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Comparison of vibration-assisted single-point and two-point incremental forming of sheet metal

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Abstract

Incremental Sheet Forming (ISF) is a versatile and economical forming process that enables the fabrication of complex shapes without tooling. The investigation compares the vibration-assisted Single-Point Incremental Forming (SPIF) and Two-Point Incremental Forming (TPIF) processes for aluminum alloys AA1100 and AA3003. A series of experiments are conducted to assess the performance of the process in terms of maximum wall angle, thickness change, surface finish, forming forces and hardness distribution. The findings show that TPIF offers enhanced dimensional control and thickness distribution control because of the supporting die, but SPIF offers better formability with larger wall angles. The use of vibration assistance leads to a substantial reduction in forming forces and improved surface quality due to reduced friction and interaction between the tool and sheet. But vibration assistance results in a slight loss of formability. Additionally, AA1100 has better ductility and formability than AA3003, while AA3003 has higher forming forces due to its higher strength. This research indicates that vibration-assisted TPIF provides the best compromise in terms of formability, surface finish and thickness distribution. These results offer guidance for the choice of forming processes in advanced sheet metal forming operations, such as in aerospace and automotive manufacturing, where efficiency and accuracy are essential factors.

Keywords: Incremental Sheet Forming; Single-Point Incremental Forming; Two-Point Incremental Forming; Vibration-Assisted Forming; Aluminum Alloys

1. Introduction

The growing need for on-demand, lightweight and complex geometric parts in industries like aerospace and automotive has required adaptable manufacturing processes. Traditional sheet metal forming technologies, while effective for high volume production, require specialised tooling and dies, leading to high costs and low flexibility [1]. On the other hand, Incremental Sheet Forming (ISF) has emerged as a promising dieless manufacturing process for the production of complex-shaped components with improved flexibility and reduced tooling cost. Among the different ISF processes, Single-Point Incremental Forming (SPIF) and Two-Point Incremental forming (TPIF) have gained much attention owing to their respective merits [2]. SPIF is a dieless forming process that uses a single forming tool, enabling high geometric flexibility and enhanced formability. But it tends to have poor accuracy and thickness uniformity [3]. In contrast, TPIF uses a partial or full die support, resulting in improved accuracy and thickness uniformity, but with lower formability.

One of the limitations of ISF processes is the large forming forces and surface damage that occurs due to the tool-sheet friction. How to overcome these challenges without affecting the formability? Recent studies indicate that vibration-assisted forming can significantly contribute in decreasing forming force, improving surface quality and improving

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material flow [4]. But the synergic effect of the vibration assistance to SPIF and TPIF processes, especially for aluminum alloys, is still poorly understood. For this purpose, two industrially important aluminum alloys, AA1100 and AA3003, are chosen because of their different mechanical properties. The former has high formability, enabling high forming processes, while the latter has high strength but low formability.

This research seeks to conduct a detailed comparison of vibration-assisted SPIF and TPIF for AA1100 and AA3003 sheets. The analysis will examine key process metrics, including maximum wall angle, thickness reduction, surface roughness, forming forces and hardness. Through a comparative study of the above-mentioned parameters, the study aims to address the following research questions: (i) What are the effects of vibration assistance on formability and process efficiency? (ii) What forming method offers the best compromise between dimensional accuracy and formability? and (iii) How can material characteristics influence the forming performance? The main contributions of the present study are: (1) comparative analysis of SPIF and TPIF based vibration-assistance, (2) quantitative analysis of mechanical and surface properties, and (3) determination of an optimal forming technique for enhanced performance.

2. Literature review

Incremental Sheet Forming (ISF) is a highly adaptable metal forming process that can generate complex shapes without specialised dies. Pioneering studies demonstrated that ISF is based on localized plastic deformation, which leads to improved formability over traditional forming processes [1]. This feature makes ISF ideal for small-batch and tailored production in aerospace, biomedical, and automotive applications. Single-Point Incremental Forming (SPIF) is one of the most researched forms of ISF because of its simplicity and its ability to produce complex shapes [3,4]. Studies have shown that SPIF can produce larger wall angles and better formability, particularly for the forming of ductile materials like aluminum alloys. However, it suffers from poor accuracy, large thinning and surface quality problems due to tool-sheet interaction [5,6]. These limits the use in high-precision components.

