ANALYSIS OF THE EFFECT OF SHOT PEENING ON THE PROPERTIES OF FSW JOINTS FOR ALUMINUM ALLOY EN AW-2024-T3

Magdalena BUCIOR[1], Paulina SZAWARA[2], Miroslav NESLUŠAN[3], Andrzej KUBIT[1], Rafał KLUZ[1]

[1]*Faculty of Mechanical Engineering and Aeronautics, Department of Manufacturing Processes and Production Engineering, University of Technology, Rzeszów, Poland, EU, magdabucior@prz.edu.pl, akubit@prz.edu.pl, rkluz@prz.edu.pl*

[2]*Faculty of Mechanical Engineering and Aeronautics, Department of Materials Forming and Processing, University of Technology, Rzeszów, Poland, EU, p.szawara@prz.edu.pl*

[3]*Faculty of Mechanical Engineering, University of Žilina, Žilina, Slovakia, EU, miroslav.neslusan@fstroj.uniza.sk*

https://doi.org/10.37904/metal.2026.5251

Abstract

Ensuring high strength at low weight in aircraft joints presents a constant challenge for designers and researchers. One widely used material in this industry is 2xxx series aluminum alloys. This study investigates the effects of shot peening on the surface layer properties of FSW-welded butt joints made from EN AW-2024 aluminum alloy in the T3 temper, both with the bare and alclad coating. The methodology involved shot peening the welded joint for 40 sec at a pressure of 0.6 MPa using 1.5 mm diameter bearing balls. The treatment generated compressive residual stresses in both material variants. Analysis of stress magnitude and FWHM values revealed greater strain hardening in the bare alloy. This trend was also evident in surface layer microhardness measurements. Surface roughness parameters improved significantly after shot peening in both cases, with particularly pronounced effects observed for the alclad variant. Roughness parameter Sa after shot peening decreased in the weld zone by 28% and 26% for the bare and alclad variants, respectively.

Keywords: Friction stir welding, shot peening, aluminium EN AW-2024 T3, residual stress, microhardness

1. INTRODUCTION

The most common joining techniques used in aircraft structures are riveting, gluing and welding. Friction stir welding (FSW), laser beam welding (LBW), and tungsten inert gas (TIG) are the three main welding techniques used to join thin-walled components [1]. There are some limitations when considering joining 2xxx and 7xxx series aluminum alloys by TIG or MIG welding, such as susceptibility to hot cracking or porosity [2]. Such defects are unacceptable and inconsistent with accepted standards. Friction stir welding is a process in which the material remains in a solid state, thus avoiding typical problems of arc welding for aluminum, such as hot cracks, porosity and a large heat-affected zone [3,4]. A tool with a flange is rotated and pressed with considerable force into the material. The friction between the tool and the material generates sufficient heat to mix it. Friction stir welding does not require the addition of weld material, but only mixes the parent material. FSW joints are characterized by good mechanical properties, particularly in terms of fatigue strength, load-bearing capacity, and tightness (important for pressure hulls) [5]. Given the constant drive for weight and cost reduction, this technology is used in aviation to join fuselage skins and wing components [6,7], especially in the case of 2xxx and 7xxx series aluminum. Despite numerous advantages, there are still problems with the fatigue behavior of FSW joints, which have not been fully understood. Welding parameters and material properties may influence the formation of discontinuities in the weld zone [8], which changes the material properties. Research conducted by Jata et al. [9] showed that the hardness of the top side of the weld is lower

than the bottom side for the 7050 aluminium alloy. Tensile stresses generated during welding and changes in the geometric structure of the surface can lead to a reduction in fatigue strength, which in turn affects the reliability of the joint.

Shot peening (SP) is a process that can improve the properties of the surface layer of FSW joints. Shot peening is a surface strengthening treatment widely used in many industries. In the aerospace industry, it is used to increase the fatigue life of parts such as landing gear, aeroengine blades or wing panels [10,11] by introducing compressive stresses in the surface layer of the material, which reduces tensile stresses. Studies conducted by Sawangpan et al [12] showed that shot peening of 2024-T3 aluminum alloy with silica particles of 0.1 mm reduces surface roughness, introduces compressive stresses and improved microhardness. In turn, authors of work [13] examined the fatigue strength of 2024-T3 aluminium after shot peening with nickel shots. They observed that the fatigue strength increased by 34% after treatment for optimal parameters.

