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Formability of Aluminum Alloys During Single Point Incremental Forming: A Review

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ABSTRACT

Single point incremental sheet metal forming has passed through a period of ample improvement with developing responsiveness from research societies and industries globally. The process has expressively spared the practice of using costly dyes, which makes it an appropriate process for manufacturing prototypes and small batch production. It also discovers easiness in fabricating components of timeworn equipment. Additionally, in recent years, aluminum alloys become the most commonly used materials in the automotive, aeronautics, and transportation industries for their structural and other applications. The effect of various process parameters on the formability of single point incremental forming of aluminum alloys has been critically surveyed. Ultimately, this article also debated the dares associated with the single point incremental forming process and recommended some correlated research regions that should charm significant research considerations in the future.

KEYWORDS

Aluminum Alloys, Formability, Single Point Incremental Forming, Tool Diameter, Toolpath, Vertical Step Size

INTRODUCTION

In the eternity of today's renovation and improvement, the superiority of custom-built merchandise in terms of quality, cost, rapid prototyping and short lead times is turning into a problem of central importance. The materials with high thermal strength, lightweight, excellent corrosion and creep resistance, high fatigue strength, high stiffness, etc. are needed. Aluminum alloys possess all of these properties which make them suitable for most of the industries. Due to these confines, highly flexible forming processes are desired. There are numerous sheet metal forming methods like Deep Drawing, Progressive and Transfer Die Forming, Spinning, High-Velocity Forming, Shear Forming, Stamping, and Incremental Sheet Forming (ISF), etc. (Schedin, 1992). The welfares of ISF processes in terms of formability, easiness in tooling, and dieless set-up have permitted the application of the process for manufacturing geometrically intricate and tailor-made parts. ISF fulfills and justifies all the above requirements with reasonable expenses. ISF was first coined and patented by Edward Leszak in Sept. 1967 (Leszak, 1967), ISF is of two types, namely negative (concave) or SPIF and positive (convex) or TPIF. In a negative sheet forming the blank is formed into the support or rig but in a positive sheet forming in addition to the tool, there is additional supportive die (partial or full die) is used (Katajarinne & Kivivuori, 2013). Japanese researcher, Iseki in 1989 done revolutionary work by using a 3-D CNC milling machine for ISF and introduced the first single point incremental sheet

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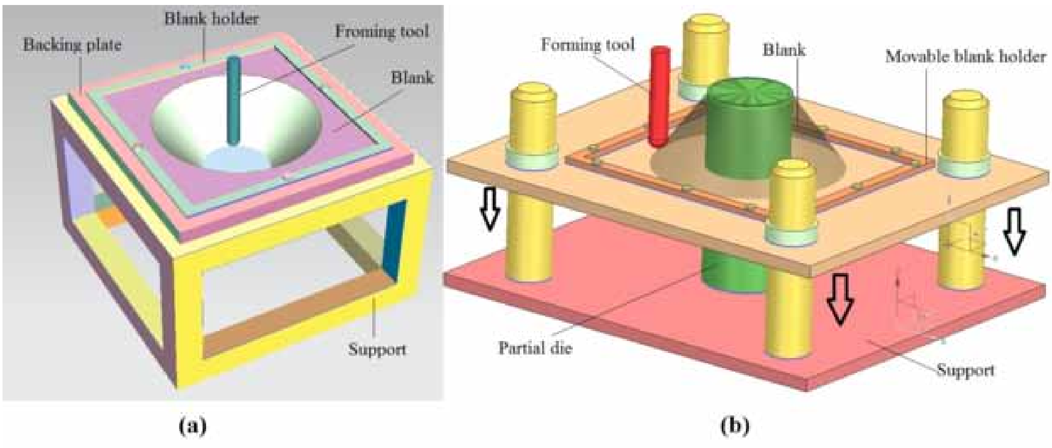
forming (SPIF) (Figure. 1a). Two point incremental forming (TPIF) (Figure. 1b) was first introduced by Mastubara (1994) (Emmens et al., 2010).

Figure 1. Pictorial explanation of (a) setup for SPIF; (b) setup for TPIF



Originally, SPIF was developed as a manufacturing process used for the production of metallic parts (Jeswiet et al., 2005), however, continuous development of SPIF makes it suitable for polymers (Martins et al., 2009), shape-memory materials (Mohammadi et al., 2015), and composite materials (Conte et al., 2017). The process has been reviewed in a current decade (Joost R. Duflou et al., 2018; Echrif & Hrairi, 2011; Li et al., 2017) but there is a lack of review article specially on single point incremental formability of aluminum alloys was noticed and require benchmark work to realize full-scale industrial use of the process for partial and complete forming of aluminum alloys. Considering the extensive knowledge transfer, as reflected by the enormous number of researches over the previous decade and the exhibited applications, the authors have united to incorporate an updated review of the cutting edge in the area SPIF of aluminum alloys. The review is organized by investigating the adequate quantity of research articles in various aspects especially to cover present applications of SPIF process in forming aluminum alloys of different grades, the fundamental knowledge and prerequisites for the process apparatus, forming principle, and important process parameters followed by the critical investigation of process parameters effect on formability of aluminum alloys in the SPIF process. The review is concluded with, the application territories of the SPIF process to deliver the present and future regions of research.

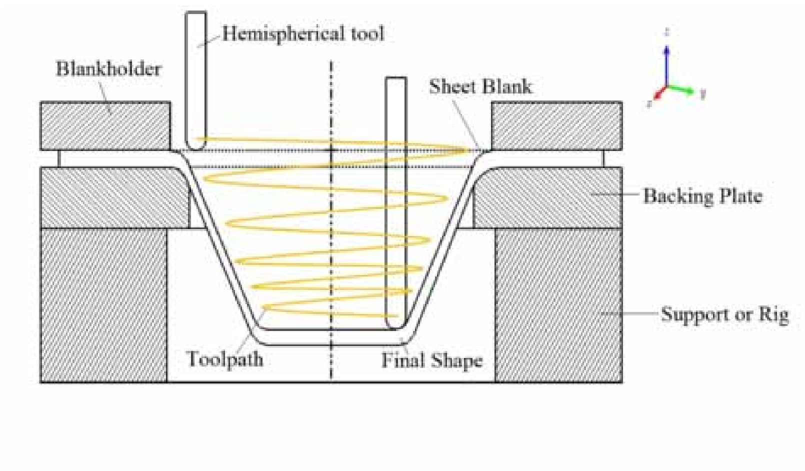
FUNDAMENTALS OF SPIF

In modern industrialization, incremental forming offers various opportunities for design engineers and producers, as dies are considered as major obstacles in automation process. Conventional forming processes are costlier than SPIF because they need a dedicated die, hydraulic press and long setup time. These benefits of SPIF attracted research scholars and industry persons more towards its technique.

