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ANALYSIS OF THICKNESS REDUCTION IN THE INCREMENTAL FORMING PROCESS OF THE CLAD ALUMINUM ALLOY EN AW 3003/EN AW 4343

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Abstract: *Clad materials are increasingly used in the automotive and aerospace industries due to the significant advantages they offer. The incremental forming process of lightweight materials is gaining more interest because it allows the production of relatively complex parts at lower costs, eliminating the need for complex and expensive molds. Understanding the phenomenon of thickness reduction is essential, as it directly influences the mechanical strength of the manufactured parts. In this work, the thickness reduction of the EN AW-3003 aluminum alloy clad with EN AW-4343 was studied following the incremental forming process. Two methods were used for the thickness reduction analysis. The first method involved non-contact optical measurement using the ARAMIS optical measurement system. The second method focused on analyzing the clad layer using optical microscopy. The obtained results enhance the understanding of the behavior of clad materials during incremental forming and may serve as a foundation for optimizing the manufacturing process.*

Keywords: *clad materials, incremental forming, thickness reduction, aluminum alloys, lightweight materials.*

1. INTRODUCTION

Incremental Sheet Forming (ISF) is a process that has become the subject of study for many researchers. This is due to the growing interest from industries such as the automotive and aerospace industries [1]. The Single Point Incremental Forming (SPIF) process was developed with the aim of manufacturing parts in single or small series productions, without the need for complex and expensive molds. Thus, by moving a punch along a predefined trajectory, it is possible to produce parts with complex shapes [2-4].

The manufacturing of lightweight components is one of the main challenges in modern transportation engineering. Engineers are focused on producing components made from materials with high strength and low density. Such alloys include aluminum alloys, magnesium alloys, and titanium alloys [5]. These materials have been studied and successfully applied in the SPIF process, providing cost reduction and, most importantly, high flexibility. However, the aerospace and automotive industries are looking for solutions to replace traditional alloys with advanced materials that combine the advantages of multiple materials into one. Clad materials and bimetals fall into this category of materials [6].

Clad material is typically a (sandwich) structure made from two or more layers, in which a base material (core) is bonded with one or two cladding layers [7]. The most commonly used such materials are those made from alloys in the 3xxx or 4xxx series. These are used in the automotive and aerospace industries (such as heat exchangers, e.g., radiators) “due to their advantages of low density, high thermal conductivity, good bonding properties, and availability” [8]. Another major advantage of this type of material is that it can be recycled and reused. It has been studied that the “EN AW 3003 clad with EN AW 4343 can be recycled and reused for the EN AW 4007 alloy” [9]. This is due to the chemical composition, which falls within the standard chemical composition limits.

Due to the use of these materials in industries where thickness reduction is essential, this topic has been extensively discussed in the literature [10]. To obtain more precise results regarding thickness reduction during the SPIF process, the influence of several parameters has been studied [11-15]. The most commonly used method for determining thickness reduction is “the non-contact optical method, which allows for measuring these values throughout the process or at its completion” [16-18].

Thus, the present study aims to investigate the thickness reduction resulting from the SPIF process applied to the EN AW-3003 aluminum alloy clad with EN AW-4343, with specific objectives including the measurement of the total thickness reduction using the ARAMIS optical measurement system, the separate evaluation of thickness reduction for each layer by optical microscopy, and the statistical analysis of the experimental data obtained.

2. MATERIALS AND METHODS

2.1 Materials

The material used in this study was a clad sheet, consisting of a base material made from an aluminum alloy (EN AW 3003) and a cladding layer made from the EN AW 4343 alloy. The total thickness of the material is 1200 μm, with the base layer having an average thickness of 1135 μm, and the cladding layer being 65 μm thick. For a better understanding of the material's structure, a schematic 3D representation of it is shown in Figure 1.

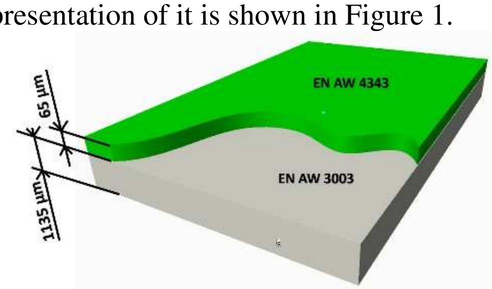

Fig. 1. 3D schematic – Clad material.