Taking into account the benefits of shot peening technology and based on previous research [14], this study investigated the effect of this treatment on the properties of joints made by the FSW method. The aim of this research was to analyze the influence of shot peening on the EN AW-2024-T3 aluminum alloy butt joints (1.7 mm thick), both in bare and alclad conditions. The comparative studies included measurements of residual stresses, surface topography and microhardness.

2. METHODOLOGY

The aluminum alloy EN AW 2024-T3 in the bare and alclad coating were used for the tests. The chemical composition and mechanical properties of this aluminum are presented in Tables 1 and 2, respectively. EN AW 2024-T3 alloy is a high-strength 2xxx series alloy (Al–Cu–Mg–Mn), widely used in the aerospace industry and structures requiring high fatigue strength. It is used in applications such as wings and fuselage sheet structures, aircraft internal structures, and external fuel tanks [6,7]. It is often used with a protective layer of pure aluminum, which provides better corrosion resistance.

The tests were conducted on the friction stir welded sheets. The FSW process was performed on a Makino PS95 CNC machine using a tool featuring a helical pin. Two 1.7 mm thick sheets were butt-welded in the force direction (perpendicular to the weld line). Welding tests were conducted using rotational speed n = 300 rpm, feed rate f = 500 mm/min, tool tilt angle 2° and pin plunge depth 1.4 mm. Butt joints of EN AW 2024-T3 aluminum alloy were subjected to shot peening and compared to untreated FSW joints, both bare and alclad coating. The shot peening process was performed using a special device, with specimens attached to the device cover. Bearing balls (1.5 mm diameter) impacted the surface at an air pressure of 0.6 MPa, achieving 100% coverage after 40 seconds. Surface residual stresses were measured using the X-ray diffraction (XRD) technique on a Proto iXRD Combo diffractometer (Cr Kα radiation, {222} planes, Winholtz–Cohen method, with elastic constants $½s_2$ = 18.5 TPa^{-1} and s_1 = −4.79 TPa^{-1}, and a penetration depth of ≈5 μm). The stresses were measured in three places: on the weld zone after welding (WZ), on the weld zone after shot peening (WZ_SP) and on the sheet – bulk stress (BS) in the tangential and axial directions. Surface geometric structure tests were performed using Alicona Infinite Focus G4 at 20x optical magnification. Surface parameters were measured in an area of 3x3 mm according to ISO 16610-21:2025 [15]. A filter λc = 0.8 mm was used in the tests. Microhardness measurements were performed using the Vickers method on an Innovatest Falcon 400 device. A load of 100 gf was assumed for the tests, which corresponds to the HV0.1 scale. The impressions of the depressions were made at regular intervals of 0.5 mm on the upper surface. The indenter loading time was 10 s. The tests were performed in accordance with the PN-EN ISO 6507-1:2017 standard [16].

Table 1 Chemical composition of EN AW-2023 T3 aluminium alloy [17], wt %

Zn	Fe	Ti	Cr	Mg	Mn	Si	Al
0.25 max	0.5 max	0.15 max	0.1 max	1.2 - 1.8	0.3 - 0.9	0.5 max	rest

Table 2 Mechanical properties of EN AW-2024 T3 aluminium alloy [17]

Properties	**$R_{0.2}$, MPa**	**R_m, MPa**	**A_5, %**	**Hardness, HV**
Value	250 - 290	360 - 425	12 - 14	110 - 130

3. RESULTS

3.1. Residual stresses

Magnitude of the tensile residual stresses in both friction welded sheets (EN AW-2024 T3 bare as well as EN AW -2024 T3 alclad) in the tangential direction is quite low as compared with the nearly stress free state in the axial direction whereas shot peening again initiates compressive stresses in both directions (**Figure 1**). Compared to the bulk stress (BS), the friction welding shift residual stress form the stress free or compressive regions towards the tensile region. In both analyzed cases, it was found that tensile stresses occur directly on the surface of the welded joint. Magnitude of these stresses is decreasing along with the increasing distance from the joint and the tensile stress becomes replaced by the compressive ones linked with the bulk stress finally. Evolution of residual stresses towards the both sides is more or less symmetric taking into consideration of the standard deviation of the measured stresses.