1. Working Principle

In SPIF process, a flat metallic sheet is progressively deformed into the targeted 3-D profile using Computer Numerical Control (CNC) controlled standard forming tool, the method is characterized through the certainty that at any time only a small part of the merchandise is genuinely being formed and the region of local deformation is moving over the complete product till the preferred geometry is acquired (Figure. 2). In SPIF tool is moved in successions (stepping down and inward or outward) of passes around the circumference of the part. As the blank is clamped in a blank holder that remains at a constant height. The tool is shifted down in the Z-axis, with fixed steps for every pass and simultaneously, a progression of curves in the X-axis and Y-axis are made via the forming tool around the profile boundary to generate the tool path, the sheet is molded into the predetermined shape or profile for the given tool path, therefore at least 3 axes CNC machines are required for forming process.

Figure 2. Graphical illustration for working principle of SPIF



2. Elements of SPIF

SPIF is a sheet metal forming process that is capable of generating complex symmetrical and asymmetrical profiles and parts without dies. SPIF can be done by using almost all the CNC milling machines, CNC incremental forming machines, CNC lathes, and industrial robots (Emmens et al., 2010; Jeswiet et al., 2005). There are four basic elements of the SPIF process are forming tool, sheet material, part geometry and tool path.

2.1 Forming Tool

The desired properties of the forming tool or punch which is used in SPIF for forming the material in predetermined shape are: high hardness(to resist wear), high fatigue strength(to resist cyclic loading), higher stiffness(to resist bending), high thermal stability (to dissipate heat), low friction coefficient (for better stability) (Hagan & Jeswiet, 2003), The materials which are used to manufacture the tool for SPIF process are high-speed steel (Mugendiran et al., 2014), tungsten carbide (Shojaeefard et al., 2019), tool steel (Maji & Kumar, 2020), stainless steel (Radhika et al., 2019), cemented carbide (Palumbo & Brandizzi, 2012) etc., the effect of different tool materials over formability in the SPIF process is never examined and reported till date. Initially, the shape of the forming tool was hemispherical and rolling ball ended (Kilani et al., 2020; Y. H. Kim & Park, 2002) upon further developments in SPIF technology flat-ended, angled, parabolic (Jeswiet et al., 2015), and oblique roller-ball tool (Lu et al., 2014), were introduced and developed which helps in decreasing friction, pressure, and improved surface finish. The diameter of the punch or tool is generally in the range of

4 mm to 20 mm for most of the applications (Bhattacharya et al., 2011; Dabwan et al., 2020; Han et al., 2013; Pandivelan et al., 2014).

2.2 Sheet Material

In SPIF different materials like metals (Aerens et al., 2010), brass alloys (Fritzen et al., 2018), polymers (I. Bagudanch et al., 2016), shape-memory foams, sandwich panels, and composite materials have been formed which are used in different industries like medical implants (Isabel Bagudanch et al., 2015), transportation, automobile, and aerospace industries. Initial sheet thickness is a crucial parameter in SPIF and has significant effects on other parameters such as tool diameter, forming force, spring back, wall angle, wall thickness, thinning ratio forming height, and so on are affected by it (Dabwan et al., 2020; Han et al., 2013). So sheet material properties can be seen as the base upon which all other parameters are selected, as the undeformed sheet thickness increases the formability also increases (Kopac & Kampus, 2005).

2.3 Part Geometry

SPIF can be used to form 3-D shapes of a wide variety such as conic, spherical, pyramidal, twisted pyramidal, parabolic elliptical, and so on in sheet blank without using dedicated tools, the quality of sharp edges between flanks of pyramidal products is better than in press working (Matsubara, 2001). SPIF can be used for forming symmetric and asymmetric parts (Fiorentino, Marenda, et al., 2012; Park & Kim, 2003). As the component formed by ISF with exponential, parabolic, circular, and elliptical generatrix, the experiments show high formability for exponential generatrix than the other three generatrices. The reason behind that was in exponential generatrix the steepness of the wall varies slowly (Pratheesh Kumar et al., 2020). Numerous complex shell structures were formed by a combination of some basic geometries orderly at the micro-level using the SPIF system (Sekine & Obikawa, 2010).

2.4 Tool Path

The tool path generation is one of the most important characteristics of the SPIF process to improve its efficiency and accuracy, in SPIF it resembles as the tool path in machining processes such as high-level finishing operation or complex profile cutting using electrochemical machining, though there is no material is removed. The simplest form of tool paths are profile and helical tool path (Figure. 3), in profile tool paths tool moves in the single plane till it again reaches its initial position and then it moves to the next plane in the downward direction from a specified distance, now tool endures its motion in the similar track as that of the previous cycle and so on till the final geometry is formed. Attanasio *et al.* (Attanasio et al., 2006), proved that it is beneficial to use tool paths with constant scallop height than constant axial increment (Figure. 4).

