Experimental Investigation of Forming Forces in Single Point Incremental Forming

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Abstract Single point incremental forming (SPIF) has been confirmed as a quiet economical process for rapid prototyping and batch-type production. It exempts complex and expensive tooling as required in the conventional sheet metal-forming processes. Investigation of forming forces becomes important for selecting the appropriate hardware and optimal process parameters in order to assure the perfection and precision of any process. Moreover, SPIF applicability can be ensured on the industrial scale when appropriate guidelines are highlighted regarding a relation between the input parameters and forming forces induced in the process. This paper investigates the influence of tool diameter, tool shape, and wall angle on the maximum axial forming forces on aluminum alloy (AA2024-O) sheets. Forming forces were recorded using a dynamometer and data logger system equipped with Microscada software. Tool shape has been proved a significant factor which affects the forming forces greatly. Combination of higher wall angle and flat-end tool with the lower side radius resulted in the fracture of components at a lower depth.

Keywords SPIF · Forming force · Process parameters · AA-2024-O · Tool shape

1 Introduction

Sheet metal forming has been an important manufacturing process in several industrial sectors. In the engineering field, parts are generally made of sheet metal particularly through conventional forming methods such as stretch forming, deep drawing,

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shearing, blanking, and bending, etc. These conventional forming techniques are expensive and uneconomical for the batch-type production due to the involvement of pressing dies and punches [1]. Batch-type production can be accomplished at the economical level using single point incremental forming (SPIF) process [2]. SPIF is also beatified with smaller lead time and negligible tooling cost for producing prototypes and smaller batch size components [3].

SPIF is a truly die-less technique which can easily form the components for aerospace, medical, and automotive sectors. The designed shape of components can be formed using a simple spherical-headed tool layer by layer as shown in Fig. 1. This die-less process can be accomplished on a CNC milling machine in order to form the predetermined shape of components. Moreover, a smaller amount of energy is required during this technique due to the incremental nature of the process. Less forming force is required in order to produce the components using the SPIF process. Forming forces are responsible for the structural integrity of the workpiece [4]. Maximum forming forces which are required to form the components define the capacity of the hardware used in this process. Hence, investigation of the maximum forming forces becomes customary to guarantee the secure utilization of the forming machinery. Forming force is the force required to deform the sheet at the tool–sheet interface. In the literature, table-type dynamometer [5–11] has mostly been used which is mounted between the machine bed and SPIF fixture.
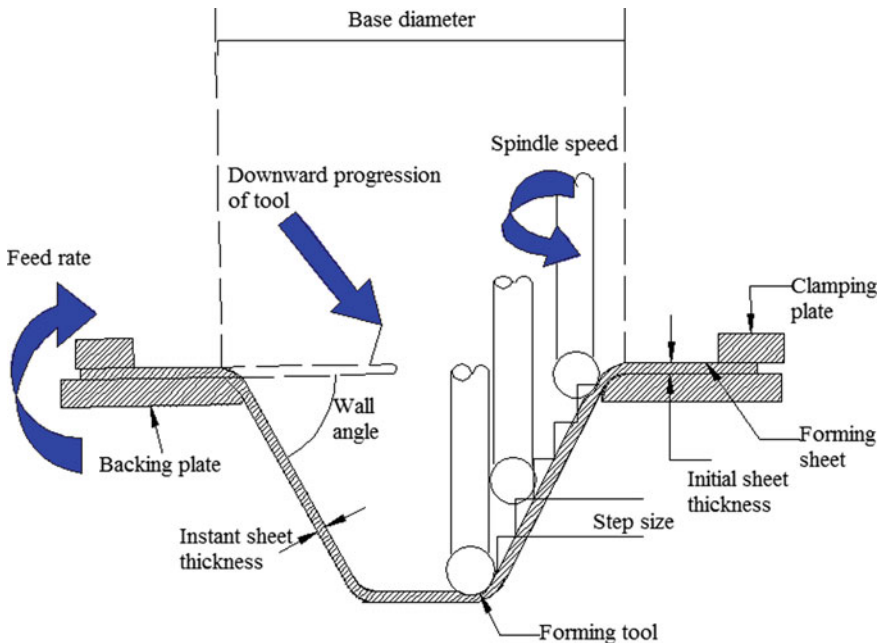
Fig. 1 Single point incremental forming

