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A Comprehensive Technical Research Review On Formability Evaluation And Enhancement Techniques For Single Point Incremental Forming (Spif) Process

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Single Point Incremental Forming (SPIF) has gained significant attention over the past two decades as a flexible and cost-effective metal forming technique, capable of producing complex, asymmetric parts without the need for dedicated dies. Unlike conventional forming methods such as stretching and drawing, SPIF achieves higher strain values on the forming limit curve (FLC), offering superior formability. However, it also presents challenges, notably in achieving high dimensional accuracy and surface finish.

This paper presents a comprehensive review of existing research focused on formability assessment and improvement strategies in SPIF. Through network analysis of keyword co-occurrence and relatedness, the study highlights the current research landscape, identifying major trends and key influencing factors. The impact of process parameters—such as forming forces, tool path strategies, tool geometry, feed rate, spindle speed, and step size—on the formability of various materials is extensively discussed. The review encompasses studies on a wide range of materials including aluminum and its alloys, steels, titanium, and polymers. Various formability enhancement techniques are also evaluated. Notably, the analysis reveals a research gap in the application of SPIF to composite materials. Despite their increasing industrial relevance, limited studies address the unique forming mechanics and behavior of composites in the SPIF process. Finally, the paper outlines future research directions aimed at improving SPIF's industrial viability, particularly through deeper exploration of composite material formability and process optimization strategies.

Keywords: Single point incremental forming (SPIF), Sheet Metal Formability, forming limit diagram, Lubrication assisted SPIF, Heating assisted SPIF.

1. Introduction:

Sheet metal forming is one of the most important manufacturing processes being widely used to manufacture low weight-to-surface area parts. In traditional forming methods, the entire material blank is deformed simultaneously in various directions by confining between the die and punch clearance. Simultaneous deformation in multiple directions induces various types of stresses and spring back effects, resulting in unpredictable formability of the part. To overcome the inherent issue of uncertain and unpredictable nature of material formability of conventional sheet metal forming, the concept of the incremental forming process has evolved, wherein, the sheet material is deformed locally in incremental steps rather than the deformation of an entire blank at a time. Incremental forming is a process of material deformation, having the capacity to produce a part with an asymmetrical axis using the same principle of localised forming of a conventional forming method [1]. Incremental forming is the economical process for prototyping and specialised part production with low volume. The process can be performed on CNC milling centres and/or with robotics assistance [2].

1.1 Formability and its Significance in Metal Forming Processes

Formability is referred to as the ability of a sheet metal to be deformed into desired size and shape without developing wrinkles, cracks or necking. It represents the state and level of strains produced in the material during plastic deformation of sheet metal. The formability of sheet metal can be evaluated by fittability, shape fixability, and fracture resistance properties of the sheet metal. Fittability refers to the degree of deviation in the formed part of the designed shape. The accuracy of shape and size of the part after forming shows its fixability. The fracture resistance is the capability of the sheet metal to deform without necking [3]. The level of strain and state of strain before the onset of necking or wrinkling can be predicted more accurately by formability. Furthermore, for different materials, the formability depends on the stress conditions due to diverse metal forming processes.

1.2 Formability Issues with Conventional Metal Forming Processes

The formability of the sheet material depends on the mechanical properties and metallurgical conditions of the material. Selection of the suitable process along with specialised tool design plays a significant role to overcome the formability limits of sheet material. Presswork hardening, non-uniform elongation, and complex stress and strain distribution limits the formability of sheet metal. [4]. Some of the most common issues during the conventional forming process include spring back, non-uniform elongation, wrinkling, micro-cracks, surface roughness etc. Non-uniform sheet material deformation results in uneven strain distribution, which produces limited formability in a particular direction. The process parameters also introduce limitations on the formability of the material. For example, in the case of composite materials, the bonding strength of the fiber metal laminates and arrangement of layers results in variation in formability [5]. Fiber metal laminates formed by conventional stretching and forming experience surface cracks, de-bonding of lamination, fiber failure, wrinkling, and stress cracking due to limited formability. In stamp forming, shape error caused by higher blank holding force with low feed rate and tool temperature also affects the formation of wrinkles and shrinkage [6]. Lightweight alloys like alloys of magnesium and titanium are very difficult to form at room temperature with conventional methods due to limited formability [7].

1.3 Possible Solutions to Formability Issues

Advanced metal forming processes like hydroforming, incremental forming, and stretch forming can increase formability and add flexibility to the material [8], [9]. To improve the formability during intricate part forming, hot stamping is used in case of press-hardening steels and cold stamping is used for the high-strength steels [4]. It has been reported that during stamp forming, fiber metal laminates generate wrinkles with an increase in depth. In order to produce wrinkle-free components using the stamp forming process, the blank should be preheated before forming. [10]. Furthermore, SPIF has also emerged as a promising solution to formability issues. The assistance of an aluminium sheet as a diaphragm and a vacuum bag facility in SPIF can help achieve wrinkle-free components [11]. SPIF can form a material which is hard to form at room temperature, with uniform thickness and achieving higher strain compared to the traditional sheet metal forming process [12]. Other advanced metal forming processes like hot stamping, hydroforming, super plastic forming, Flexible rolling and high pressure sheet metal forming (HPSMF) possess the capabilities to reduce material consumption, processing steps, tooling cost reduction, and reduce the environmental impact [8], [13].