Figure 3. Commonly used tool paths in SPIF (a) profile (b) helical

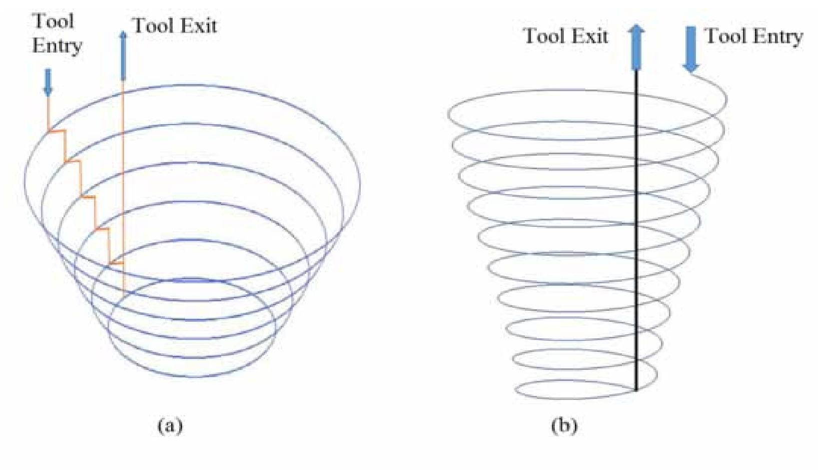
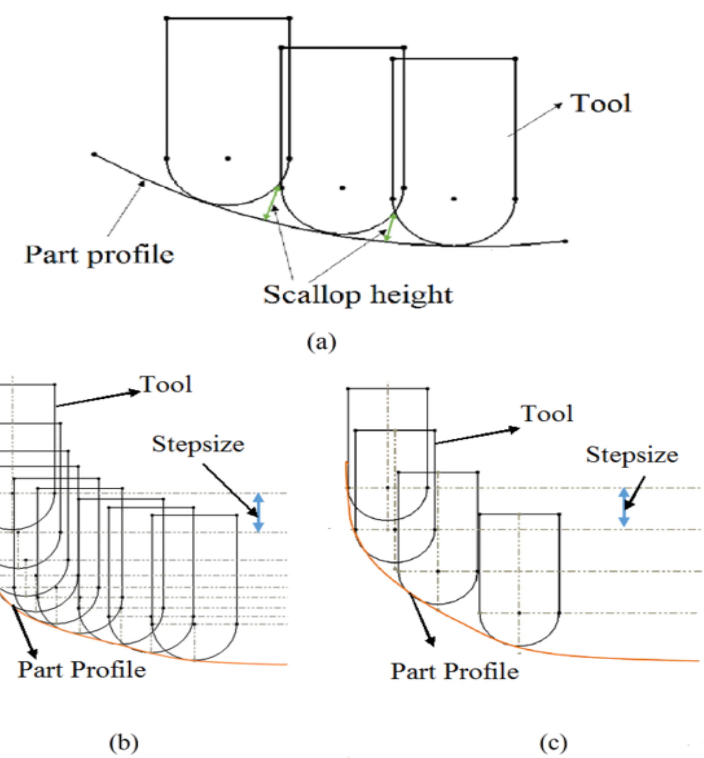


Figure 4. Graphical demonstration of (a) scallop height concept; (b) toolpath with constant scallop height strategy; (c) toolpath with constant axial incremental strategy



3. ADVANTAGES AND LIMITATIONS OF SPIF

The principal advantages of SPIF are: (i.) No need for a dedicated die; (ii.) no need for the separate machine; (iii.) Less rigidity in the machine is required; (iv.) Efficient utilization of raw material; (v.) Rapid prototyping with high flexibility; (vi.) the method is suitable for small batch productions. Though, the process has some limitations which are (a.) It is a slower process; (b.) Multistage forming is required for straight walls. (c.) Significant spring-back in formed parts (Martins et al., 2009; Trzepieciński et al., 2018).

4. APPLICATIONS OF SPIF PROCESS

SPIF process is capable to form a variety of advanced materials as its efficiency is not limited by the chemical, electrical, and thermal properties of work material to be formed. SPIF have or can be applied in:

4.1 Automotive Field

In the automotive sector, Aston Martin, Jeep Honda and Toyota, and Amino Corporation developed various parts for example hood assembly, inner panel, heat or noise shield, logos, feature lines on the door, fender attaching boss pockets, etc., (Hagan & Jeswiet, 2003; Tekkaya et al., 2015) also Ford Motor Company show its interest in using dieless incremental forming for fabrication of sheet metal components in its car manufacturing sector under its project "Rapid Free Form Sheet Metal Forming Technology (RAFFT)" partnered with The Boeing Company, MIT and Penn State Erie (Ghulam Hussain et al., 2019).

4.2 Medical Field

SPIF is highly preferred in the manufacturing of medical implants, because of its advantages of rapid prototyping, high-customized products, and single product with reasonable cost, for example, ankle support of deep drawing quality steel, the medical prosthesis of titanium and polycaprolactone (Fiorentino, Marenda, et al., 2012), a maxillofacial implant made from titanium (Araújo et al., 2013), knee implants of titanium (Oleksik et al., 2009), cranial geometry of biocompatible polymer (Isabel Bagudanch et al., 2015) and so on (Boulila et al., 2018; Centeno et al., 2017; Fiorentino, Marzi, et al., 2012).

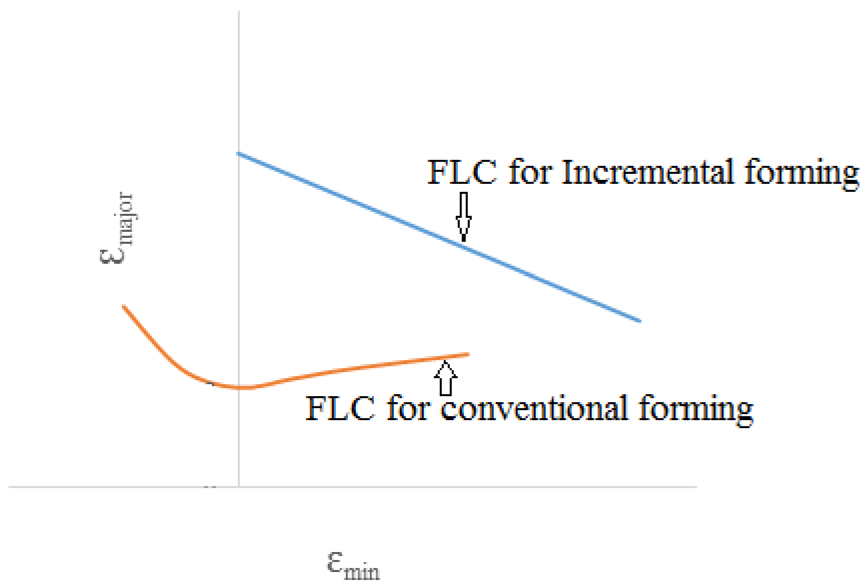
4.3 Other Fields

A different type of application of SPIF is found by researchers in the forming of absorber fins for solar collectors (Schreiber & Schaeffer, 2019) and especially sandwich panels/sheets, which are mainly used in major industries due to their favorable properties as lightweight structures, better dent resistance, and high vibration damping characteristics (Jackson et al., 2008; J. Liu et al., 2013). In aerospace industries, SPIF is mainly used for the fabrication of various parts of fighter planes, aircraft, space rockets, space shuttles, passenger planes, and cargo airplanes (Gupta et al., 2019).