1.1 History of SPIF

Li et al. [5] deduced a model for predicting the forming forces based on the deformation analysis. The proposed model was validated by investigating the influence of different step sizes in order to produce the conical and pyramidal frustums by experimental tests on AA7075-O sheets. Results showed that the predicted and experimental results were found in good correlation. Liu et al. [11] investigated the impact of tool path strategies and wall angle on AA7075-O sheets. Results showed that the axial peak forces were found to be increased with the rise in wall angle. Bagudanch et al. [12] and Centeno et al. [13] performed experimental tests on PVC and AISI 304 stainless steel sheets, respectively. They found that the maximum axial forces increased with the rise in punch diameter. Petek et al. [14] also observed a similar trend of maximum axial forces. Oleksik et al. [15] investigated the effects of different tool diameters (12, 16, 20 mm) on forming forces during the SPIF process and elaborated the mathematical models. Results showed that the axial forming forces were much higher than those occurred in the x-direction. Fiorentino et al. [16] studied the influence of angular step sizes (2°, 4°, 6°) using the positive die on FeP04 deep drawing steel sheets. They found that the axial force was greater than that occurred in x-axis and y-axis. It has been revealed from the literature that the force component in the axial downward direction (F_z) of the forming tool is much more than the other two force components (F_x and F_y). Hence, determination of the axial force component becomes customary for the safe utilization of the hardware.

This work presents the investigation of input factors on axial peak forces on AA2024-O sheets. The impacts of tool shape, wall angle, and tool diameter have been investigated for conical frustums. Three different shapes of the forming tools have been investigated in this study. Table 1 and Fig. 2a represent the geometry of forming tools used in this study. Table 2 shows the input factors which are studied in this paper. Each input factor was investigated at three levels. Other input factors were taken constant as feed rate 1500 mm/min, wall angle 64°, tool diameter 11.60 mm, spindle speed 1000 rpm, sheet thickness 1.2 mm, and step size 0.5 mm. Castrol Alpha SP 320 was used for the lubricating purpose at the contact zone of tool and sheet.

2 Materials and Methods

2.1 Experimental Set up

A CNC milling machine has been used for experimental tests (Fig. 2b). Table 3 represents the chemical compositions of the AA2024-O aluminum alloy sheets. Conical frustums of 120 upper diameters have been designed for forming operation up to 70 mm forming depth. Lower diameters of conical frustums were controlled by wall angles.

Table 1 Geometrical details of forming tools

Tool diameter	Side radius of flat-end tool	Radius of hemispherical end tool	Symbol
T_D (mm)	r (mm)	R (mm)	
7.52	1.40	–	FlatEnd-R1
	2.00	–	FlatEnd-R2
	–	3.76	Hemispherical
11.60	1.98	–	FlatEnd-R1
	2.85	–	FlatEnd-R2
	–	5.80	Hemispherical
15.66	1.85	–	FlatEnd-R1
	3.76	–	FlatEnd-R2
	–	7.83	Hemispherical
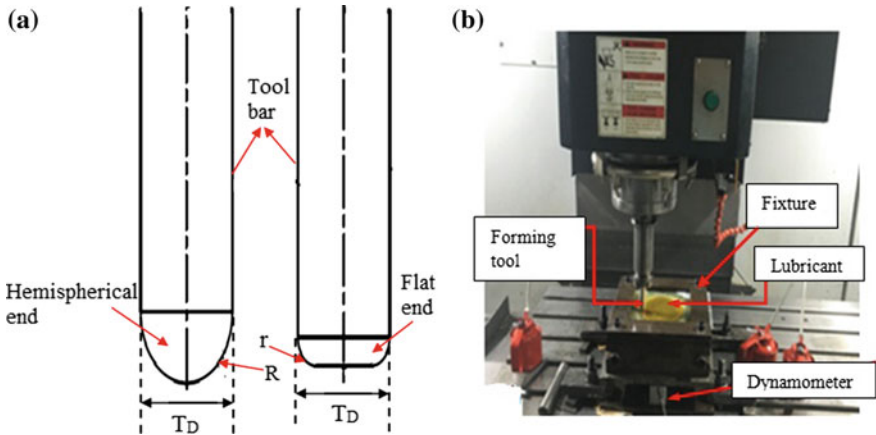
Fig. 2 Experimental set up