Shot peening completely eliminates the residual stresses created during welding, and typical compressive stresses occur on the surface. Furthermore, it can be reported that this process suppresses the residual heterogeneity with respect of the welding joint and the neighbouring region when the differences among the residual stresses at the joint and the joint free regions tends to vanish. Shot peening represents a severe plastic deformation of the surface which initiates dislocation slip and remarkable increase in the dislocation density within the affected layer. FWHM (Full Width at Half Maximum) of XRD patterns clearly demonstrates that the FWHM after shot peening in weld zone is more as compared with the initial state after welding. The FWHM value after SP increased from 2° for WZ to 3° for bare aluminium and to 2.8° for alclad, taking into account the measurement error. This parameter is usually linked with microhardness of the investigated region and the corresponding dislocation density. The magnitude of compressive stresses as well as the FWHM for EN AW-2024-T3 bare are more as that for EN AW-2024-T3 alclad which indicates higher degree of the work hardening for this alloy.

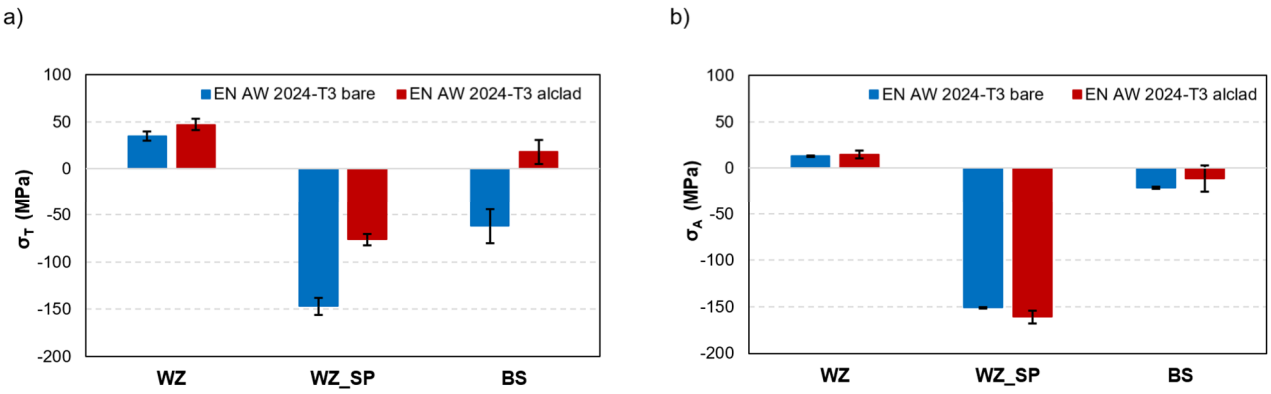

Figure 1 Distribution of residual stresses in a) tangential direction b) axial direction

3.2. Roughness

Figures 2 and 3 show surface topographic maps for welded and shot peened joints, both in the WZ zone and on the sheet. Shot peening of the weld zone reduced the tool mark created during the FSW process. In both analyzed cases (**Figure 2b, Figure 3b**), a decrease in surface parameters was observed in the weld area. The value of the Sa parameter, describing the arithmetic mean height of the 3D surface after process, was in

the range of Sa = 2.141 µm - Sa = 2.653 µm, which is a decrease of 26-28% for alclad and bare aluminum, respectively, compared to WZ after FSW process.

By analyzing the surface in the WZ of the EN AW-2024 aluminum alloy in state T3 (**Figure 2a, 2b**), one can observe typical surface topography views characteristic for FSW (**Figure 2a)** and shot peening (**Figure 2b**). Although the Sa parameter values are similar, they differ in asymmetry, extremes, and the dominance of valleys/peaks. The surface after FSW is dominated by deep valleys Sv (maximum valley depth) compared to maximum peak height Sp, where the ratio Sv/Sp = 1.39 indicates that the valleys are clearly deeper than the peaks are high, but this asymmetry is not exceptionally strong. Shot peening reduced the maximum peak heights from Sp = 25.302 µm to Sp = 12.973 µm, creating a surface with a predominance of deep valleys. This is also confirmed by the negative skewness value Ssk = -1.531 µm. The parameter ratio Sv/Sp = 3.37 after SP indicates a strong asymmetry of the surface topography. The surface after SP is also characterized by a high kurtosis value Sku = 12.577, indicating numerous deep depressions created as a result of the balls impacting the surface.