FORMABILITY IN SPIF PROCESS

The formability of a material is defined as it is the ability of material that how easier it can be deformed without fracture. The forming limit curves (FLCs) are generally used as a suitable tool for estimating the formability of sheet metals. The FLC in ISF is dissimilar from that in the conventional forming process, it is a straight line with a negative slope (approx.-1) as shown in Figure. 5 in the region where the minor strains are positive in FLD, (Filice et al., 2002; Shim & Park, 2001) it confirms that formability in the SPIF process is much higher than the conventional forming process (Jeswiet & Young, 2005).

Figure 5. Forming limit diagram showing FLC for Incremental Sheet Forming process and Conventional forming



EFFECT OF PROCESS PARAMETERS ON FORMABILITY IN SPIF OF ALUMINUM ALLOYS

5. VERTICAL STEP SIZE

The vertical step size is the distance by which the tool move in a downward direction after completion of a loop at the same level or at the same plane, or it is the distance by which the tool moves forward in a downward direction after completing a loop on the spiral path. A summary of publications related to the effect of an increase in vertical step down on the formability of aluminum alloys is given in Table 1. The minimum and maximum vertical step values which were used by investigators are 0.0508 mm and 1 mm respectively. The majority of researchers reported vertical step size as an important process parameter and by increasing its value formability decreases, only Liu et al. (Z. Liu et al., 2013) reported an increase in the formability of AA7075-O with increment in vertical step down. Also, some studies showed minimum step size was optimal for formability improvement, and Khalatbari et al. (Khalatbari et al., 2015) advocated the maximum value of step size for optimum formability. A variety of outcomes were reported by investigators about the relationship between vertical step size and formability of aluminum alloys. Therefore, it can be observed that a clear picture of the effect of step size on formability is still a debatable topic and must be considered for future investigation because its interaction effect with other parameters on formability is a gap between understandings in SPIF.

Table 1. Publications considered in this work to study the effect of increase in vertical step down on formability of aluminum alloys

Publications	Aluminum alloy	Vertical Step Down (mm)	Effect on Formability of Aluminum Alloys				Remarks
			Increases	Decreases	Not Significant	Optimum	
(Y. H. Kim & Park, 2002)	1050	0.1, 0.3, 0.5		x			
(Bhattacharya et al., 2011)	5052	0.2, 0.5, 0.8					First increases then decreases.
(Z. Liu et al., 2013)	7075-O	0.2, 0.5	x				
(Khalatbari et al., 2015)	3003-H12	0.1, 0.36, 0.49, 0.62, 0.88				x	Optimum at 0.49 mm
(Filice et al., 2006)	1050-O	0.3, 0.1		x			
(Ham & Jeswiet, 2006)	3003-O	0.0508, 0.127, 0.254		x			
(Manco & Ambrogio, 2010)	6082-T6	0.3, 0.1			x		
(G. Hussain et al., 2010)	2024	0.08, 0.36, 0.78, 1.2, 1.48		x			
(Do et al., 2017)	5052	0.4, 0.7, 1				x	Optimum at 0.4 mm
(Mulay et al., 2017b)	5052-H32	0.2, 0.4, 0.6				x	Optimum at 0.2 mm
(Xiao et al., 2019)	7075-O	0.3, 0.5, 0.7		x			
(Kumar et al., 2019)	2024-O	0.2, 0.5, 0.8		x			

6. TOOL PARAMETERS

Tool parameters have their significant influence on formability during the SPIF process, tool parameters include tool diameter, tooltip or tool end shape, and tool material. The summary of the literature review related to increasing in tooltip diameter/ radius and tool shapes are given in Table 2 and Table 3. Tool parameters are dominant factors that affect the formability of materials in the SPIF process. The different values of tool diameters were used by investigators ranging from 2.5 mm to 30 mm. Research has proven that tools with smaller tip diameter were preferred for enhancing formability as compared to tools with bigger tip diameters, because of a highly focused region of deformation that sources high strain and results in better formability. According to Matsubara (Matsubara, 2001) with the help of a tool made from hardened cold die steel most of the materials like aluminum, mild steel, copper, stainless steel, gold, silver, platinum, etc. can easily be formed. The effect of tool material on response parameters in the SPIF process was never studied, investigated, or reported, so it can be a major area for investigation in future research activities.

Table 2. Publications considered in this work to study the effect of increase in tool diameter on formability of aluminum alloys

Publications	Aluminum alloy	Tool Tip Diameter/ Radius (mm)	Effect on Formability of Aluminum Alloys			Remarks
			Increase	Decrease	Optimum	
(Li et al., 2014)	7075	10, 20, 30	x			
(Maji & Kumar, 2020)	5083	6, 8, 10				Formability first increases then decreases
(Y. H. Kim & Park, 2002)	1050	5,10, 15			x	10 mm diameter shows best formability.
(D, 2013)	3003-O	5.08, 10.16 (Hemispherical); 5.08, 2.54 (Flat end radius)				Formability first increases then decreases
(Ham & Jeswiet, 2006)	3003	4.7625, 12.7		x		
(Ham & Jeswiet, 2007)	5754, 5182, 6451	4.7625, 6.35, 9.525		x		
(Kumar et al., 2019)	2024-O	7.52, 11.6, 15.66 (Hemispherical tool); 1.40, 2, 1.98, 2.85, 1.85, 3.76 (Flat end radius)	x			
. (Carrino, Giuliano, et al., 2006)	Aluminum	2.5, 5	x			
(Ziran et al., 2010)	3003-O	4,6,10 (Hemispherical diameter); 1,2,3 (Flat end radius)				Formability first increases then decreases.
(G. Hussain et al., 2013)	2024-O	3.5, 5.12, 6.752, 10				Formability decreases when initial sheet thickness (T_0) was 0.9mm and it increases when T_0 was 3mm. Optimum R/ T_0 = 2.
(Al-Ghamdi & Hussain, 2015)	2024-O, 2024T6, 1060-O, 1060H2, 5083-O, Steel DS, Cu H59	1, 1.5, 1.8, 2,2.2, 2.5, 3, 3.5				Formability first increases then decreases. Optimum R/ T_0 = 2.2.
Mulay et al. (Mulay et al., 2017a)	5052 H32	8, 10, 12		x		
Pandivelan et al. (Pandivelan et al., 2018)	5052	8, 10, 12		x		

