials may be attractive as an alternative mechanical surface treatment method.

The aim of the present work was to investigate the possibility of fatigue strength improvement by deep rolling and burnishing process of welded aluminium alloys in larger scales compared to the low-scale specimens in the previous study [16]. Furthermore, recommendations of the process parameters for both processes for the posttreatment application of welded joints should be made.

2 Specimen manufacturing

Previous studies [16] on the deep rolling process of comparably small round bar specimens made of EN AW 5083, S355J2 + N and S690QL showed that the weld toes were not completely treated at every position, especially for the investigated steels. Therefore, both surface treatment processes

were applied at butt joints made of the AlMg alloy EN AW 5083 (AlMg4,5Mn0,7) with larger dimensions, given in Fig. 1a. The mechanical properties of these base materials are given in Table 1.

The EN AW 5083 specimens were manufactured by metal inert gas (MIG) welding (process 131 according to EN ISO 4063) with a universal power source type Fronius CMT Advanced 4000 Rand with an industrial robot. The welding parameters are summarized in Table 2. The cross-section of the welds are shown in Fig. 1b.

3 Post weld treatment

The post weld treatment was applied with a hydrostatic mounted Ecoroll tool (type HG4). The process parameters according to the previous investigations [16] were used. Additionally, a mechanical mounted burnishing tool (type DDW 0°) of the company Baublies with a diamond tip was used. For the application, both tools were mounted at a CNC milling machine. Thereby, the following process parameters could be varied: contact force F (or pressure p and spring stroke h), feed rate V and stepover distance a . For a direct comparison of both tools and processes, the feed rate and stepover distance were fixed to $V = 1000$ mm/min and $a = 0.1$ mm. These values were recommended from both tool manufacturers. The pressure of the hydrostatic mounted tool (HG6) and the spring stroke (DDW 0°) was selected to reach a similar contact force for both tools. For this, the contact force according to previous investigations [16] at round bar specimen made of EN AW 5083 was used. However, it

Table 1 Mechanical properties of the base materials

Material	Yield strength [MPa]	Tensile strength [MPa]	Elongation [%]
EN AW 5083	203	325	24,5

Fig. 1 a Specimen geometry, b cross-sections of the weld

Table 2 Welding parameters

Material	Current [A]	Voltage [V]	Speed [cm/min]	Wire rate [m/min]	Wire diameter [mm]	Weld material
EN AW 5083	220	25	45	8.5	1,2	AX-AlMg5

should be mentioned that the spring stroke during treatment is not constant especially when the tool is in contact with the weld bead. Thus, it is strongly assumed that the contact force of the mechanical mounted tool is higher at the treatment of the weld toe. Different contact forces were used to investigate the surface state (roughness, hardness, residual stress) after treatment (see following section). Additionally, another hydrostatic tool with a tool radius of 6.5 mm (HG6) was used. The higher diameter of the sphere leads with the same pressure of 150 bar to a significant higher contact force of 1990 N. The parameters are summarized in Table 3.

Previous investigations [16] showed also that a proper treatment notch ground at the weld toe is crucial to maximize the fatigue improvement by deep rolling of welds. To assure this issue, 3D surface scans with an optical 3D laser microscope (Keyence VK-9700) with a step size of 0.5 μm were performed from the treated weld toe in as-welded, deep rolled and burnished condition, illustrated in Fig. 2. As shown, the displayed area at the weld toe was not completely treated in deep rolled condition. In burnished condition in the displayed area, the notch at the weld toe was completely removed. However, this was not the case for every specimen. For both processes, there are still some locations where the original weld toe was not completely deformed after treatment.

As comparison of the new post weld treatment by deep rolling and burnishing, ultrasonic impact treatment (UIT) was performed at the investigated butt joints. The UIT was performed with the stress voyager tool of the company

SONATS with a pin radius of 2 mm. The power of this device was set to the minimum of the device (10% of max.) to avoid extensive plastic indentation at the treated material. This corresponds to the amplitude of the sonotrode of 20 μm . As comparison for the treatment of butt joint made of S690QL [17], an amplitude of 60 μm was used (97% of max. power).