2. Incremental sheet metal forming (ISMF):

Incremental forming technology is comparatively a newer and advanced forming process amongst the wide range of forming processes. Incremental type of sheet metal forming process, also known as die-less sheet metal forming, deforms the sheet material in small localised incremental steps without using a die support. It has proved to be an important process for specialised and small-batch component production. Unlike the conventional forming process, ISF does not require a specialised die, which leads to saving the time and cost of manufacturing the dedicated die for the process. In recent years, the research and advancements in the ISF process have drawn the attention of automobile, aerospace, and biomedical implant manufacturers to manufacture specialised and customised parts [14], [15], [16]. Although the first incremental forming was demonstrated in the year 1967 by Leszak [17], due to its inherent limitations like slow production rate, limited formability limits, instant spring back, lack of geometric accuracy and poor surface finish has demanded technological solutions to these issues. To find solutions, the process has witnessed considerable technological research efforts in the last two decades in terms of the development of various variants of this process.
In order to have a look at the bigger picture, 537 relevant research papers ranging from 1980 to 2021 were selected and bibliometric analysis was carried out. For the co-occurrence of key words, 3 or more co-occurrences were considered. The network analysis map is shown below:

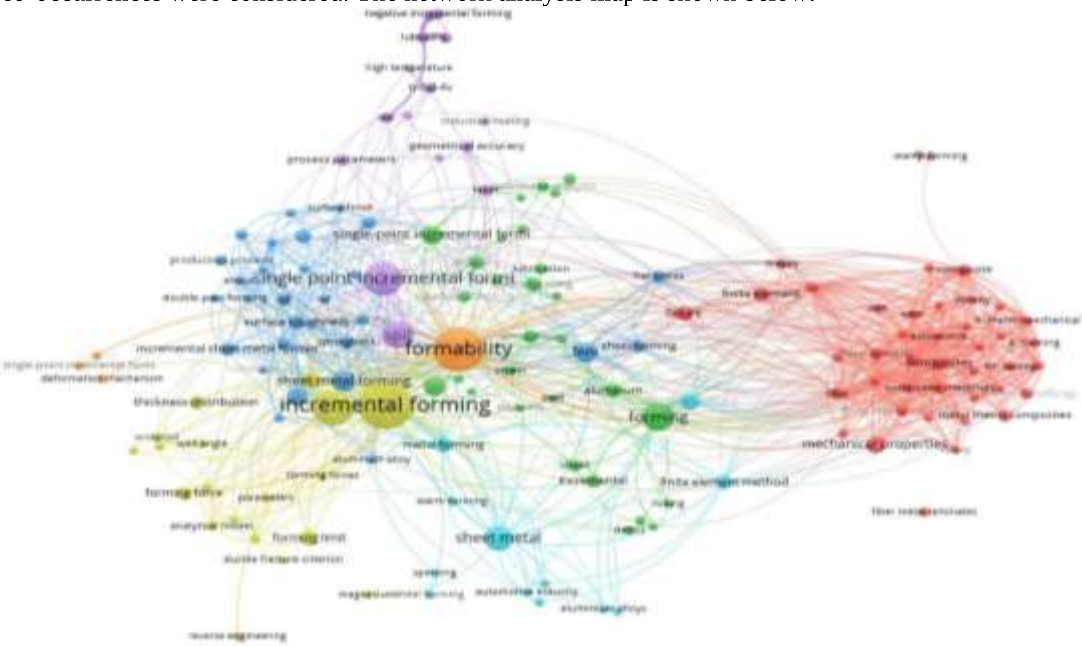

Figure 1 Network analysis Map of co-occurrence of keywords

The bigger the circle of label, the more the occurrence of that key word. Also, the distance between the two key words indicates the relatedness of these keywords in terms of co-occurrence. It can be seen that incremental forming, sheet metal forming, single point incremental forming and formability are closely linked and co-occurred more frequently. This also helps us understand various aspects researchers consider while working on single point incremental forming. i.e. stamp forming and fiber metal laminates occur quite far from incremental forming and hence very less relatedness with incremental forming.

Bibliometric analysis of various terms used in title and abstract of these papers revealed point incremental forming and metals as shown below indicating not only the co-occurrence but also the major research focus:

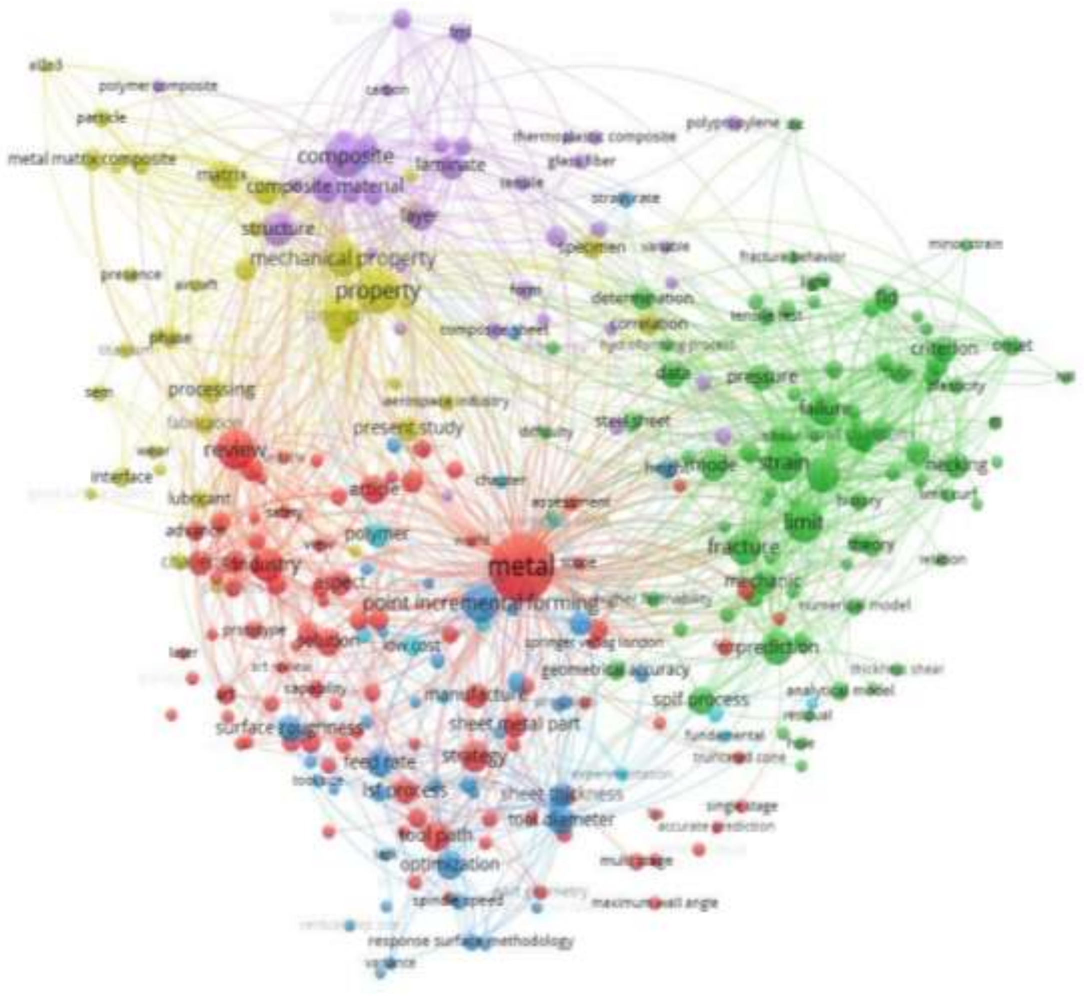

Figure 2 Network analysis Map of co-occurrence of common terms

It can be clearly seen that the single point incremental forming (SPIF) is one of the important recent trends which is presented as a big circle in the blue cluster, and it is very closely related with the metals which is presented by another big circle in the red cluster. Other notable research trends related with SPIF in blue cluster are sheet thickness, tool diameter, feed rate etc. There are 5 other clusters which show the relatedness of different research topics with each other. For example, green cluster shows relatedness of research on topics including strain, limit, fracture pressure etc. while purple cluster has research topics focusing mainly on composites forming.

Various new methods of incremental forming are developed like Single-Point Incremental Forming (SPIF), Two-Point Incremental Forming (TPIF) with partial die and full die, and Counter Tool Incremental Forming (CTIF) [18]. Amongst all variants, SPIF is the most versatile due to its applicability for wider ranges of formability limits of different materials without dedicated specialised die.

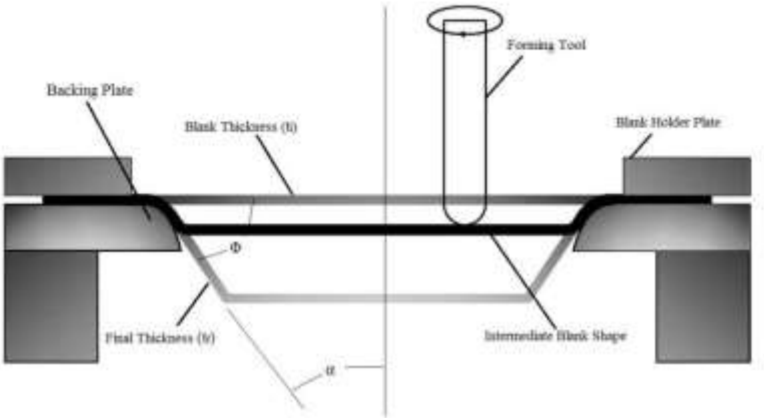

Figure 3 Diagrammatic representation of SPIF

2.1 Principle of Single Point Incremental Forming (SPIF) Process:

A diagrammatic representation of forming through a single point (SPIF) is shown in Figure 1. SPIF setup comprises basic components like a backing plate, blank holder, rotating forming tool with single point contact, and the sheet metal blank. Figure 1 shows the semi cone angle α, and $\Phi = \pi/2 - \alpha$ is the drawing angle between the surface of the inclined wall and the initial flat sheet. In the SPIF process, sheet metal is fixed at the edges by a clamp holder and unsupported from the bottom side. The forming can be executed supported or unsupported by the backing plate. To form the sheet blank in the desired shape, the tool path needs to be generated with the assistance of part programming through a computer-aided manufacturing software package.