Table 3. Publications considered to study the effect of tooltip shape on formability of aluminum alloys

Publications	Aluminum alloy	Tool Shape	Preferred tool
(Y. H. Kim & Park, 2002)	1050	Hemispherical and Ball tool	Ball tool
(D, 2013)	3003-O	Angle, Flat, Hemispherical, Parabolic	Parabolic
(Lu et al., 2014)	1100, 2024, 5052 and 6111	Hemispherical ended and oblique-roller ball ended	Oblique-roller ball ended
(Kumar et al., 2019)	2024-O	Flat end, Hemispherical end	Hemispherical end
(Ziran et al., 2010)	3003-O	Flat end, Hemispherical end	Flat end tools with lower radius
(Vanhove et al., 2019)	5754	Elliptical tool and hemispherical tipped tool	Elliptical tool.

7. FEED RATE AND SPINDLE SPEED

Feed rate (in mm/min) is the distance traveled by the tool per unit time around the sheet blank in a pre-defined path according to the CNC program. The machining time is directly influenced by feed rate, as the value of feed rate increases, the machining time decreases accordingly. Wide ranges of feed rates (40-12000 mm/min) and spindle speed (0-20000 rpm) were used by various researchers. The effect of the increase in feed rate and spindle speed on the formability of aluminum alloys are given in Table 4 and Table 5 respectively. Feed rate and spindle speed are dominant factors for the formability of SPIF parts because with the increase in forming speed and spindle speed the friction profile and heat generation get affected and the mechanical properties of sheet metal changes. Most of the investigators advocated increment in feed rates was unfavorable, whereas increment in spindle speed was favorable for material formability and other researchers investigated to get the optimum values of feed rate and spindle speed.

Table 4. Publications considered for this work to study the effect of increase in feed rate on formability of aluminum alloys

Publications	Material	Feed Rate (mm/min)	Effect on formability of Aluminum alloys			Remarks
			Increase	Decrease	Optimum	
(Pandivelan et al., 2014)	AA5052	300, 600, 900			x	900 mm/min is optimum value of feed rate.
(Bhattacharya et al., 2011)	AA5052	40,60,80				Feed rate was insignificant factor.
(Khalatbari et al., 2015)	AA3003-H12	800-5000				-------------------do----------------
(Ham & Jeswiet, 2006)	AA 3003	1270, 2540		x		
(G. Hussain et al., 2010)	AA2024-O and AA2024 pre-aged	373- 4,500		x		Formability of annealed AA2024 was not affected and decreases in pre-aged AA2024.
(Pandivelan et al., 2018)	AA5052	120, 200, 280			x	Minimum value of feed rate was optimum for maximum formability.
(Z. Liu & Li, 2019)	Al-Cu Composite	1000-4000		x		
(Shanmuganatan & Senthil Kumar, 2014)	AA3003	100, 1500, 2000			x	2000 mm/min was the optimum values.
(Pereira Bastos et al., 2016)	AA1050-H111, DP600, DP780 and DP1000	1500-12000				Increasing feed-rate reduces formability in steels but aluminum alloy was insensitive to feed rate deviations.
(Alinaghian et al., 2017)	AA6061	40-80			x	40 mm/min feed rate resulted in maximum formability.
(Azhiri et al., 2020)	AA5052	200-800		x		
(Z. Wang et al., 2020)	AA2024-T and AA5052-H32	600-2000			x	The optimum values of feed rate was1500-2000 mm/min.

Table 5. Publications considered for this work to study the effect of increase in Spindle Speed on formability of aluminum alloys

Publications	Material	Spindle Speed (rpm)	Effect on formability of Aluminum alloys			Remarks
			Increase	Decrease	Optimum	
(Pandivelan et al., 2014)	AA5052	300, 450, 600			x	450 rpm is the optimum value of spindle speed.
(Khalatbari et al., 2015)	AA3003-H12	0-3000			x	3000 rpm was optimum value.
(Ham & Jeswiet, 2006)	AA 3003	100, 600	x			
(Pandivelan et al., 2018)	AA5052	300, 450, 600			x	Minimum value of feed rate and maximum spindle speed were optimum values.
(Shanmuganatan & Senthil Kumar, 2014)	AA3003	2000, 3500 5000			x	5000 rpm is the optimum value of spindle speed.
(Alinaghian et al., 2017)	AA6061	800-1600			x	At 1600 rpm spindle speed maximum formability can be achieved.
(Z. Wang et al., 2020)	AA2024-T and AA5052-H32	0-6000			x	The optimum value spindle speed was 4500-6000 rpm.
(Obikawa et al., 2009)	Aluminum	0-20000	x			
. (Xu et al., 2013)	AA5052	0-7000	x			
(Buffa et al., 2013)	AA1050-O, AA1050-H24, AA6082-T6	100–10,000	x			Formability was not effected by heat treatment.
(Borrego et al., 2016)	AA7075	0, 1000			x	

7. PART GEOMETRY AND SHEET METAL PROPERTIES

Part geometry compiles the various dimensions of the component to be formed like maximum permissible forming angle without fracture, maximum depth of the parts to be formed without failure, various shapes which can be successfully formed, etc. Accordingly, the part geometry and sheet material properties are highly influencing parameters for formability in the SPIF process of aluminum alloys. Tables 6, 7, and 8 comprise summaries of the effect of part geometry, sheet thickness, and mechanical properties of sheet material on the formability of aluminum. Studies show that part geometry was a highly influencing factor for formability, and it depends upon the slope of the generatrix of a part being formed, wall angle, part depth, and so on. With an increase in sheet thickness as the volume of material available for forming increases so higher formability can be attained while SPIF of aluminum alloys. The sheets of different thickness range between (0.28 mm to 2.1 mm) were used for studies, also flat and embossed sheets were used by Do et al. (Do et al., 2016). The studies indicated that formability improved with the use of thicker sheets, some optimum values of sheet thickness were also reported by some researchers. The studies indicated that formability improved with the use of thicker sheets, some optimum values of sheet thickness were also reported by some researchers. Likewise, the formability of sheet material also depends upon mechanical properties of the material, as the highest strain hardening coefficient, the highest percentage elongation, tensile area reduction, etc.