4 Surface state before and after treatment

Roughness, hardness and residual stress measurements were performed for the characterization of the surface state before and after treatment. Further investigations [16] also revealed that a high contact force in combination with a high coverage leads to process-induced surface defects and a high roughness in case of deep rolling of the base material EN AW 5083. It could not be excluded that this affects the fatigue performance in a negative way. For this issue, the surface roughness R_z and R_t according to DIN 4768:1990–05 was measured within a distance of 4.8 mm transverse to the treatment direction by a tactile roughness measurement device type Hommel T8000 according to DIN EN ISO 3274:1998–04, displayed in Fig. 3. Roughness and waviness were separated according to DIN EN ISO 4287:2010–07. As roughness values were evaluated as representative parameter for the surface topography because the evaluated waviness of the flat surface was low comparable to the evaluated roughness values. As shown, a low contact force leads to a low

Table 3 Process parameters for deep rolling and burnishing of EN AW 5083 butt joints

Process	Unit	Deep rolling	Burnishing
Tool	-	HG4 / HG13	DDW 0°
Manufacturer	-	Ecoroll AG	Baublies AG
Tool diameter d	mm	<u>4</u> / 13	4
Pressure p	bar	100 / 150 / <u>200</u>	-
Contact force F	N	125 / 188 / <u>251</u> / 1990 (HG13)	80 / 130 / <u>260</u> / 380
Spring stroke h	mm	-	0,5
Feed rate V	mm/min	1000	1000
Stepover distance a	mm	0,1	0,1

The underlined parameter are used for the treatment of the fatigue test specimens.

Fig. 2 Profile measurement of welded specimens made of EN AW 5083 in as-welded, deep rolled and burnished conditions

Burnishing – mechanical tool DDW 0°

Deep rolling – hydrostatic HG4 / HG13 tool

Fig. 3 Surface layer of deep rolled and burnished specimens depending of the contact force F

roughness for both tools (diameter 4 mm). However, with the hydrostatic HG13 tool, a significant lower roughness was determined compared to the hydrostatic HG4 tool even for a significant higher contact force. The initial roughness values of the surface in delivered condition were $R_z = 15.3 \mu\text{m}$ and $R_t = 18.3 \mu\text{m}$. The determined roughness after the treatment with the mechanical tool (DDW 0°) was for every investigated set of process parameters higher than after the treatment with the hydrostatic tools (HG4 and HG13).

To estimate the degree of work hardening, hardness measurements on the hardness scale HV0.05 (according to DIN EN ISO 6507–1) were performed at the weld toe at the cross-section of the specimen shown in Fig. 4. The measurements were performed with a microindenter device type Fisherscope ST200 according to DIN EN ISO 14,577–1. The depth profiles of the hardness measurements are shown in Fig. 4. As illustrated, higher microhardness at the notch root at the weld toe could be determined with the mechanical tool

Fig. 4 Hardness depth profiles

compared to the hydrostatic tool. The hardness increase is higher with higher applied contact force. However, no significant hardness increase was determined for the HG4 tool for every applied contact pressure.

The residual stress analysis were performed by X-ray diffraction analysis with Cu α -radiation at the aluminium (422) lattice plane. The measurements were performed with a diffractometer type Pulstec μ -360, based on the $\cos \alpha$ method [18, 19]. The reliability of this method in combination with the 2D detector compared to the commonly used $\sin \psi \psi^2$ method [20] was achieved by [21, 22]. The collimator diameter (measurement diameter) was 1 mm and the X-ray incident angle 20° for all measurements. The residual stress depth profiles were measured with the hole drilling method according to ASTM E837–20. Elastic constants for the evaluation $E = 69.7$ GPa and $\nu = 0.348$ were used. Due the application of the strain gages for the measurements, the residual stress depth profiles were measured in a distance of 5 mm from the weld toe but inside of the treated area.