To address these issues, Two-Point Incremental Forming (TPIF) has been developed, with a partial or full die support. Researchers have demonstrated that TPIF enhances dimensional accuracy and thickness uniformity, offering more support during the forming process [7]. The die minimises distortions and improves wall thickness. But TPIF can potentially reduce formability due to the constraining effect on material flow, which limits its use in complex shapes. Innovative approaches have been explored to improve ISF processes through hybrid forming methods like vibration-assisted forming [8,9]. Using ultrasonic or mechanical vibration has been found to decrease the forming forces, due to reduced effective flow stress and friction at the tool-material interface. This leads to better surface quality, tool wear and improved formability. Furthermore, vibration assistance has been reported to assist in better strain distribution and reduced springback, improving part quality.

In addition, some research has explored the use of aluminum alloys, such as AA1100 and AA3003, in incremental forming. AA1100, due to its high ductility, has better formability and can achieve a larger wall angle, while AA3003 has higher strength but lower ductility, requiring higher forming forces and lower deformation [10]. These behaviors demonstrate the significance of material choice in ISF. Although considerable progress has been made, little work has been reported on the simultaneous effects of vibration assistance for SPIF and TPIF processes for various aluminum alloys. Current research tends to concentrate on individual methods, rather than a comparative analysis. Hence, there is a need to study the effect of vibration-assisted SPIF and TPIF on the formability, surface roughness, and thickness variation of different materials. This research fills this gap by offering a comparative analysis of vibration-assisted SPIF and TPIF for AA1100 and AA3003, which can help in fine-tuning process parameters and choosing suitable forming techniques.

3. Methodology

The current work investigates experimentally the vibration-assisted Single-Point Incremental Forming (SPIF) and Two-Point Incremental Forming (TPIF) processes for the aluminum alloys AA1100 and AA3003. The approach aims to assess the effect of forming strategy and vibration assistance on the performance of key parameters in figure 1.

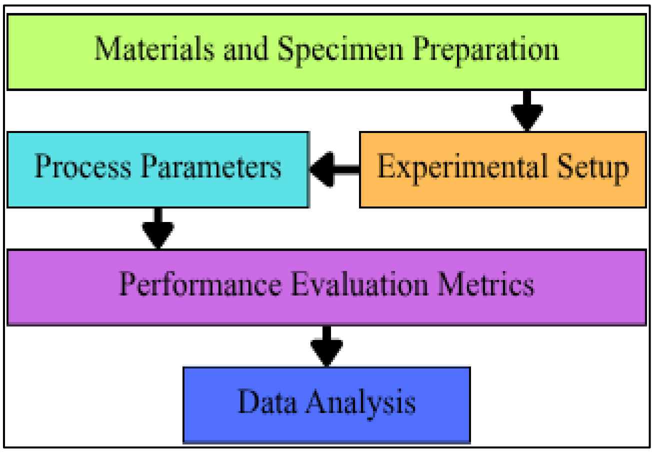

Figure 1 Methodology for SPIF and TPIF with Vibration Assistance

3.1. Materials and Specimen Preparation

Aluminum sheets, AA1100 and AA3003 with uniform thickness, available commercially were chosen. These were cut into square blanks of the same size. The yield strength, tensile strength and elongation of the material were taken into account to study the material's forming behavior.

3.2. Experimental Setup

The incremental forming experiments were carried out on a CNC incremental forming machine. The sheet was formed by a hemispherical tool following a tool path. In the case of TPIF, a partial die was placed under the sheet for improved accuracy. The process was vibration assisted by employing a controlled oscillating device attached to the forming tool.

3.3. Process Parameters

Critical process parameters were kept constant for comparison. These include the tool diameter, step size, feed and spindle speed. The vibration frequency and amplitude were chosen from previous research to reduce forces without compromising stability.