Table 6. Summary of publications considered to review the effect of part geometry on formability of aluminum alloys

Publications	Material	Range of Parameter	Effect on formability of Aluminum alloys			Remarks
			Increase	Decrease	Optimum	
(Shim & Park, 2001)	AA1050	Circle, Triangle, Square, Square with round corners, Pentagon, Hexagon and Octagon			x	Maximum forming depth can be reached in circle.
(G. Hussain et al., 2007)	Al alloy (LY12M)	Exponential, Circular, Parabolic and Elliptical Generatrix			x	Exponential generatrix show highest value of formability.
(Ham & Jeswiet, 2007)	AA6451, AA5182, AA5754	Dome, Cone, Pyramid			x	Formability was highest in pyramid shape and lowest in dome shape.
(Ham & Jeswiet, 2006)	AA 3003	Base Diameter (mm): 101.6 and 158.75 Depth (mm): 3.56 and 127				Formability was insensitive to both of the parameters.
(Malwad & Nandedkar, 2014)	AA8011	Wall Angle: 55º,65º,75º		x		Greater formability in sheets when the wall angle value of part was below 75º

Table 7. Summary of publications considered for the effect of increase in sheet thickness on formability of aluminum alloys

Publications	Material	Category of Parameter	Range of Parameter	Effect on formability of Aluminum alloys			Remarks
				Increase	Decrease	Optimum	
(Jeswiet & Young, 2005)	AA3003, AA5754	Sheet thickness	1.02 and 1.21	x			
(Pandivelan et al., 2014)	AA5052	Sheet thickness	0.8 -1.2 mm	x			Maximum formability at 1.2 mm thickness of sheet was achieved.
(Bhattacharya et al., 2011)	AA5052	Sheet thickness	0.28, 0.49, 0.71mm	x			
(Ham & Jeswiet, 2007)	AA6451, AA5182, AA5754	Sheet thickness, Materials	AA6451: 0.8- 1.545 mm AA5182: 0.93- 1.5 mm AA5754: 0.93- 1.45 mm			x	Formability was highest at middle level of sheet thickness and lowest in 6451 sheets.
(Ham & Jeswiet, 2006)	AA 3003	Sheet thickness	0.81, 1.2, 2.1 mm	x			
(Mulay et al., 2017a)	AA5052H32	Sheet thickness	0.8 -1.2 mm			x	Formability was highest at middle level of sheet thickness.
(Do et al., 2016)	Al3004	Sheet Property	Flat and Embossed			x	Formability of embossed sheet is higher than flat sheet.
(Jeswiet et al., 2002)	AA 3003	Sheet thickness	0.8, 1.3 and 2.1 mm	x		x	
(Abd Ali et al., 2019)	Al/stainless steel (SUS) bimetal	Sheet Arrangement	Al/SUS SUS/Al	x			Formability boosted when SUS layer was on upper side.

Table 8. Summary of publications considered to study the effect of mechanical properties of sheet on formability of aluminum alloys

Publications	Material	Mechanical Properties	Effect on formability of Aluminum alloys			Remarks
			Increase	Decrease	Optimum	
(Fratini et al., 2004)	Cu, Brass, Steels, AA1050-O, AA6114-T4	Strength coefficient, UTS, Strain hardening coefficient, Normal anisotropy index, Percentage elongation	x			Formability was highest in material which have highest strain hardening coefficient and highest percentage elongation.
(Ghulam Hussain et al., 2010)	AA-2024O	Stiffness		x		
(Al-Ghamdi & Hussain, 2015)	AA 2024O, AA2024T6, AA 1060O, AA1060H2, AA 5083O, Steel DS, Cu H59	Yield Stress, UTS, Percent elongation, Strength co-efficient, Strain-hardening exponent and Tensile area reduction	x			Formability of material is directly proportional to tensile area reduction.
(Abd Ali et al., 2019)	Al/stainless steel (SUS) bimetal	Young modulus, Yield strength, Tensile strength, Hardening coefficient, Strain hardening exponent, Tensile reduction of area	x			Formability boosted when SUS layer was on upper side. The formability of the bilayer sheets is governed by the tensile area reduction of the upper layer.
(G. Hussain et al., 2009)	Aluminum alloys, Steel, Brass, Cu, Titanium	Yield Stress, UTS, Percent elongation, Strength co-efficient, Strain-hardening exponent, Anisotropy and Tensile reduction of area			x	Tensile reduction of area seemed as the only main property influencing the formability in SPIF.
(Ghulam Hussain et al., 2012)	AA-2024O, AA2024T Cu -H28, AA1060H24 AA-1060O	Reduction in area at tensile fracture, Hardening exponent and Tensile elongation	x			Formability was highly sensitive to reduction in area at tensile fracture.

9. TOOL PATH

Generally, two types of tool paths are used in the SPIF process namely profile tool path i.e. increment in a downward direction is constant between contours and helical tool path i.e. having continuous movement of the tool in descending direction covering the whole shape of the part to be formed. In the SPIF process, the tool path plays a vital role in the formability of aluminum alloys. The summary of publications aimed at the effect of tool path on formability is given in Table 9. The outcomes of numerous experimental work show various tool path strategies were used by researchers as single-pass, double-pass, multi-pass, inward, outward, 2.5-D, spiral, profile, constant z level, feature-based, etc.