In the case of the aluminum alloy with alclad in the WZ zone (**Figure 3a**) one can observe the predominance of the maximum peak height (Sp) over the maximum valley depth (Sv). A positive value of Ssk = 0.9676, close to 1, indicates a convex surface with a predominance of higher peaks. Shot peening in the WZ (**Figure 3b**) significantly reduces the peaks, creating a smoother surface with fewer peaks (Sku) and an almost symmetrical distribution (Ssk close to 0). In turn, shot peening the base sheet significantly increased the roughness parameters, creating a surface typical of shot peening (**Figure 2d, Figure 3d**). The parameters Sp and Sv after shot peening are similar, indicating a more uniform surface. This is also confirmed by the skewness value Ssk, close to 0, indicating a symmetrical distribution of peaks and valleys. A kurtosis value of Sku <3 indicates smaller extremes on the surface [18]. The alclad layer for the surface in its initial state does not change the roughness parameters and the values are similar (**Figure 2c, Figure 3c**).

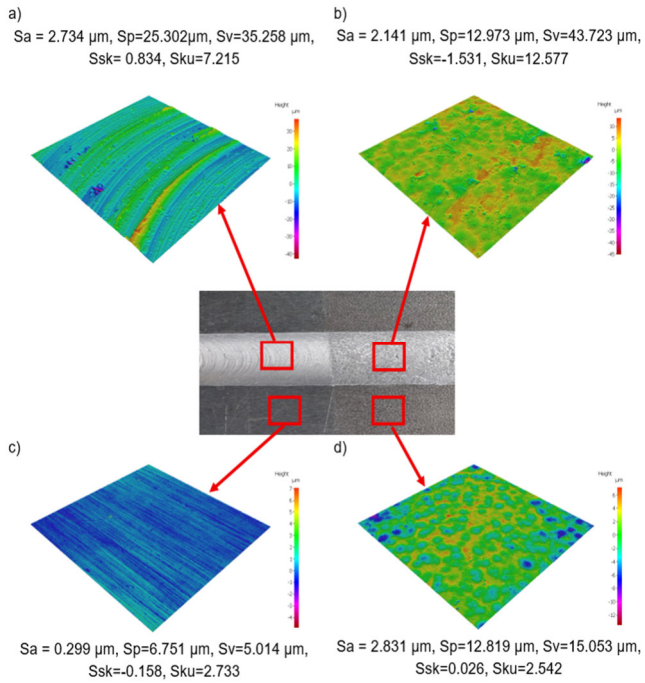

Figure 2 Surface roughness for EN AW-2024 T3 a) in WZ after FSW, b) in WZ after shot peening, c) S (base sheet), d) S after shot peening

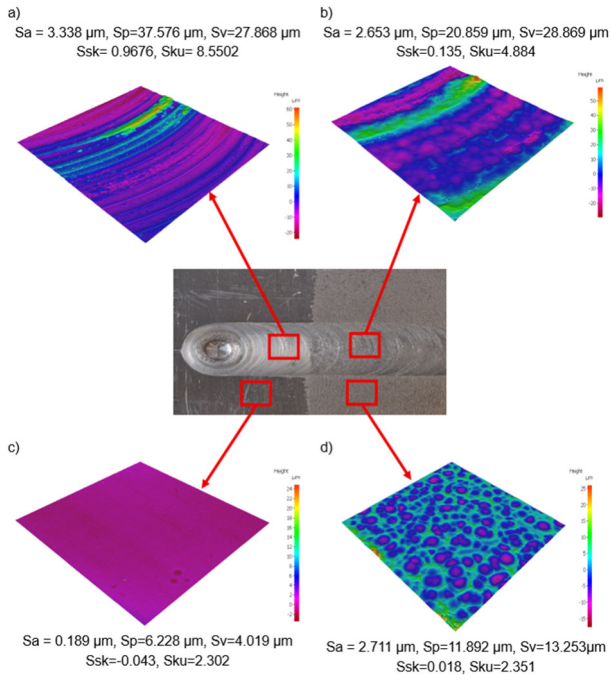

Figure 3 Surface roughness for EN AW-2024 T3 Alclad a) in WZ after FSW, b) in WZ after shot peening, c) S (base sheet), d) S after shot peening