2.2 Incremental forming

To obtain a truncated cone-shaped part, the SPIF process was used. It was made from a sheet metal blank with dimensions of 240 × 240 × 1.2 mm. The blank was positioned using a vertical clamping support. Figure 2 shows the part's dimensions, along with the diameter of the tool used for its production. It can be observed that a punch with a diameter of 10 mm was used to form a part with a height of 35 mm and an angle of 55˚ to the horizontal plane. Additionally, the blank was positioned so that the cladding layer (EN AW 4343) was in contact with the tool used for deformation.

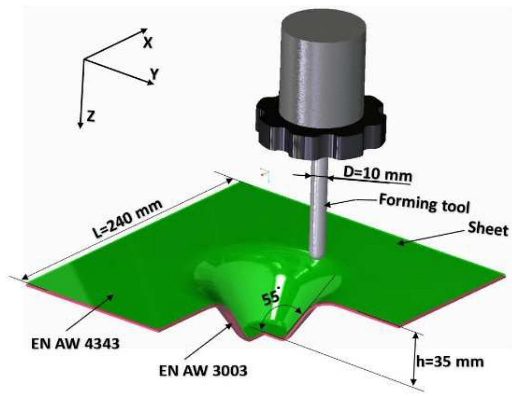

Fig. 2. Geometry and dimensions of the Part.

The SPIF process was performed using a KUKA KR 210-2 industrial robot equipped with a KR C2 control unit. This industrial robot is a 6-axis robot and can develop a maximum load of 2100 N. In order to carry out the process, the 3D model of the part was imported into the SprutCam software, which allowed the creation of a spiral-type trajectory, with the punch advancement occurring along the Z axis.

2.3 Optical and microscopic measurement methods for thickness reduction

The data regarding thickness reduction following the SPIF process were obtained using two methods: the ARAMIS optical measurement system and microscopy. The first method provided real-time information on the evolution of thickness reduction. Since the ARAMIS optical system transmits information about material thinning only based on the outer surface of the part, i.e., the side opposite to the one in contact with the tool, it provides values related only to thickness reduction, without considering the internal layers. To overcome this limitation, an optical microscope was used to measure the material layers.

Thus, for the microscopic investigation, it was necessary to prepare the samples taken from the three zones of the specimen in advance. Zone I is representative of the flat (undeformed) area of the part (position 1), zone II represents the conical wall (measurement positions range from 2 to 6), and zone III is associated with the radius area of the small base of the conical frustum (positions 7 and 8). These zones, along with the measurement positions, are shown in Figure 3.

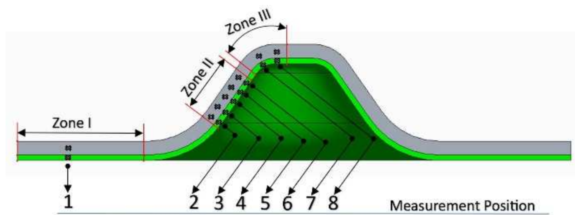

Fig. 3. The analyzed zones of the part and the measurement positions.

After the three samples were taken, they were polished (500, 1000, 1200, and 2000 grits), buffed (3 μm), and embedded in resin. To obtain a more precise visualization of the two aluminum alloy layers, a chemical solution containing HF (2 ml HF, 3 ml HCl, 5 ml HNO3, and 190 ml H2O) was used. The samples were immersed in this solution for 15 seconds before visualization, then washed with distilled water and dried. The three samples prepared for microscopic analysis are shown in Figure 4. The microscope used to obtain the images was the Olympus GX5 optical microscope (magnification 10x). The images obtained were introduced into the QuickPHOTO software, which allowed for precise measurement of the material layers. Thus, the thickness of the layers was obtained for zone I, where the measurement was performed in a single position. For zone II, five measurements were made in five different positions along the length of the conical frustum, and in zone III, five measurements were made in two different positions.

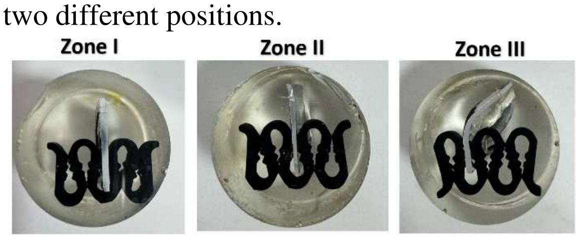

Fig. 4. Material samples prepared for microscopic analysis.

3. RESULTS

3.1 Thickness Reduction: Measurements with the ARAMIS Optical Measurement System

The measurements performed using the ARAMIS optical measurement system, following the SPIF process, allowed for the determination of thickness reduction across the entire surface of the analyzed part. Figure 5 illustrates the variations in thickness based on the deformed area. As observed, the optical method indicates a maximum thinning value of 0.6422 mm/mm, located in the conical section, closer to its larger base. As previously mentioned, these results are relevant only for thin and homogeneous materials and are not applicable to clad materials. However, this measurement was carried out in order to compare the results obtained optically with those determined through microscopic analysis.