Table 9. Publications considered to study the effect of toolpath on formability of aluminum alloys

Publications	Material	Tool path Strategy	Part Geometry	Remarks
(T. J. Kim & Yang, 2000)	Aluminum	2.5 D and Spiral Single pass and double pass	Ellipsoidal Cup and Clover Cup	Double-pass forming strategy can be used for formability improvement.
(Skjoedt et al., 2007)	Steel or Aluminum	Profile and Helical Single pass	Pyramid, Cone and Muffler	Spiral tool path was advantageous over profile toolpath in formability improvement without scar marks on formed geometries.
(J. R. Duflou, Verbert, et al., 2008)	Al3003-O, AA3103, Ti Grade 2	Profile Multi-step	Cylindrical, Non-rotative and Complex	Application of multistep toolpath increases formability of material.
(Do et al., 2016)	AA3004	Profile Inward and Outward	Pyramid	Formability is better in 3-D sheets (embossed) of AA3004 is better when outward path is used for forming.
(Kitazawa et al., 1996)	Aluminum	Profile (Inward and outward)	Elliptical, Circular and conical	Higher formability was attained with inward toolpath strategy.
(Yamashita et al., 2008)	Assumed	Profile and Helical Shift the starting point of loop	Quadrangular pyramid	For improving formability the tool must travels in helical manner and indented at suggested corner of the product.
(Rauch et al., 2009)	AA 5086	Intelligent CAM programmed tool path	Pyramid	Intelligent CAM programmed tool path improved formability.
(Z. Liu et al., 2014)	AA7075-O	outward, CW and CCW Single pass and Multi-pass	Ellipsoidal cup and Free-form shape	Application of multistep toolpath increases formability of material.
(Lingam et al., 2016)	AA8011, AA5052	Inward Multi-pass	Stepped Profile	Multistage SPIF with inward toolpath shows improvement in formability of Aluminum alloys.
. (Mohanty et al., 2017)	Simulation	Profile (Circular and Square) and Helical (Asymmetric)	Circular, Square and Asymmetric	By using MATLAB simulation and continuous robotic manipulator, the toolpath design for three types of sheet-metal component geometries has been efficiently produced for ISF.
(Zhu & Li, 2018)	AA1060	Multi-directional and single directional slant toolpaths, With supportive dies.	Complex	The parts with forming angle more than 90º can be easily formed in single stage via the 5-axis CNC ISF toolpath.
(J. Wang et al., 2019)	AA 1060	Equal diameter spiral tool path	Conical frustum	Formability increases with application of equal diameter tool path.
(Nirala & Agrawal, 2020)	AA6061-T6	Fractal geometry based tool path (FGBIT). Spiral tool path and constant Z	Square Cup	Improvement in formability of parts was noticed by using novel FGBIT.

10. FORMING TEMPERATURE

Generally, at high temperatures the materials become soft and their ductility, malleability increases and the hardness decreases. The changes in described mechanical properties significantly affect the formability of the materials because due to the high temperature the forming force required for forming the component decreases, and hard to form materials are effortlessly formed. The effect of forming temperature on the formability of aluminum alloys was summarized in Table 10. The forming temperature and heat treatments significantly affect the microstructure, lubrication conditions, friction conditions, and mechanical properties of materials. Various types of heating arrangements were used by different researchers, for example, laser heating, friction heating (using higher spindle speed), electric heating, dynamic local heating, etc. for increasing forming temperature while SPIF of aluminum alloys. Some investigators also used annealing time and temperature as input parameters, the result shows higher formability can be achieved in aluminum alloys when the heating temperature was above 200º C.

Table 10. Summary of publications considered to study the effect of increase in forming temperature on formability of aluminum alloys

Publications	Material	Forming Strategy	Remarks
(J. R. Duflou, Callebaut, et al., 2008)	AA5182 and 65Cr2	Dynamic local heating	Formability was improved.
(Göttmann et al., 2011)	TiAl6V4	Laser-assisted Heating	Formability was improved.
(Golovashchenko & Krause, 2005)	AA 6111-T4	Heat treatment (Time 15 s to 120 s and temperature range 250-300 ºC)	AA6111 samples at 250 °C for 30 s delivered acceptable recovery to increase formability, and can be more economical alternative then hot forming.
. (G. Hussain et al., 2010)	AA 2024	Annealing and Pre-aging	Annealed AA2024 sheets shows higher (approx. 30%) formability.
. (Xiao et al., 2019)	AA7075-T6	Heating (Temperature range 20-200 ºC)	The formability of AA7075 was not significantly affected by forming temperature range 20º C to 80º C but after that the formability rapidly increase with increase in forming temperature up to 200 ºC.
(Shanmuganatan & Senthil Kumar, 2014)	AA3003-O	Frictional heating	Higher spindle speed increases the formability.
(Buffa et al., 2013)	AA1050O, AA1050H24 AA6082-T6	Frictional heating	Maximum improvement in formability was noticed in AA6082T6 sheets.
(J. R. Duflou et al., 2007)	TiAl6V4, 65Cr2	Laser Heating	Formability was improved.

Table 10 continued on next page

Table 10 continued

Publications	Material	Forming Strategy	Remarks
(Ambrogio et al., 2012)	AA2024-T3, AZ31B-O and Ti6Al4V	Electric-hot forming	Enhancement in formability was noticed in three lightweight alloys used in aviation industries.
(Otsu et al., 2014)	A2017-T3	Frictional heating	Higher spindle speed increases the formability.
(Lehtinen et al., 2015)	AA1050, Cu, DC04	Local Heating	Maximum wall-angle improvement in Cu sheets and no improvement in wall angle for DC04 sheets.
(Mohammadi et al., 2016)	AA2024-T3	Annealing, Tempering and Laser-assisted Heating	Annealing permits to increase the formability angle by 41% with respect to the tempered sheets. Laser-assisted forming improves formability.
(Gatea et al., 2017)	6092Al/SiCp composite	T6 and O-condition annealing	Formability was improved in AMC sheets after O-heat treatment conditions.
(Ghaferi et al., 2019)	AA6061	Heat treatment cycles	Heat treatment cycle (a. annealing; b. SPIF; c. solid solution heating; d. aging) can increase the formability of AA6061 pyramid.
(Vahdani et al., 2019)	Ti-6Al-4V, AA6061 and DC01	Electrically-hot SPIF	Electrically-hot SPIF has improved the formability of all the three materials.

11. LUBRICATION CONDITIONS

Lubrication helps in decreasing friction between the tool and sheet blank, reducing tool wear rates and improving tool life, improving surface quality by declining the quantity of work hardening and surface damage due to friction, and improving formability by removing hindrances in tool path and smooth-rolling or slipping of the tool over the blank surface and so on. The lubrication conditions in SPIF are an important parameter to study with respect to the outcome of experimental studies. Numerous researchers have investigated, the effect of lubrication conditions on the formability of aluminum alloys, the outcomes of scientific studies are summarized in Table 11. The effects of lubrication conditions were studied by investigators using a variety of oils, grease, and solid lubricants and dry conditions and results show advantages of application of lubricant as compared to dry conditions in terms of increased formability, reduced friction forces, and decrease in frictional heat generation.