3.4. Performance Evaluation Metrics

The formability of SPIF, TPIF, and their vibration-assisted variants was assessed based on maximum wall angle (formability limit), thickness variation and reduction, surface roughness (Ra), forming forces and post-formed hardness variation. Thickness was measured at different depths to understand the thinning of the material, and surface roughness was measured with a profilometer to determine surface finish. Dynamometers were used to measure the forming forces during the experiments, and the Vickers hardness test was conducted to evaluate the changes in material hardness due to plastic deformation and work hardening.

3.5. Data Analysis

The data was evaluated both graphically and comparatively. Data was examined to determine trends in different processes and materials to assess the influence of vibration assistance. The data were also interpreted to identify the best forming strategy in consideration of formability, surface finish and microstructural integrity.

4. Results and Discussion

The next section provides more detailed insights into how different incremental forming approaches affect mechanical properties, thickness and formability. Particular focus is placed on the effects of vibration assistance on the resulting hardness, thickness distribution along the depth of the sheet, and strain distribution. Such factors play a key role in determining the integrity and performance of formed parts under various forming conditions.

Table 1 Material Properties of AA1100 and AA3003

Material	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)	Hardness (HV)
AA1100	30	95	40	28
AA3003	55	145	30	40

The basic mechanical properties of AA1100 and AA3003 are listed in Table 1, which play an important role in the incremental sheet forming process. The findings show that AA1100 has lower yield strength and ultimate tensile strength, but higher elongation than AA3003. This increased ductility of AA1100 allows it to undergo more plastic deformation, and is therefore more suitable for forming operations that require high formability. On the other hand, AA3003 has a higher strength and hardness, which leads to higher resistance to deformation and hence higher forming forces. But it has lower formability due to its lower elongation. These inherent material properties play a significant role in shaping the performance of the different forming processes (SPIF, TPIF, vibrationassisted SPIF, vibration-assisted TPIF).