Table 2 Process parameters and their levels

Parameter	Level 1	Level 2	Level 3
Tool diameter (mm)	7.52	11.60	15.66
Tool shape	FlatEnd-R1	FlatEnd-R2	Hemispherical
Wall angle (°)	60	64	68

Table 3 Chemical compositions of aluminum alloy used

Chemical composition (weight %)									
AA2024-O	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn
	91.50	0.10	4.60	0.30	1.70	0.80	0.50	0.10	0.20

Table 4 Forming force test results with different process parameters

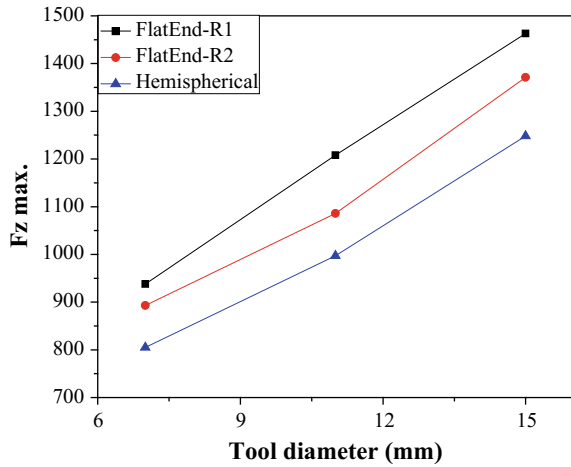| Forming force test results for tool diameter and tool shape				Forming force test results for wall angle and tool shape			
Sr. no	Tool diameter	Tool shape	Fz max	Sr. no	Wall angle	Tool shape	Fz max
1	7.52	FlatEnd-R1	938	10	60	FlatEnd-R1	1078
2	7.52	FlatEnd-R2	893	11	60	FlatEnd-R2	982
3	7.52	Hemispherical	805	12	60	Hemispherical	905
4	11.60	FlatEnd-R1	1208	13	64	FlatEnd-R1	1210
5	11.60	FlatEnd-R2	1086	14	64	FlatEnd-R2	1091
6	11.60	Hemispherical	997	15	64	Hemispherical	991
7	15.66	FlatEnd-R1	1463	16	68	FlatEnd-R1	1352
8	15.66	FlatEnd-R2	1371	17	68	FlatEnd-R2	1294
9	15.66	Hemispherical	1248	18	68	Hemispherical	1219

2.2 Methodology for Force Measurement

Forming forces in the axial direction (F_z) have been measured using a strain gauge-based dynamometer which was mounted below the fixture as shown in Fig. 2b. A data logger system equipped with Microscada software has been provided to the dynamometer in order to facilitate the processed force values in a PC-based environment. On the application of the load, the conducting material of strain gauge provides voltage as an output which is proportional to the elastic deformation. The analog signals of voltage received from strain gauge are required to convert into digital signals to display the real-time online observation of forming forces during operation. ADC 0808 analog to digital converter has been used in the data logger system for this purpose.