3. Formability Evaluation in Single Point Incremental Forming Process

Formability of sheet metal is defined as an ability to form the material without exhibiting necking during sheet metal forming. In SPIF, formability can be determined through the forming of the maximum forming wall angle (φ) and semi cone angle (α) from the flat sheet metal blank. Forming of maximum wall angle without failure from the sheet is considered to be the indication of the formability for the particular material. Different shapes like a hemispherical, hyperbolic-sided cone, pyramid, straight-sided cone, and shape with five lobes are formed to evaluate formability [19]. Park et.al. [20] experimented with difficult-to-form parts under various forming conditions. It was concluded from the experiment on the aluminium sheet that the positive forming method proved to be better than the conventional forming as the plane strain mode of deformation plays a vital role to influence the result. In the case of negative incremental forming, sharp corners and edge formation is difficult due to the biaxial mode of deformation. It has been reviewed from the research that the role of forming angle, strain condition, and sheet thickness is important for the formability evaluation [12].

3.1 Forming Limit Diagram

Keeler introduced the concept of forming limit diagrams in the year 1961, which was later modified and extended in the year 1968 by Goodwin [21]. The forming limit diagram was derived from the experiments for estimating the necking and local fracture also called Keeler–Goodwin diagram. It has been accepted by almost all sheet metal forming simulation software. Conventionally the formability limit in sheet metal forming was predicted by forming limit diagram (FLD). The principal in-plane strains at failure construct the strain-based failure criteria. The values of major and minor strains in the surrounding area of the crack were plotted for the construction of FLD. The range of safe forming and failure was defined by forming a limit curve. Panich et.al. [22] have found that, as the process changes, the strain path or forming history may change. Strain paths of uniaxial and biaxial stretching conditions result in Forming Limit Curve (FLC) from the sheet formability tests. In-plane strains (ε_1, ε_2) can be determined by circle grid analysis and a computer-aided measuring system. The values of strain when plotted on strain space are known as strain-based forming limit diagram [23].

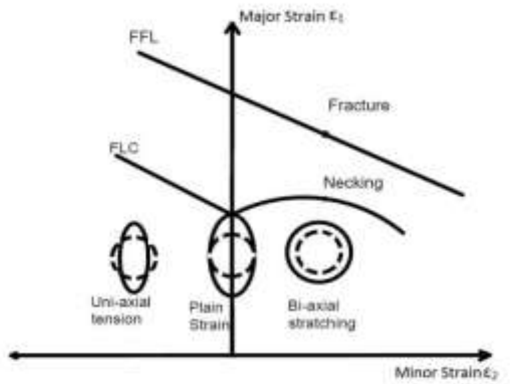

Figure 4 Diagrammatic representation of Forming Limit Diagram

Figure 2 shows a schematic representation of forming limit in principal strain space known as FLC and Fracture Forming Limit line (FFL) with typical strain path. Isik et.al. [23] found that the value of major plane strain ε_1 increases towards the fracture forming limit as the drawing angle increases during the forming of a truncated cone-shaped part under a plane strain state. The plane strain (laterally) and biaxial stretching (at the intersections) have appeared in different strain loading conditions during forming the truncated pyramidal component.

3.2 Effect of Process Parameters on Formability

The best possible accuracy and shape can be generated by selecting optimised process parameters. The study of the process parameters can help to effectively and efficiently form the desired shape with greater accuracy and surface finish. Spindle speed, feed rate, incremental depth, tool shape and size, forming force, and tool-path strategies are the process parameters, which may affect the SPIF process, are considered for the review in this paper. Important research works related to the effects of parameters on SPIF performance are discussed below.

3.2.1 Forming Forces

Force requirement during machining and forming depends on the material properties and process conditions. It is also considered while choosing the right setup design for the process. Koh et.al. [24] compared the forming force requirement in machining and forming. It was reported that the magnitude of forces in the Y and Z direction is the same but the phase is different. Forming force requirements in both X and Y directions are ten times higher, however, it is forty times larger in the Z direction than machining. Forming forces provide important insight into the deformation mechanism which helps monitor the process along with the failure prediction [25]. Arfa et.al. [26] have found that with an increase in sheet thickness, the required forming forces have increased significantly for aluminium alloy sheet Al 3003-O. Ali et.al. [27] have found that as the incremental depth increases, the requirement of forming forces also increases during forming of PVC material. The friction between tool and sheet increases temperature and hence the forming force is reduced. The tendency of wrinkling reported with the higher incremental depth due to large in-plane forces.