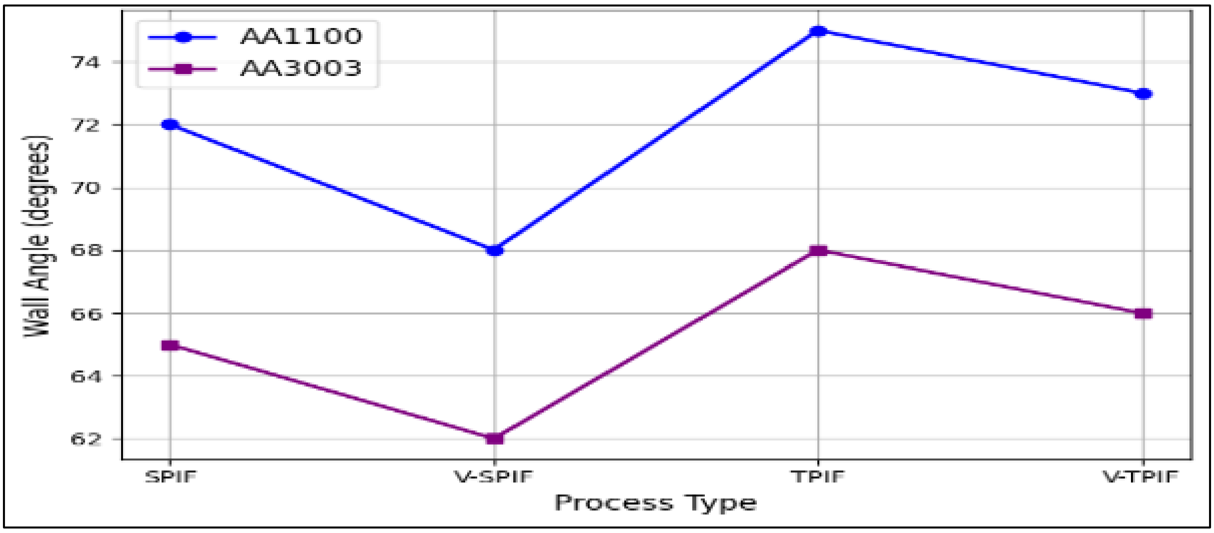

Figure 2 Maximum Wall Angle vs Process Type

The maximum wall angle is a measure of the forming process, and is shown in Figure 2. It can be seen that TPIF produces a higher wall angle than SPIF because of the die, which stabilises the deformation of the material. Further, AA1100 shows higher wall angles as compared to AA3003 due to its higher ductility. The use of vibration assistance leads to a minor decrease in the maximum wall angle for both alloys. This phenomenon is likely due to the changes in friction and flow stress, which lead to a modified strain distribution and slightly shifted forming limit. In conclusion, SPIF offers more flexibility, and TPIF offers more stability and increased deformation limits.

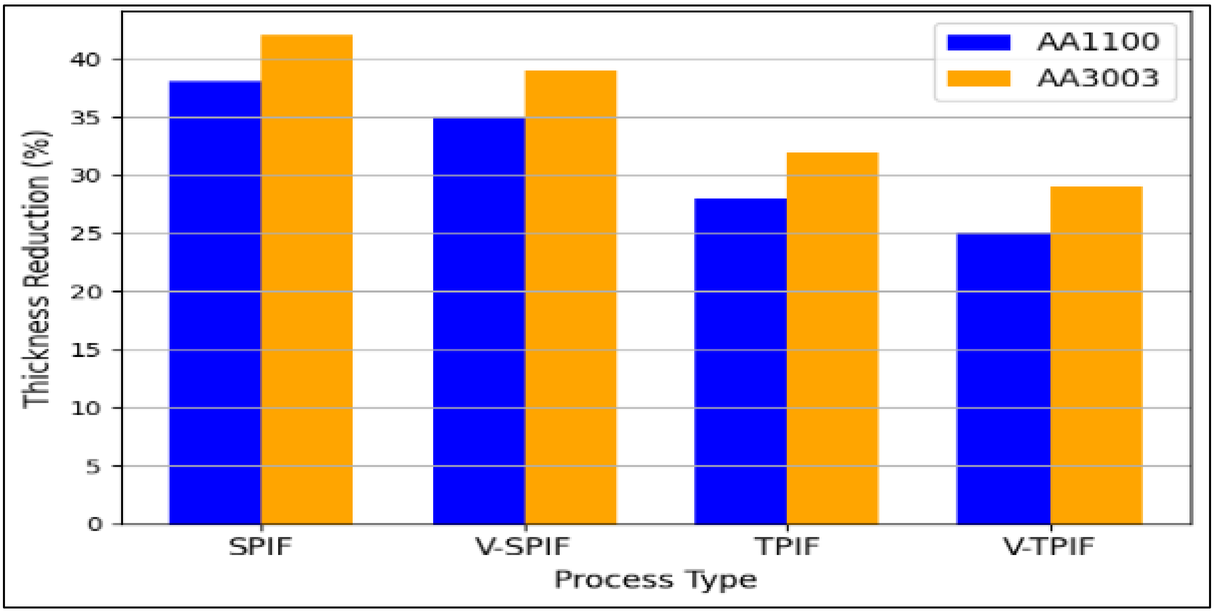

Figure 3 Thickness Reduction vs Process

The graph (Figure 3) compares thickness reduction in various forming processes. It can be seen that SPIF has the highest reduction in thickness as there are no constraints to support the material, resulting in local thinning. On the other hand, TPIF demonstrates a remarkable improvement in thickness reduction as the support reduces the stress concentration. Vibration also aids thickness distribution by promoting material deformation and eliminating localized stress. Thinning is slightly greater in AA3003 than AA1100 due to the lower ductility of AA3003, which restricts its deformation capacity. This comparison shows the benefits of TPIF and vibration for preserving structural integrity.