3 Results and Discussion

Experimental test results of different input factors on the forming forces are given in Table 4. Maximum axial forming forces (F_z max.) are taken into account for analysis.

Figure 3 shows the impacts of tool shape with the different tool diameters on the maximum axial forces. An increase in tool diameter resulted in the increment of forming forces. This is due to the fact that the larger contact zone occurs at the tool–sheet interface for larger tool diameter. Hence, more material is to be formed at that instant. Forming forces were found to be influenced significantly by changing the shape of the forming tool. Maximum axial forces were found to decrease with the increase in the side radius of the forming tool. This trend of decreasing force with the

increase in the side radius was consistent for all levels of the tool diameter investigated in this study. When tool shape was changed from FlatEnd-R1 to Hemispherical end, maximum axial forces (F_z max) decreased approximately 14.17, 17.46, and 14.69% for 7.52, 11.60, and 15.66 mm tool diameters, respectively. Similarly, maximum axial forces were found to decrease by 35.88, 34.86, and 35.49% for FlatEnd-R1, FlatEnd-R2, and Hemispherical shape, respectively, when tool diameter was reduced from 15.66 to 7.52 mm.

Figure 4 shows the impacts of tool shape with the wall angles on maximum axial forces. Axial peak forces were found to increase with the increase in wall angle of conical parts. Moreover, sheet fracture was observed with 68° wall angle specimens for all shapes of the forming tools. This may be due to the fact that the higher wall angle results in excessive sheet-thinning according to sine law [17] which leads to an earlier fracture of the sheet material. In the case of the conical frustum of 64° wall angle, fracture occurred for FlatEnd-R1 and FlatEnd-R2 tool shapes. This can be due to the fact that the smaller radius of the tool increases penetration into the sheet and removes materials in the form of chips. Hence, a smaller radius of the tool-tip leads to cracking of the sheet material resulting in the lower forming depth. When tool shape was changed from FlatEnd-R1 to Hemispherical end, maximum axial forces (F_z max) decreased approximately 16.04, 18.10, and 9.83% for 60°, 64°, and 68° wall angles, respectively. Similarly, maximum axial forces were found to decrease by 20.26, 24.11, and 25.75% for FlatEnd-R1, FlatEnd-R2, and Hemispherical shape, respectively, when the wall angle was reduced from 68° to 60°.

Fig. 4 Effects of wall angle
and tool shape on maximum
axial forces
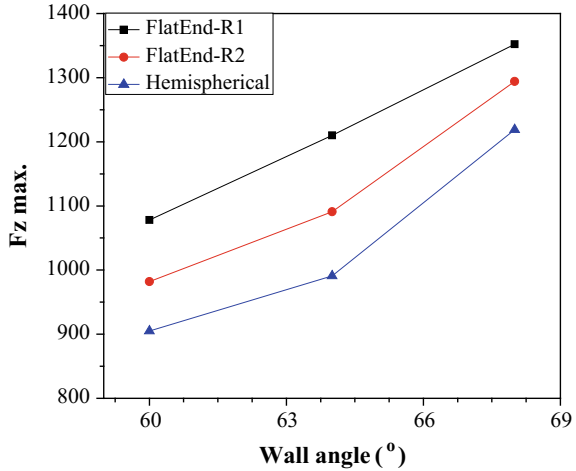
4 Conclusions

In this study, the axial forming forces have been investigated using the SPIF process on AA2024-O aluminum alloy sheets. For this purpose, the conical frustums of constant wall angle have been formed in order to investigate the impact of input factors. An increase in tool diameter resulted in the increment of the forming forces. Increasing side radius of flat-end tools resulted in the decrement of the forming forces. The shape of the tool has also been proved a significant factor during this process. Less forming forces are required to deform the sheet with the hemispherical end tools as compared to those required with the flat-end tools. Combination of flat-end tools having lower side radius and higher tool diameter requires higher forming forces in order to produce the components during the SPIF process. On the other hand, the hemispherical end tools with lower tool diameter resulted in lower forming forces required to produce the parts. Increase in wall angle led to an increase in the forming forces. Combination of higher wall angle and flat-end tool with lower side radius resulted in the fracture of components at a lower depth. Future work would focus on the analysis of thickness distribution and dimensional accuracy of the formed components which seeks importance and suitability in setting guidelines for the industrial application.