Jeswiet et.al. [28] have found that the highest forming forces were observed at the area of maximum draw angle φ_{max}. It is evident from the literature that a higher forming force is required with increasing sheet thickness and the highest forming forces were reported at the maximum draw angle φ_{max} [28]. Vanhove et.al. [29] tested aluminium alloy AA5182-O with high-Speed SPIF (HS-SPIF) and measured the impact of friction forming forces in material formability limit. Forming forces F_t and F_r slightly decreased with constant lubrication and cooling. The highest forming angle of 65° with the 600 m/min feed rate can be achieved at room temperature, which indicates a favourable effect on ductile behaviour. Al-Obaidi et.al. [30] have reported that the formability of high-strength alloys was very poor during forming at room temperature. Increment in forming limit was achieved by assistance with induction heating which also helped reduce the forming forces. Forming forces during GR (Groove) test for both Cu/Al and Al/Cu arrangement in all experiments, that the higher forming force is required in Al/Cu layer arrangement. However, Al/Cu layer placement results in uniform distribution of thickness in TP tests with a multi-pass forming strategy. However, forming forces are reduced with the assistance of heating the forming material. In the case of laminated composite, the forming forces depend upon the material having contact with the forming side. Forming of polycarbonate sheet revealed that with a rotating forming tool, horizontal forming forces can be reduced, and hence, the forming force requirement will be less.

3.2.2 Tool-path Strategies

The tool path is an important parameter to affect the thickness variation and formability of the material. Final part geometry and surface roughness are also influenced by the selection of tool path strategies. Malyer [31] observed that the downward movement of the tool on the same line leads to the thinning phenomenon while tool movements from one pass to another reduces thinning for S235JR steel alloy. Liu et.al. [32] reviewed that profile tool-path induced greater surface inaccuracy and thinning path with respect to the coiled tool path while forming aluminium alloy Al1050. The tool movement was observed to influence the surface condition of the component and tool path strategy. It was concluded in [33] that embossed sheet forming resulted in the superior forming angle and part accuracy with the inward tool path, as compared to the non-embossed Aluminium 3004-P sheet. While forming polycarbonate blank with the incremental forming process, M. Durante et.al [34] focused on the effects of tool-path by applying two different strategies namely UTP (unidirectional tool-path, counter-clockwise order) and ATP (alternate spiral tool-paths, rotating the spirals in anti-clockwise and clockwise order). Figure 3 shows a schematic diagram of both strategies.

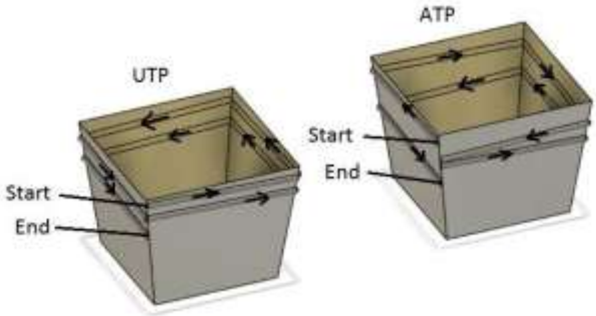

Figure 5 Schematic representation of UTP and ATP

The ATP strategy was proved best with a fixed tool end to enhance formability and reduction in defect while forming a polycarbonate sheet. ATP with a rotating tool enabled the reduction of forming forces in horizontal direction considerably [34]. Various tool path strategies had been reported by different researchers, like unidirectional, bidirectional, profile tool path, and helical tool path. In the case of aluminium and steel alloys, helical tool path improves surface roughness and thinning, however with an embossed sheet of aluminium, better formability can be achieved by inward tool path. It has been reported that during the forming of polycarbonate material, an alternate spiral tool path proved best for increased formability [34].

3.2.3 Tool Shape & Size

Tool shape and size are determined based on the requirement of support and interaction of the tool and blank along with forming force required to form the material. The zone of deformation depends on the tool radius which affects the strain values and hence the formability [12]. Al-Ghamdi et.al. [35] reported that the relative value of tool radius and blank thickness derived from the experiments on aluminium, steel, and copper affected the SPIF process. With the critical value of the tool radius, stable deformation can be achieved which leads to maximising the formability. Critical radius is also termed as threshold tool radius and it is independent of the material properties. It was concluded that with the tensile area reduction, the formability of the SPIF was improved. Maqbool et.al. [36] have investigated the influence of tool radius on geometrical accuracy as well as the mode of deformation which ultimately affects the formability. The deformation mechanism comprises membrane stretching, bending and through-thickness deformation irrespective of the formed part. Forming of DC04 steel and aluminium alloy EN-AW-5005 with SPIF shows better geometrical accuracy with lower tool radius and step-depths because of the smaller participation of the bending deformation condition to the overall plastic work. Due to the contribution of bending, the geometrical accuracy deteriorates with increased wall angle. Maqbool et.al. [37] reported that it was significant that the smallest tool diameter and in transverse motion lead to increased residual stresses upon trimming during the forming of aluminium alloy EN-AW-5005. The consequently larger deviation was reported with the smallest diameter of a tool in the trimming condition. Ziran et.al. [38] have found that greater profile accuracy can be achieved through a tool with the flat end compared to the tool with the hemispherical end while forming an AA3003O sheet. Formability can be increased with a properly chosen lower-end radius. Comparatively lower forming forces are needed when forming with a flat end tool. Kim et.al. [39] have concluded from the forming of aluminium 1050 sheet that compared to the hemispherical head tool, the ball tool was more effective to improve formability, furthermore, a small amount of friction will help to improve formability. Researchers have also examined the influence of tool shape and size on the formed part surface quality. Taherkhani et.al. [40] have concluded from the forming of Al 3105 that the smallest diameter of the tool can minimise dimensional error and with the largest tool diameter the achieved surface roughness was lower. Jagtap et.al. [32] have found that the surface quality is affected the most by the influence of tool diameter during forming aluminium alloy- Al1050. Better surface finish can be achieved with a larger tool diameter. It has been reported from the reviewed work that the tool shape and size influence formability, forming forces, and part accuracy to a great extent. It was reported that with a flat end tool, forming forces required to form the material were lowered and greater accuracy was achieved. However, the hemispherical tool and ball-ended tool improves the formability. The formability of the SPIF process has been also influenced by the relative value of tool radius and blank thickness.