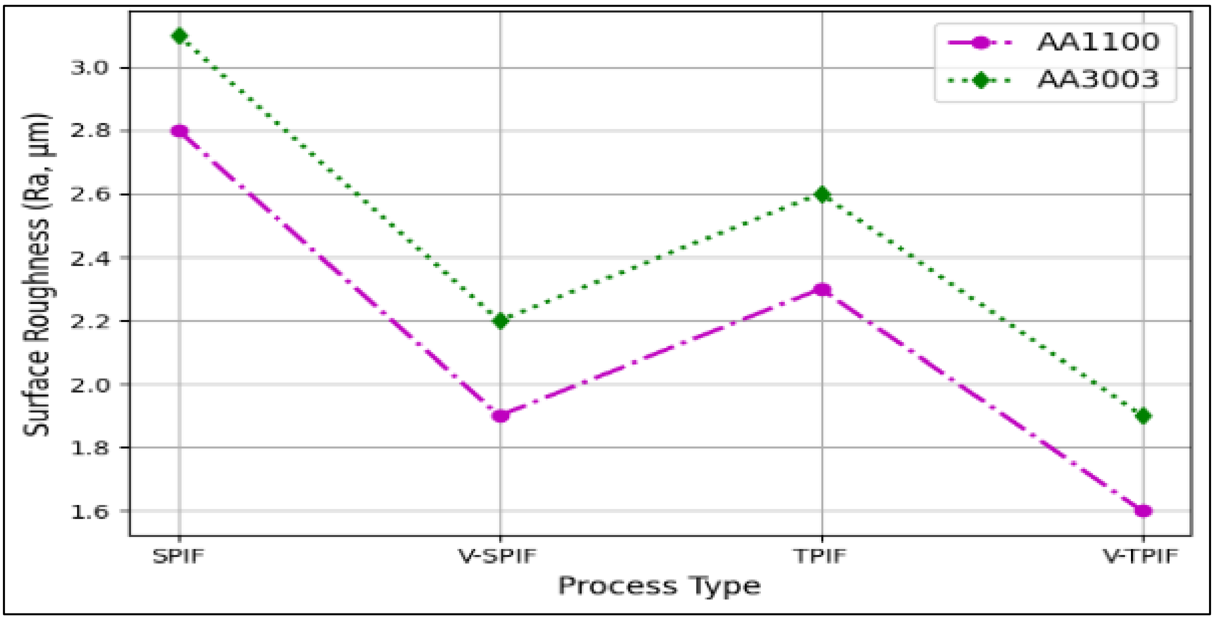

Figure 4 Surface Roughness Comparison

The surface roughness under various forming conditions is shown in Figure 4. It is clear that vibration-assisted processes (V-SPIF and V-TPIF) produce much smoother surfaces than the conventional processes (SPIF and TPIF). This improvement is attributed to lower friction and smoother tool contact due to vibration. V-TPIF has the smoothest surface, as it combines the advantages of vibration assistance and die support. Also, the surface of AA1100 is slightly smoother than AA3003, as the former is softer and deforms more easily. These results confirm that vibration assistance is very effective in enhancing surface properties.