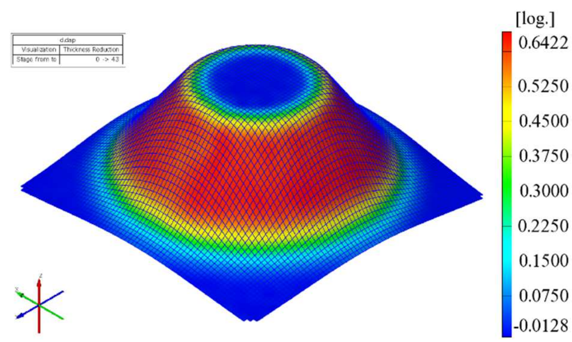

Fig. 5. Thickness reduction: ARAMIS Optical System.

3.2 Thickness reduction: optical microscope measurements

In order to determine the thinning of each material layer, measurements were performed using an optical microscope. Figure 6, Figure 7, and Figure 8 present representative microscopic images of the three analyzed zones, highlighting the geometric and structural changes of the layers following the SPIF process. The measurement results are centralized in Table 1, which includes the measured thickness values for each layer in the three different zones. For Zone II and Zone III, five measurements were taken, from which the average thickness and relative thinning of each layer were calculated.

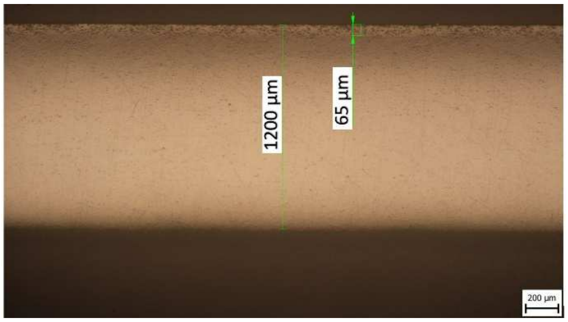

Fig. 6. Measurement of layer thickness: Zone I.

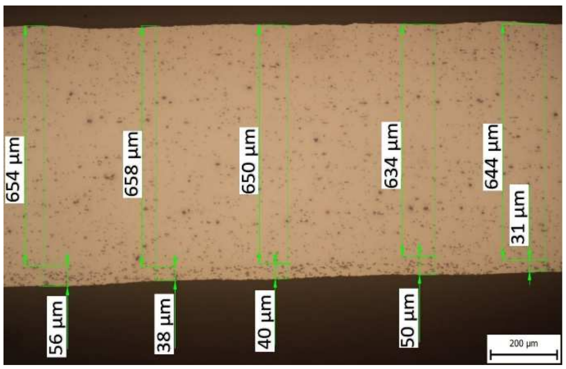

Fig. 7. Measurement of layer thickness: Zone II.

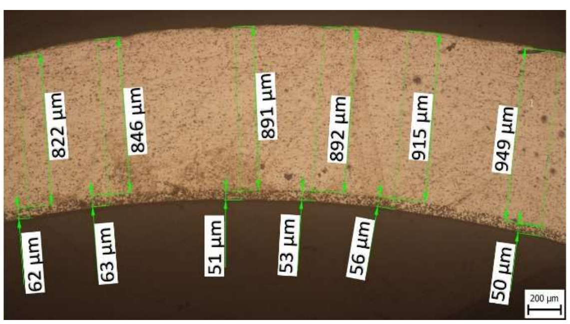

Fig. 8. Measurement of layer thickness: Zone III.

Table 1

Results: Average Thickness and Relative Thinning

Zone	EN AW 3003 [µm]	Rel. thin. [%]	EN AW 4343 [µm]	Rel. thin. [%]
I	1135	-	65	-
II	648,6	42,85	42,28	34,95
III	987,3	13,01	59,7	8,15

The data obtained from measuring the samples taken from the three zones of the truncated cone-shaped part revealed that the relative thinning of the two materials is most pronounced in the cone section, with 42.85% for the base material and 34.95% for the clad material.

Thus, a clear trend of pronounced tapering in the cone trunk area (Zone II) can be observed, followed by a decrease in the degree of tapering in the cone trunk radius area (Zone III).

After completing the measurements, the results were statistically processed. For this purpose, the Anderson-Darling test was applied to verify the normality of the data. Figure 9 and Figure 10 show the statistical distribution graphs (probability plots) for the two material layers. These graphs were selected because, in position 1 of zone II, the relative thinning is the most pronounced.