3.2.4 Spindle Speed

Researchers have used different spindle speeds depending on a type of the materials, decided by the tool and sheet interaction zone and the heat produced during forming. Spindle speed largely influences the forming force and the material formability due to heat generation between tool and sheet contact area [41]. Yoga Anjaneyulu et.al. [42] have plotted the forming limit diagram for various speeds while forming the blank of grade 2 titanium and examination of the fracture behaviour related to speed showed that 600 rpm spindle speed was the maximum. Mugendiran et.al. [43] studied optimization with the central composite design applying response surface methodology during forming of Al 5052 alloy and reported that spindle rotation 1931 rpm, 654mm/rev feed with 0.65 mm step size will give least Ra of 2.45 μ m and highest t of 0.753 mm, which indicates the usefulness of the studied parameters. Bagudanch et.al. [44] reported that the higher spindle rotation not only decreases the force requirement but also increases the formability of Polyvinyl Chloride (PVC) material. However, M. Ali et.al. [27] have found that the forming of polymer material with SPIF did not result in- significant improvement in formability with increased tool rotation speed. Increased tool rotation speed encourages wrinkling. Galling and premature failure of the sheet during forming was also reported with too high tool rotation speed for PVC material. Spindle speed plays an important role to increase formability, especially in the forming of metallic material. Higher spindle speed during the forming of metallic material increases friction and hence temperature, which leads to a decrease in the forming forces and an increase in formability. Too high spindle speed for polymer material causes wrinkling and galling resulting in premature failure. Hence, the requirement of research to optimize th spindle speed for the given material is much needed.

3.2.5 Feed Rate

The rate of feed is considered a very important process parameter because it decides the overall forming time. The higher feed rate can reduce forming time, and hence be considered a favourable factor for acceptance of SPIF in industries. The relative motion between blank and tool surface is the deciding factor for temperature increased by friction and hence formability [12]. Ambrogio et.al. [45] experimented with high-speed incremental forming, considering the feed rate as an influential parameter for microstructure and micro-hardness for commercially pure Titanium ASTM grade 2 and the a–b alloy Ti6Al4V ASTM grade 5 sheets. An increment in feed rate resulted in an increment in strain rate but it did not affect the microstructure of the material since the amount of employed mechanical energy was insufficient for the increment in the heat, hence the microstructure remains unaffected. Compared with the micro-hardness of the as-received sheet to the formed sheet, it was evident that only a 20% increment in hardness was reported of the formed sheet of Ti6Al4V alloy formed at the greatest feed. Hamilton et.al. [46] have reported that for the greater feed and spindle speed the similar grain structure and thickness distribution observed while forming Al3003-H14. Ambrogio et.al. [47] have experimented on pure aluminium (AA-1050-O) and reported that the same formability was achieved with high speed. There is very little effect of feed rate on surface roughness and material thinning. An increment in feed rate causes an increment in strain rate. However, the feed rate did not influence the grain structure.

3.2.6 Incremental Depth (Step Size)

Step depth plays an important role to decide the tool path strategies, moreover, it influences the surface quality of the formed part [12]. Taherkhani et.al. [40] reported during the forming of Al 3105, with the highest step depth and highest feed rate values, the shortest forming time (FT) can be achieved resulting in a high degree of surface roughness. Echrif et.al. [48] have concluded that the most influencing parameters are tool geometry and step depth during forming of AA1050-O aluminium alloy considering the surface irregularity. As the tool diameter increases and step depth decreases, the surface of the component will be smoother. Al-Ghamdi et.al. [49] experimented with different grades of aluminium, steel, and copper and concluded that an increment in the forming depth leads to an increase in the stress level in the material, which encourages pillowing tendency. The pillow defect affects formability and geometrical accuracy unfavourably. Uniform thickness variation can be achieved with spiral tool path trajectory and appropriate tool size and step depth. The location of the minimum thickness has been determined by step depth [50]. Step depth affects stress levels, thickness distribution as well as surface roughness. It had been concluded that with increased step depth, stress level, thickness variation, and surface roughness were increased. Therefore, the requirement of research to optimise the step depth in relation to formability for the given material is much needed.