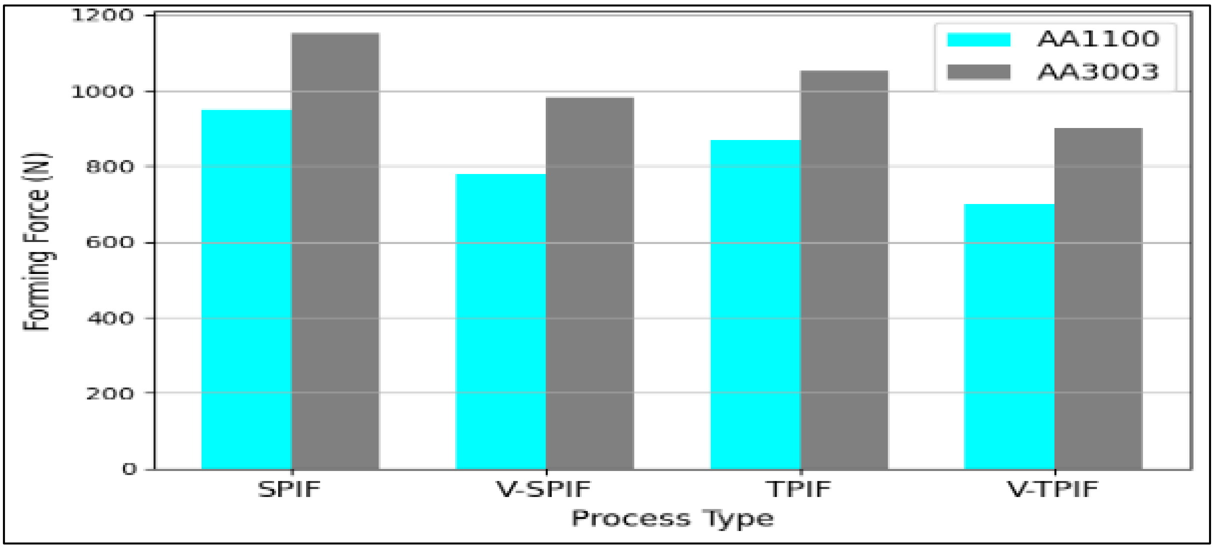

Figure 5 Forming Force Comparison

The forming forces for various manufacturing processes and materials are shown in Figure 5. It can be seen that the forming forces for AA3003 are greater than those for AA1100, owing to the increased strength and hardness of AA3003. SPIF has the highest forming force followed by TPIF, which has lower forces due to better load distribution. The use of vibration in SPIF and TPIF results in a substantial decrease in forming forces, with the lowest force in V-TPIF. This can be explained by the reduction in flow stress and friction between the tool and the sheet due to vibration. The results show that vibration assistance improves the efficiency of the process and tool life.