The residual stress depth profiles (longitudinal and transverse direction) were shown in Fig. 5. As illustrated, the residual stress at the surface in the transverse direction is significantly higher than in the longitudinal direction for both processes. Also, the compressive residual stress at the surface increases with a higher contact force. Process-induced compressive residual stresses could be determined until a depth of 1 mm under the surface. The measurements show also the tendency that higher contact force lead shifts the compressive residual stress to higher depths. In direct comparison of both tools (hydrostatic HG4 tool and mechanical DDW 0° tool), it was determined that the HG4 tool leads to higher compressive residual stresses for a similar contact force.

Further, residual stress measurements in two directions were performed at the treated butt joint on a line perpendicular to the weld. The results are illustrated in Fig. 6. In as-welded condition, no significant residual stresses could be determined in transverse and longitudinal direction. After mechanical surface treatment, high compressive residual stress were determined in the area of the weld toe for both processes. However, the determined residual stress after the treatment with the HG4 tool was with -360 MPa in transverse direction explicit higher than with the DDW 0° tool with -190 MPa.

5 Fatigue test

For the determination of the fatigue performance, fatigue tests were performed in as-welded, deep rolled and burnished conditions. In each condition, at least 13 specimens were tested. The fatigue tests were performed under pure tension loading (stress ratio $R = 0.1$). The tests were

performed at an electro-magnetic resonance test machine RUMUL Testronic 150 K. The failure of the specimens was divided into failure from base material, failure from weld toe and no failure. Specimens with no failure have not been considered for the evaluation.

The results of the fatigue tests are shown in Fig. 7. The statistical analysis were performed according to DIN 50,100–2016-12 and in accordance to the IIW guideline [23]. Therefore, the nominal stress range at a survival probability of 95% at 2×10^6 load cycles was evaluated and is summarized in Table 4. The raw data for evaluation is summarized in Table 5.

A significant fatigue strength and fatigue life improvement could be reached for both investigated posttreatment processes. The increase of fatigue strength in deep rolled condition was 81% and 86% in burnished condition compared to the as-welded condition. Furthermore, only slight differences were observed between both treatment conditions. The results at both conditions are inside of the same scatter range. The evaluated fatigue strength (variable slope) in as-welded condition was higher than the compared case (No. 211) of the IIW recommendation [23] of 32 MPa. Furthermore, a significant fatigue improvement by 72% was determined in UIT condition compared to as-welded condition. However, the achieved fatigue strength by UIT was slightly lower than the determined fatigue strength in deep rolled and burnished condition of more than 80% (for a variable slope k). In the IIW recommendation for hammer peening, an improvement factor of 1.5 is given for aluminium welded joints with a FAT class of 40 MPa or lower (slope $k = 5$). In this case, this corresponds to the FAT class of 36 MPa. The improvement factor for deep rolling and burnishing in that case is around 2 and therefore significantly higher under consideration of $k = 5$. However, it should be mentioned that for a positive mean stress ($R > 0$), the FAT values for hammer peening of aluminium welded joints [2] correspond to the maximum applied nominal stress S_{max} . Considering this for a direct comparison of the evaluated maximum nominal stress $S_{max,5\%}$ of 58 MPa for deep rolling and 57 MPa for burnishing for a survival probability of 5% at 2×10^6 load cycles at slope of $k = 5$ with the recommend FAT(S_{max}) classes, the values are in the range of the maximum recommended FAT class of 56 MPa, showed in Fig. 7. At least a similar fatigue life improvement like hammer peening in investigated case is assumed.

6 Conclusion

The focus of this work was the approval of deep rolling and burnishing for the mechanical post weld treatment of aluminium welded joints in larger scales after previous investigations at comparable small size round bar specimen

Fig. 5 Residual stress depth profiles after deep rolling and burnishing

made of EN AW 5083, S355J2 + N and S690QL [16]. As a reason of comparable low contact force, compared to high-frequency mechanical impact treatment, of less than 380 N, the investigations are limited to butt joints made of EN AW 5083 with a comparable low yield strength of 203 MPa. Different contact forces for both processes (deep rolling and burnishing) were applied. For the deep rolling process, two hydrostatic mounted tools with a diameter of 4 mm and 6.5 mm were investigated (HG4 and HG6 tool). For the burnishing process, a mechanical mounted tool with a diamond

tip (diameter 4 mm) was used (DDW 0°). Furthermore, a set of specimens made of EN AW 5083 was treated by ultrasonic impact treatment.