3.3. Microhardness

Microhardness was measured on the top surface of the specimen in the weld zone and on the sheet (**Figure 4)**. Comparing the microhardness results in the weld zone for the bare EN AW 2024-T3 and alclad alloy, it can be seen that they are strongly correlated with the FWHM value; as the FWHM value increases, the microhardness also. It is clearly visible that after SP, in both cases, the microhardness increased from 96 HV 0.1 to 156 HV0.1 for the bare alloy and from 76 HV0.1 to 116 HV0.1 for the alloy with the alclad layer in the weld zone. For the bare alloy, the microhardness distribution is typically W-shaped, with a 63% decrease in microhardness in the WZ. However, in the case of an alloy with an alclad layer, the opposite phenomenon is observed. In the pure aluminum layer mixes with the core material, which causes the material to harden and increases its microhardness by 53% in the WZ. Shot peening increases microhardness on the bare aluminum and alclad surfaces by 21% and 111%, respectively.

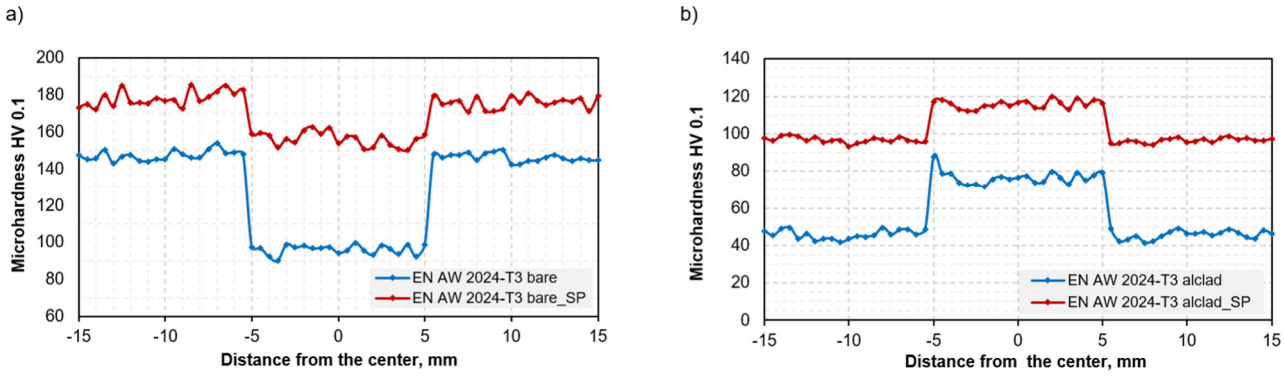

Figure 4 Microhardness profiles measured on the top surface of the FSW joint before and after shot peening for a) EN AW 2024-T3 bare alloy, b) EN AW 2024-T3 alclad alloy

4. CONCLUSION

The aim of this article was to compare the properties of the surface layer of FSW joints made of EN AW 2024-T3 bare and alclad alloys after surface treatment. The tests showed that shot peening in both cases improved the properties of FSW joints, particularly in the weld zone. Shot peening introduced compressive stresses of approximately -150 MPa in the weld zone. The FWHM value increased by 1° for bare aluminum and by 0.8° for alclad compared to WZ after FSW. These values indicate a higher degree of work hardening of the alloy. This is also confirmed by the obtained microhardness results. Shot peening increased the microhardness in the WZ from 96 HV0.1 to 156 HV0.1 for the bare alloy and from 76 HV0.1 to 116 HV0.1 for the alclad alloy. Shot peening reduced the tool mark resulting from FSW welding. This is also confirmed by the lower values of roughness parameters. In summary, it can be stated that shot peening had a positive effect on the properties of the surface layer of the EN AW 2024-T3 alloy, both bare and alclad.

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