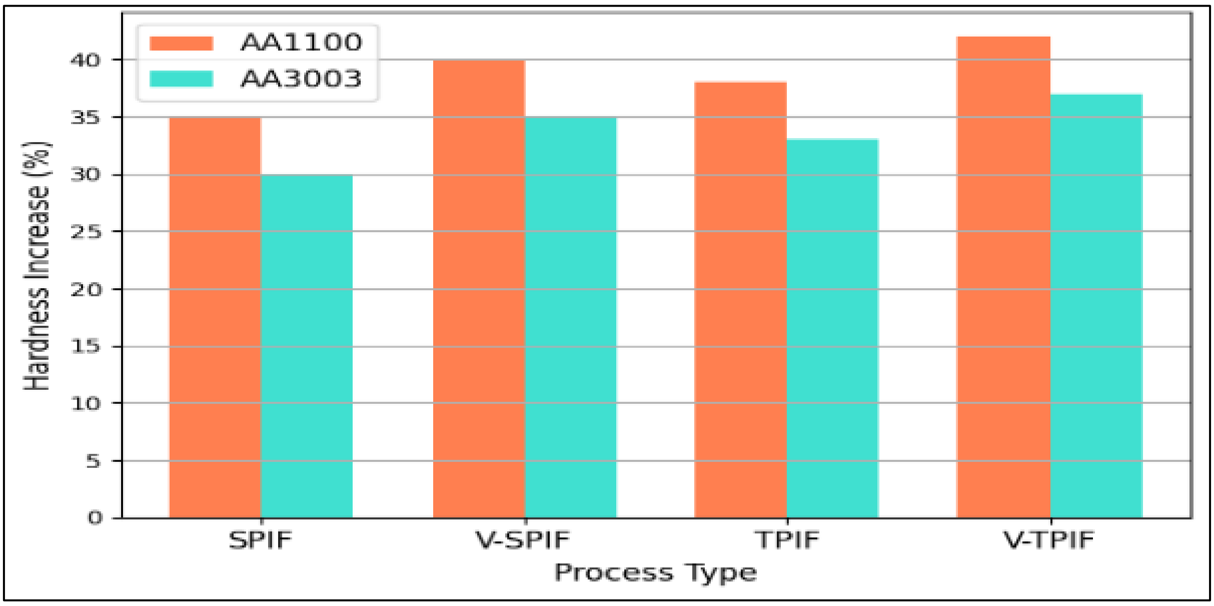

Figure 6 Hardness Variation

The changes in hardness of AA1100 and AA3003 after various forming processes are shown in Figure 6. It is evident that all processes lead to an increase in hardness, due to strain hardening effects from plastic deformation. Comparing the materials, AA3003 exhibits higher hardness values because it has a higher initial strength. Moreover, the vibration-assisted processes (V-SPIF and V-TPIF) show a higher increase in hardness than conventional processes. This improvement is attributed to better strain distribution and re-deformations in the material due to oscillatory motion, which leads to increased work hardening. The findings support the observation that vibration assistance enhances the surface and force parameters, but also increases the material's strength.

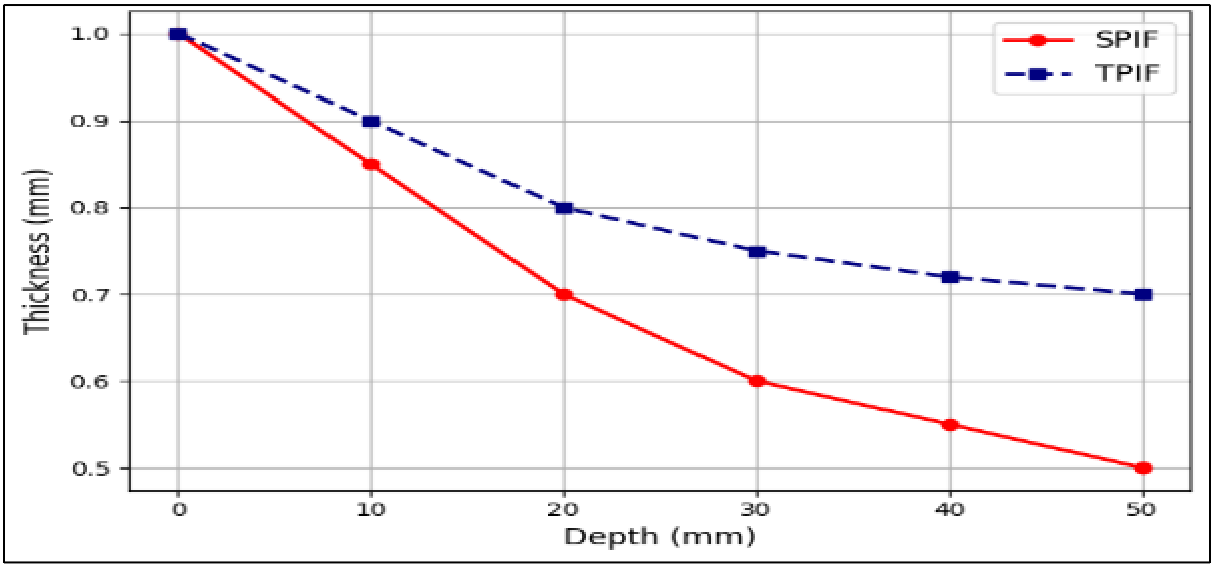

Figure 7 Thickness Distribution Along Depth

Figure 7 shows the distribution of sheet thickness along the depth of the product. It can be seen that in SPIF, there is considerable thickness variation, especially at higher depths, as no constraints are present. However, TPIF results in more uniform thickness distribution as the die provides support to distribute the deformation. Vibration assistance also helps improve thickness uniformity by further facilitating material flow and strain distribution. Moreover, AA1100 demonstrates a more gradual thickness distribution than AA3003, which has lower ductility. These results indicate the benefit of TPIF and vibration assistance in enhancing the stability and preventing failure.