Table 11. Publications considered in this work to study the effect of lubrication conditions on formability of aluminum alloys

Publications	Material	Lubrication Conditions	Remarks
(Y. H. Kim & Park, 2002)	AA1050	With and without lubrication.	Little amount of friction is favorable for formability improvement.
(Lu et al., 2014)	AA1100, AA2024, AA5052 and AA6111	Reduce friction by using of Oblique roller ball tool	Increase in friction the formability of aluminum alloys decreases.
(Obikawa et al., 2009)	Aluminum foils	Hydrodynamic lubrication(Water)	Increase in formability of aluminum foils was observed.
(Xu et al., 2013)	AA5052-H32	Laser Surface Textured (LST) tool (Increased friction)	The decrease in formability of AA5052 sheets due to LST tool and increase in friction.
(Vahdani et al., 2019)	Ti6Al4V, AA6061 and DC01	Graphite, MoS2, Graphite-based anti-seize, Copper-based anti-seize	Graphite was the optimal lubricant for attaining maximum formability.
(Carrino, Di Meo, et al., 2006)	AA1050-O	No lubrication, Standard lubrication and Continuous lubrication	Decrease in formability could be witnessed only for great variation of friction forces (lubricated against dry conditions).
(Gulati et al., 2016)	AA6063	Dry, Coolant and Grease	Grease was the optimal lubricant for attaining maximum formability.
(Amini et al., 2017)	AA1050-O	With and without lubrication and ultra-sonic-vibration-assisted tool	Formability enhanced vastly (48%) when ultra-sonic-vibration-assisted SPIF was done in presence of a lubricant.
(Baruah et al., 2017)	AA5052	Dry, Grease and Oil	Grease was the optimal lubricant for attaining maximum formability
(Oraon & Sharma, 2020)	AA3003	Dry and Graphite	An improvement in formability of AA3003 was observed by using lubricant.
(Chen et al., 2019)	AA6061 and AISI304	No lubrication, Machine oil and MoS_2	MoS_2 was the optimal lubricant for attaining maximum formability in AA6061
(Chang & Chen, 2020)	AA2024 and AA7075	Lubrication in three sheet SPIF	No effect of lubrication on formability of AA2024 and AA7075 sheets was observed.

CONCLUSIONS

Major conclusions might be drawn from current work regarding several aspects of SPIF.

- Some researchers claimed that the step size does not affect formability, some claimed that an increase in step size has a positive effect on formability while others have confidence that bigger step size has a destructive effect on formability.
- The effect of tool parameters on formability is not clear due to some investigators reported enhancement in formability by using larger diameter tools while others believe that higher formability can be attained by using tools with smaller diameters, because of smaller contact area, a lesser amount of friction, and minor deformation region.
- Tools with different shapes are used during the SPIF process by various researchers some believe ball-ended tools are better than hemispherical tools for formability improvement, some believed hemispherical tools are better than flat-ended tools, some advocated flat-ended tools are better than hemispherical tools, also some researcher used tools with different shapes (elliptical tool, oblique roller ball) than conventional tool shapes (flat-ended, hemispherical and ball ended) and

reported success in attaining higher formability, but optimum shape of tool for attaining higher formability is not clear till date.

- The strength of the tool to tolerate various forces of the SPIF process is the limiting factor for a minimum value of tool diameter that can be used for forming. The value of the ratio between tool radius and initial sheet thickness (R/Tb) lies between 2 and 5, the results are still debatable.
- In the majority of researches low feed rate and high spindle speed are used to enhance formability in SPIF of sheets but according to some investigator's feed rate and spindle speed have no significant on formability of sheets.
- Higher formability was reported by some researchers in parts having continuous or faster-changing slope (exponential) than parts that have a constant slope (straight line).
- An increase in formability was reported by researchers with an increase in sheet blank thickness and by using embossed sheets for forming as compared to flat sheets.
- Formability was only increased due to an increase in the tensile reduction area of material and no effect on the formability of material due to other mechanical properties like strain-hardening coefficient, work-hardening exponent and percentage elongation.
- The selection of tool path and forming strategy are the most influencing factors for improving formability. Inward forming strategy, multi-pass forming strategy over single-pass forming strategy, multistage forming strategy over single-stage forming strategy are inspiring strategies to improve formability in SPIF of parts.
- To accomplish forming at an elevated temperature many strategies are used to increase forming temperature which includes laser-assisted SPIF, hot SPIF, electric-hot SPIF, frictional heating, dynamic heating, resistance heating, and heat treatments. The research outcomes show annealing is considerably better than pre-aging, tempering, and hot SPIF process. The improvement in the formability of aluminum alloys was observed while forming at elevated temperatures.
- The little amount of friction was helpful in improving the formability in the SPIF of sheet blanks. The type of lubricant has a slight influence on formability but the presence of lubricant while forming improves formability dramatically as compared to dry or no lubrication condition.

ISSUES TO BE CONSIDERED IN FUTURE RESEARCH ACTIVITIES

In the grace of extensive literature review on SPIF process, there are numerous inquiries still to be replied to enhance applicability and acceptability for commercialization of the SPIF process in industries. Therefore, the following areas have to be researched to enhance the process capability:

- The advance technologies could be developed for SPIF technique to reduce forming time to increase the acceptability of the process in forming industries for mass production.
- The effect of forming temperature on various responses was summarized in this article, some process variants are used for SPIF at elevated temperatures. Therefore, it can be noticed that elevated-temperature SPIF is capable to improve the performance of the process and it is still an enduring research area, which desires to be extensively considered for research in the future.
- The research in the field of some process variants and applications like micro-SPIF, use of dummy sheets of different thicknesses, material and positioning while forming and many more are in their childhood stage and need an enormous amount of research to reach the maturity stage of progress.
- Lack of standardization in tool path according to part geometry, the direction of tool, multistage forming needs more investigations to be done by aiming at acquiring industrial and commercialization opportunities.
- . The parameters like tool size and shape are considered by a sufficient number of investigators but influences of tool material, tool life or tool wear, tool surface roughness, and new tooltip shape on forming output response characteristics were neglected by the researchers which prove the need of exploration in the mentioned area related to the tool.

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