Roughness, hardness and residual stress measurements were performed for the characterization of the surface layers after treatment. High compressive transverse residual stresses could be determined after deep rolling for every investigated material. The surface roughness was significantly decreased by this process compared to the original condition for all applied contact forces. The roughness

Fig. 6 Surface residual stress profiles after deep rolling and burnishing

Fig. 7 Fatigue test results of specimens in as-welded, deep rolled and burnished condition

Table 4 Evaluated fatigue data

Material	Fatigue strength $\Delta S_{5\%}^*$ (fixed slope)	Inversal slope k (fixed)	Fatigue strength $\Delta S_{5\%}^{**}$ (variable slope)	Inversal slope k (variable)	SD(log N_F)**
As-welded	26	3	44	4.8	0.176
Deep rolled	52	5	81	9.5	0.244
Burnished	51	5	80	9.6	0.203
UIT	55	5	76	11.9	0.198
IIW (as-welded) [23]	32	3	-	-	-
IIW (hammer peening) [2]	36	5	-	-	-

*Maximum nominal stress at 2×10^6 load cycles and a survival probability of 95%

**Standard deviation of log(N_F) according to DIN 50,100–2016-12 for evaluation with variable k

Table 5 Fatigue test data of butt joints at $R = 0.1$

As-welded		Burnished		Deep rolled		UIT	
ΔS	N_F	ΔS	N_F	ΔS	N_F	ΔS	N_F
100	60,700	140	16,600**	140	28,500	100	140,200
100	100,500	140	18,600**	120	77,100	95	241,100
80	220,600	140	20,900	100	10,000,000*	90	300,600
80	276,800	130	25,200	130	35,500	95	455,800
110	92,200	140	32,900	110	296,600	85	513,000
70	482,200	130	54,900	140	32,200	85	736,400
120	36,200	140	60,100	130	23,200	90	753,900
70	260,300	120	75,100	120	95,700	80	2,014,000
130	14,300	120	104,900	110	343,400	85	2,283,550
90	92,500	110	116,800	105	177,600	80	3,660,200
60	1,575,600	110	371,300	105	784,700		
60	574,300	100	481,300	100	358,900		
50	10,000,000*	100	684,800	105	376,100		
		100	1,554,200**				
		100	10,000,000*				

*No failure, **failure at base material.

after deep rolling was slightly lower than the roughness after burnishing. Microhardness measurements were performed to quantify the degree of work hardening in the fatigue critical area of the weld toe. However, for deep rolling, no significant hardness increase could be determined for some of the applied contact forces. Together with optical investigations, this leads to the conclusion that low contact forces (around 125 N) are not enough to cause plastic deformations at the notch root of the weld toe. With similar contact forces, the hardness increases (at the weld toe) more by burnishing than by deep rolling. However, significant higher compressive residual stresses (up to -360 MPa) in transverse direction were induced by deep rolling compared to burnishing.

Fatigue tests were performed under full tensile loading ($R=0.1$) for all investigated processes (deep rolling, burnishing, UIT). Significant fatigue life improvement was determined by all processes. Only slight differences were observed between the fatigue strength in deep rolled and burnished condition. The fatigue improvement by UIT was slightly lower compared to the other processes. It is assumed that comparably high indentation depths of >0.3 mm compared with the specimen thickness of 6 mm lead to a higher local stress concentrations after UIT treatment and could affect the fatigue strength of the treated specimen. Compared to this, the low intensity processes of deep rolling and burnishing may be an alternative posttreatment of such low strength materials. However, it should be mentioned that further investigations need to be done to optimize the process parameters for this comparable new methods for the post weld treatment of welded joints. It is assumed that the optimum contact force in connection with the tool diameter

was not reached in this investigation because the weld toe was not completely deformed during treatment.

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Declarations

Conflict of interest The authors declare no competing interest.

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