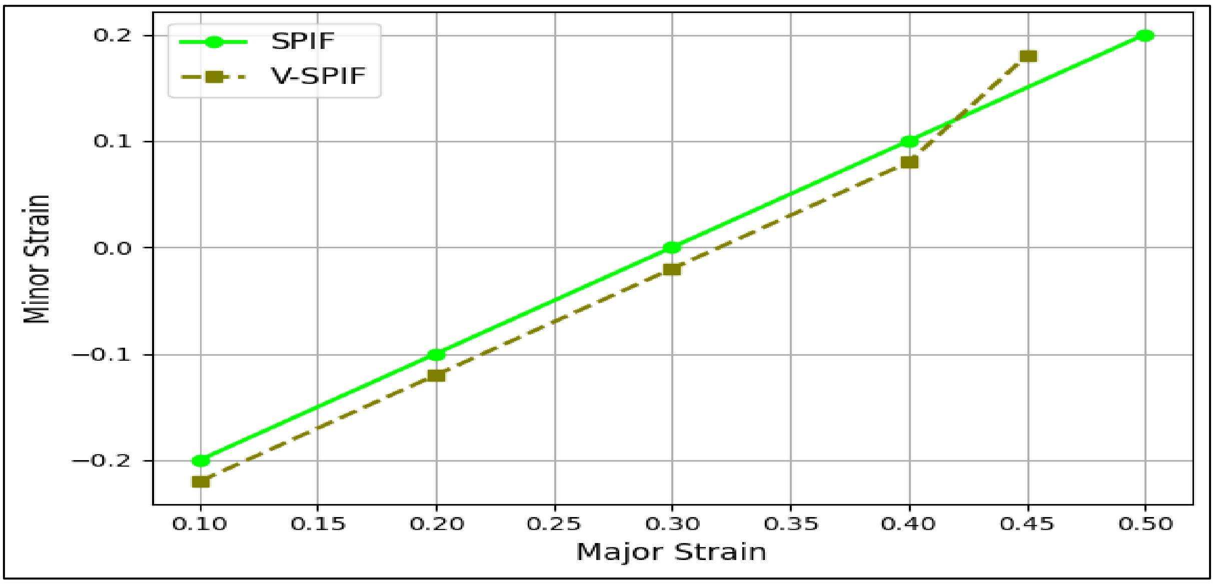

Figure 8 Formability Limit Diagram (FLD/FFL)

Figure 8 shows the Formability Limit Diagram (FLD), which displays major and minor strains at different forming conditions. As demonstrated, SPIF demonstrates higher strain limits than TPIF, which suggests that it is more formable because of the less constrained material flow. But TPIF exhibits more stable deformation. Vibratory assistance results in a slightly downward shift in the forming limit curve, implying a slight decrease in formability. This is likely due to a change in friction and strain path during vibration. However, vibration-assisted forming processes still provide satisfactory formability with enhancements in surface quality and force reduction. AA1100 consistently yields higher strains than AA3003, proving to be more ductile.

In summary, the findings confirm the different benefits of the various forming techniques depending on the performance criteria. SPIF offers better formability but TPIF offers better thickness and dimensional accuracy. Vibration assistance plays a pivotal role in improving the efficiency of the forming process by decreasing forming forces, improving surface finish, and facilitating drawing. Thus, vibration-assisted TPIF presents itself as the most comprehensive technique, providing the best mix of strength, quality and efficiency for advanced sheet metal forming processes.

5. Conclusion

This research has compared the performance of vibration-assisted Single-Point Incremental Forming (SPIF) and Two-Point Incremental Forming (TPIF) of aluminum alloys AA1100 and AA3003. The findings revealed that SPIF exhibits higher formability, with higher maximum wall angles, but less dimensional accuracy and uniform thickness distribution, due to the absence of die support, compared to TPIF. Vibration assistance led to a considerable reduction in forming forces and an improvement in surface quality due to reduced friction and improved material flow. But vibration assistance led to a slight decrease in formability. Additionally, the superior formability of AA1100 was confirmed by its higher ductility level, while the higher forming force was needed for AA3003 due to its higher strength. Overall, vibration-assisted TPIF was identified as the most suitable process in terms of formability, surface finish and thickness variation. In conclusion, the results indicate that the choice of forming process should consider the trade-off between dimensional accuracy and forming ability. Potential future research could involve the optimization of vibration parameters and the investigation of new alloys and complex shapes.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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