Table 1 Summary of major effects of SPIF process parameters on formability

Sr. No.	Process parameter	Major effects reported on parameters	Major effects on formability	Limitations
1	Forming forces	Maximum draw angle and sheet thickness	Hearing assistance can reduce forming force requirement and improves the formability	Higher forming force is required for maximum draw angle
2	Tool path strategies	Forming forces, surface roughness, and formability	The helical inward tool path proved best to improve formability.	Tool path strategies may vary with the material.
3	Tool shape and size	Geometrical accuracy and forming force	Hemispherical tool and ball-ended tool improves the formability.	The pillowing tendency is encouraged with a very small tool diameter.
4	Spindle speed	Forming forces and surface roughness	Higher spindle speed for metallic material decreases forming force requirement and increases formability.	Increased tool rotation speed leads to wrinkling in polymer material.
5	Feed rate	Strain rate	Not much influences the formability.	-
6	Incrementa l depth (Step size)	Surface quality and stress level	With lower step depth, formability may improve.	Very high step depth leads to pillowing tendency.

4. Enhancement in SPIF to Improve Formability

Improper material deformation and lack of lubrication are considered the main causes for poor formability in the SPIF process. Specifically, lightweight engineering materials like magnesium and titanium alloys, are very difficult to form due to their very limited plastic deformation at normal temperature. Improper material deformation issues can be overcome by providing external heat assistance along with an incremental forming path, which was hard to achieve with conventional forming [7]. Surface finish is an important quality characteristic of SPIF products from the quality and aesthetic point of view. However, lack of proper lubrication severely affects the material flow under a strained state, which may result in poor surface finish. Efficient and sufficient externally applied lubrication assistance effectively improves surface finish by controlling fracture strain, maximum forming angle, and deformed surface profile [71]. With the assistance of heating and lubrication in SPIF, formability and the surface finish can be improved.

4.1 Heating Assisted SPIF

Researchers have developed and demonstrated different methods to apply heating for the SPIF process, like friction heating, halogen lamp heating, laser heating, hot fluid and hot air heating, electrical heating, and induction heating. The effects of the different heating sources on the SPIF process are discussed in the following sections.

4.1.1 Friction Heating

In the SPIF process, the friction heat may generate between the tool and the blank surface because of intense rubbing friction. When the generated heat is controlled and utilised properly, it helps to ease material deformation without affecting tool wear. M. Durante et.al. [51] have used the heat generated for improvement in formability limit. J. Park et.al. [52] have reported enhancement in plastic deformation due to locally generated heat by friction between the high speed of rotating tool and sheet of magnesium alloy. P. Gupta et.al. [53] have found that tool sheet interface temperature can be increased by increasing spindle speed and maintaining the high feed. If the temperature goes beyond a certain limit, sheet damage is initiated. At high temperatures, more slip planes will be activated resulting in easy and fast dislocation movements, which may eventually reduce the force requirement and increase the plasticity limit. J. Jeswiet et.al. [19] have found that in SPIF, rotating tool surfaces slide over the sheet surface experiencing sliding friction, which causes excessive heating. It was proven experimentally that the heat produced by sliding friction is proportional to the relative movement between the tool and the blank surface. The impact of tool rotation on surface roughness, temperature, and forming forces on aluminium alloys shows that high-speed spindle rotation can lower the force requirement and improves formability. G. Ambrogio et.al. [54] have investigated the effect of blank thickness, angle of inclination, coil pitch, tool diameter, and feed rate on aluminium alloy (AA5754) and a titanium alloy (Ti6Al4V) during high-speed forming. It was concluded that the feed rate and coil pitch contributed significantly in improving process productivity and product quality along with the material formability with the assistance of only friction heating.

4.1.2 Laser heating

Laser heating assisted SPIF Laser beam is concentrated locally to the tool sheet contact area for the heating purpose. Application of Laser heating may help to produce a highly localised and controlled heating zone in the blank material, which minimises the undue temperature effects in the surrounding material. However, the arrangement of the laser heating system proves to be expensive. J.R. Duflo et.al. [55] have concluded that the localised laser heating assistance enhances geometrical accuracy along with better spring back behaviour. The formability of the material can be improved with dynamic local heating for the materials having lower formability at room temperature. A. Mohammadi et.al. [56] have reported improvement in the formability of hard-to-form material had been achieved by laser heat support to form components incrementally. To simulate the process with all parameters, a transient heat transmission investigative study was carried out. A.Göttmann et al. [57] have experimented on Ti Grade

2 and Ti Grade 5 (TiAl6V4) assisted with laser heating and were able to achieve higher forming depth compared to the conventional cold forming in the case of TiAl6V4.

4.1.3 Electrical Heating

As the current flows from the tool sheet contact area, heat is generated due to the high-current density. This principle can be implemented to have electrical heating assistance in SPIF. To restrict the current flow in undesirable areas, insulation is provided. D. Adams et.al.[58] have concluded that current density plays an important role to enhance formability compared to current magnitude during forming 6061-T6 Al. G. Fan et.al. [59] have found that as the electrical current rises, the heating also gets amplified which leads to improving the formability of difficult to form materials like AZ31 magnesium and TiAl2Mn1.5 titanium alloys. However, the greater values of feed rate, step size, and tool radius results in a decrease in the temperature and hence formability. G. Ambrogio et.al. [60] have found that by increasing the formability of the AZ31 sheet by applying electrical heating to the whole sheet, maximum formability was reported at 250ºC. The electrical heating assistance forming process was also investigated for aluminium alloy AA2024-T3, the magnesium alloy AZ31B-O, and the titanium alloy Ti6Al4V. It was concluded that formability has improved compared to the cold forming process but the surface finish was deteriorated due to electrical heating assistance [61]. G. Palumbo et.al. [62] have investigated the combined effect of electric heating and friction heating on titanium alloy Ti6Al4V forming. Furthermore, the friction heating generated through spindle rotation can help to stabilise the onset of necking up to a higher level. B. Saidi et.al.[63] have concluded that with cartridge heating assistance, the forming wall angle 55º has been achieved for Ti–6Al–4V titanium sheet. Moreover, the improvement in the forming limit was also reported with an increased temperature range.