The normality test showed that, for measuring the thickness of each layer in the three zones, the p-values are all above 0.05, indicating that the measured values conform to a normal distribution.

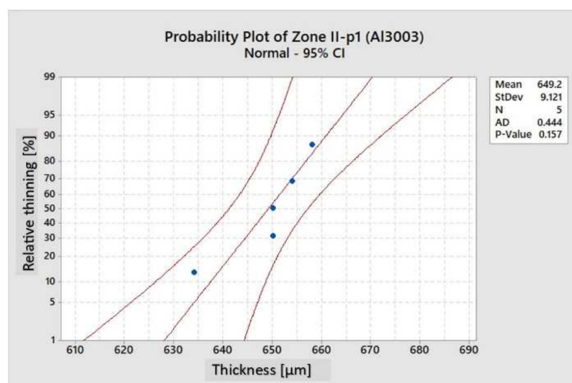

Fig. 9. Probability plot: Zone III, position 1, EN AW 3003.

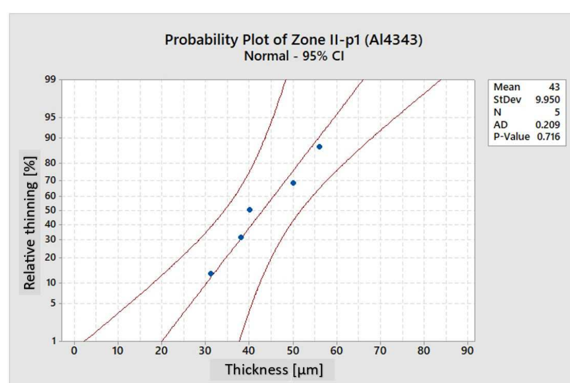

Fig. 10. Probability plot: Zone III, position 1, EN AW 3003.

4. CONCLUSION

This study was conducted for the first time on this type of material. The main objective of the work was to analyze the behavior of the clad material following the SPIF process, focusing on the reduction in thickness. The results obtained demonstrate that this type of material withstands the deformations that occur during the process.

The area most affected by thinning was the conical frustum, an observation confirmed by both measurements taken with the ARAMIS optical system and microscopic analysis. After the measurements, it was found that the clad layer (EN AW 3003) withstood the reduction in thickness, even though it was the most exposed during the SPIF process, having a smaller thickness compared to the base layer. Additionally, the clad layer was not removed and showed no signs of separation from the base material.

All of these aspects indicate that the studied material has good resistance to the SPIF process, without significant losses of the coating.

5. REFERENCES

[1] Gohil, A., Modi, B., Experimental determination of fracture forming line for AA1100 aluminum sheet in single point incremental forming process, Materials Today: Proceedings, ISSN 2214-7853, 2023.

[2] Rosca, N., Oleksik, M., Rosca, L., Avrigean, E., Trzepieciński, T., Najm, S.M., Oleksik, V., Minimizing the Main Strains and Thickness Reduction in the Single Point Incremental Forming Process of Polyamide and High-Density Polyethylene Sheets, Materials, 16(4):1644, 2023.

[3] Bologa, O., Breaz, R.E., Racz, S.G., Crenganiş, M., *Decision-making Tool for Moving from 3-axes to 5-axes CNC Machine-tool*, Procedia Computer Science, ISSN 1877-0509, 91, 184-192, 2016.

[4] Racz, S.G., Crenganiș, M., Breaz, R.E., Bârsan, A., Gîrjob, C.E., Biriș, C.M., Tera, M., *Integrating Trajectory Planning with Kinematic Analysis and Joint Torques Estimation for an Industrial Robot Used in Incremental Forming Operations*, Machines, ISSN 2075-1702, 10, 2075-1702, 2022.

[5] Trzepieciński, T., Oleksik, V., Pepelnjak, T., Najm, SM, Paniti, I., Maji, K., Emerging Trends in Single Point Incremental Sheet Forming of Lightweight Metals, Metals, 11(8), 1188, 2021.

[6] Mohsan, A.U.H., Zhang, M., Zhai, M., Wang, Y., Ullah, M., Shu, X., Zhao, S., Effect of Dilution on Microstructure and Phase Transformation of AlCrFeMnNi High-Entropy Alloy by Resonant Ultrasonic Vibration-Assisted Laser Cladding, Materials, 18(3):695, 2025.

[7] Mikhaylovskaya, A.V., Mochugovskiy, A.G., Kotov, A.D.; Yakovtseva, O.A., Gorshenkov, M.V., Portnoy, V.K., Superplasticity of Clad Aluminium Alloy, J. Mater. Process. Technol., 243, 355–364, 2017.