References

1. Kim YH, Park JJ (2002) Effect of process parameters on formability in incremental forming of sheet metal. J Mater Process Technol 130:42–46
2. Li P, He J, Liu Q, Yang M, Wang Q, Yuan Q, Li Y (2017) Evaluation of forming forces in ultrasonic incremental sheet metal forming. Aerosp Sci Technol 63:132–139

3. Wu SH, Reis A, Andrade Pires FM, Santos AD, Barata da Rocha A (2012) Study of tool trajectory in incremental forming. Adv Mater Res 472:1586–1591
4. Bagudanch I, Centeno G, Vallellano C, Garcia-Romeu ML (2013) Forming force in single point incremental forming under different bending conditions. Procedia Eng 63:354–360
5. Li Y, Daniel WJ, Liu Z, Lu H, Meehan PA (2015) Deformation mechanics and efficient force prediction in single point incremental forming. J Mater Process Technol 221:100–111
6. Azevedo NG, Farias JS, Bastos RP, Teixeira P, Davim JP, de Sousa RJA (2015) Lubrication aspects during single point incremental forming for steel and aluminum materials. Int J Precision Eng Manuf 16:589–595
7. Mohammadi A, Qin L, Vanhove H, Seefeldt M, Van Bael A, Duflou JR (2016) Single point incremental forming of an aged AL–Cu–Mg alloy: influence of pre-heat treatment and warm forming. J Mater Eng Perform 25:2478–2488
8. Duflou JR, Callebaut B, Verbert J, De Baerdemaeker H (2008) Improved SPIF performance through dynamic local heating. Int J Mach Tools Manuf 48:543–549
9. Al-Obaidi A, Kräusel V, Landgrebe D (2016) Hot single-point incremental forming assisted by induction heating. Int J Adv Manuf Technol 82:1163–1171
10. Asghar J, Reddy, N (2013) Importance of tool configuration in incremental sheet metal forming of difficult to form materials using electro-plasticity. In: Proceedings of the World Congress on Engineering 2013, vol 3, pp 1734–1738
11. Liu Z, Li Y, Meehan PA (2013) Experimental investigation of mechanical properties, formability and force measurement for AA7075-O aluminum alloy sheets formed by incremental forming. Int J Precision Eng Manuf 14:1891–1899
12. Bagudanch I, Garcia-Romeu ML, Centeno G, Elías-Zúñiga A, Ciurana J (2015) Forming force and temperature effects on single point incremental forming of polyvinylchloride. J Mater Process Technol 219:221–229
13. Centeno G, Bagudanch I, Martínez-Donaire AJ, Garcia-Romeu ML, Vallellano C (2014) Critical analysis of necking and fracture limit strains and forming forces in single-point incremental forming. Mater Des 63:20–29
14. Petek A, Kuzman K, Kopac J (2009) Deformations and forces analysis of single point incremental sheet metal forming. Archives Mater Sci Eng 35:35–42
15. Oleksik V, Pascu A, Gavrus A, Oleksik M (2010) Experimental studies regarding the single point incremental forming process. Acad J Manuf Eng 8:51–56
16. Fiorentino A, Ceretti E, Attanasio A, Mazzoni L, Giardini C (2009) Analysis of forces, accuracy and formability in positive die sheet incremental forming. Int J Mater Form 2:805–808
17. Jeswiet J, Micari F, Hirt G, Bramley A, Duflou J, Allwood J (2005) Asymmetric single point incremental forming of sheet metal. CIRP Annals Manuf Technol 54:88–114