[8] Ebrahimi, SH.S., Dehghani, K., Aghazadeh, J.; Ghasemian, M.B., Zangeneh, S., Investigation on microstructure and mechanical properties of Al/Al-Zn-Mg–Cu laminated composite fabricated by accumulative roll bonding (ARB) process, Materials Science and Engineering: A, ISSN 0921-5093, 718, 311-320, 2018.

[9] Kropf, B., Cvahte, P., Arzenšek, M., & Kraner, J., Cold Rolling Technology Optimization for EN AW 4343/3003/4343 Cladded Aluminum Alloys and Influence of Parameters on Microstructure, Mechanical Properties and Sustainable Recyclability, Metals, 14(2), 230, 2024.

[10] Mercedes M.G, Nathan A.L., Joseph D.F., Mitchell R.W., Douglas A.B., Robert G.L., Analysis of geometric accuracy and thickness reduction in multistage incremental sheet forming using digital image correlation, Procedia Manufacturing, ISSN 2351-9789, 34, 950-960, 2019.

[11] Shamsari, M., Mirnia, M.J., Elyasi, M, Hamid, B., Formability improvement in single point incremental forming of truncated cone using a two-stage hybrid deformation strategy, Int. J. Adv. Manuf. Technol., 94, 2357–2368, 2018.

[12] Bologa, O., Breaz, R.E., Racz, S.G., *Using the Analytic Hierarchy Process (AHP) and*

fuzzy logic to evaluate the possibility of introducing single point incremental forming on industrial scale, Procedia Computer Science, ISSN 1877-0509, 139, 408-416, 2018.

[13] Racz, S.G., Breaz, R.E., Bologa, O., Tera, M., Oleksik, V.S., *Using an Adaptive Network-based Fuzzy Inference System to Estimate the Vertical Force in Single Point Incremental Forming*, International Journal of Computers Communications & Control, ISSN 1841-9836, 14(1), 63-77, 2019.

[14] Crenganiș, M., Breaz, R.E., Racz, S.G. Gîrjob, C.E., Biriș, C.M., Maroșan, A., Bârsan, A., *Fuzzy Logic-Based Driving Decision for an Omnidirectional Mobile Robot Using a Simulink Dynamic Model*, Applied Sciences, 14(7), 3058, 2024.

[15] Racz, S.G., Crenganiș, M., Breaz, R.E., Maroșan, A., Bârsan, A., Gîrjob, C.E., Biriș, C.M., Tera, M., *Mobile Robots—AHP-Based Actuation Solution Selection and Comparison between Mecanum Wheel Drive and Differential Drive with Regard to Dynamic Loads*, Machines, 10(10), 886, 2022.

[16] Vanhulst, M., Vanhove, H., Carette, Y., Waumans, S., Duflou, J.R., Analysis of Thickness Distributions Calculated from Surface Strains Obtained through Digital Image Correlation for Incremental Sheet Forming, Key Engineering Materials, 926, 875–882, 2022.

[17] Racz, S.G., Breaz, R.E., Bologa, O., Terra, M., Oleksik, V., Using an Adaptive Network-based Fuzzy Inference System to Estimate the Vertical Force in Single Point Incremental Forming, International Journal of Computers Communications & Control, 14, 63-77, 2019.

[18] Bologa, O., Breaz, R.E., Racz, S.G., Using the Analytic Hierarchy Process (AHP) and fuzzy logic to evaluate the possibility of introducing single point incremental forming on industrial scale, Procedia Computer Science, ISSN 1877-0509, 139, 408–416, 2018.

Analiza reducerii grosimii în procesul de deformare incrementală a aliajului de aluminiu placate EN AW 3003/EN AW 4343

Materialele placate sunt din ce în ce mai utilizate în industriile auto și aerospațială datorită avantajelor semnificative pe care le oferă. Procesul de formare incrementală a materialelor ușoare atrage un interes tot mai mare, deoarece permite producerea unor piese relativ complexe la costuri mai mici, eliminând necesitatea matrițelor complexe și scumpe. Înțelegerea fenomenului de reducere a grosimii este esențială, deoarece influențează direct rezistența mecanică a pieselor fabricate. În această lucrare, a fost studiată reducerea grosimii aliajului de aluminiu EN AW-3003 placat cu EN AW-4343 în urma procesului de formare incrementală. Au fost utilizate două metode pentru analiza reducerii grosimii. Prima metodă a implicat măsurarea optică fără contact utilizând sistemul de măsurare optică ARAMIS. A doua metodă s-a concentrat pe analiza stratului placat prin microscopie optică.

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