4.1.4 Induction Heating

In induction heating assisted SPIF, the sheet is heated by electromagnetic induction in which the eddy current is produced in sheet metal that leads to heating. Al-Obaidi et.al.[30] [64] have concluded that the forming force requirement is significantly reduced, during the forming of advanced high-strength steel (AHSS) with induction heating assistance. G. Francesco et.al. [65] have reported that carbon steel (magnetic) and titanium alloy Ti6Al4V (non-magnetic) having poor formability at room temperature can be formed with induction heating assisted SPIF.G. Ambrogio et.al.[66] have found that more effective temperature control was possible with induction heating compared to electric heating systems. Lower surface roughness and lower spring back were reported with the induction heating system.

4.1.5 Halogen lamp heating

The halogen lamp heating assistance for SPIF is provided from the backside of the sheet by the number of halogen lamps in motion with the forming tool. The heat is provided locally in nature but it is not localised thoroughly.

M. Okada et.al. [67] observed that carbon fiber reinforced thermoplastics (CFRTP) sheets show plasticity at 200°C in the forming. At the centre of the optical axis of the halogen lamp, the temperature was higher and increased as the thickness of the worksheet increased. Formability has improved with increment in worksheet thickness. The temperature distribution was linear from the optical axis of the halogen lamp. S. W. Kim et.al. [68] have concluded that the formability of the AZ31 sheet can be improved with halogen lamp heating. Moreover, hard to form material at room temperature can also be formed with the heating assistance, which favours the acceptance of the different materials in the industry.

4.1.6 Hot Fluid & Hot Air Heating

In hot fluid and hot air heating assisted SPIF, the heat transfer takes place through convection. The sheets have to experience heat globally compared to other methods applying it locally. A higher temperature range can be achieved through hot fluid compared with hot air heating. L. Galdos et.al. [69] have applied heated fluid as heating assistance while forming AZ31B magnesium alloy. Full recrystallization of the component at 250°C enabled the highest angle 60º through forming which was otherwise difficult to be achieved at room temperature.

S. Zhang et.al. [70] have found that during forming of AZ31B magnesium alloy with oil bath heating assisted SPIF, formability is the most influenced by the temperature. It was concluded that at the temperature of 250°C, the highest angle of 68.144º was achieved through the applied design of the experiment and optimization method. H. Wang et.al.[71] have found the improved tendency in forming limits for AA2024 with hot fluid assistance SPIF. Y. H. Ji et.al.[72] have reported an increment in the forming rate of magnesium alloy (AZ31) blank with heating assistance with a hot air blower above 150°C. Y. H. Ji et.al. [73] observed that as the heating rises, the formability of magnesium alloy (AZ31) blank rises during the forming of different cone angles Furthermore, the progressive method of forming enables one to achieve a circular cup with a greater angle of inclination. Al-Obaidi et.al. [74] have successfully formed a part with a wall angle greater than 50° of PA6GF47 (GFRP) material through hot air heating assisted SPIF.

Table 2 Summary of heating techniques used to enhance the formability of SPIF

Author	Year	Heating Method	Material	Research Findings	Reference
Friction heating					
J. Jeswiet et.al.	2005	Friction heating	3003-0 aluminium	The heat produced by sliding friction between the tool and blank surface reduces forming force requirement and enhances formability.	[19]
M. Durante et.al.	2009	Friction heating	aluminium alloys	The heat generated due to high-speed tool rotation can decrease the forming force requirement.	[51]
J. Park et.al.	2010	Friction heating	Magnesium alloy	Locally generated heat has enhanced plastic deformation.	[52]
G. Ambrogio et.al.	2015	Friction heating	Aluminium alloy (AA5754), titanium alloy (Ti6Al4V)	Optimise tool feed and step depth can improve formability only by friction heating.	[54]
P. Gupta et.al.	2017	Friction heating	AA5754-H32	Increasing spindle speed and maintaining high feed reduces the force requirement and increases the plasticity limit.	[53]

Laser Heating					
J. R. Duflou et.al.	2008	Laser-assisted heating	Al 5182, 65Cr2	Dynamic local heating can improve dimensional accuracy and formability.	[55]
A. Göttmann et.al.	2011	Laser-assisted heating	Ti Grade 2 and Ti Grade 5 (TiAl6V4)	Higher forming depth can be achieved compared to cold forming.	[57]
A. Mohammadi et.al.	2014	Laser-assisted heating	AA5182-O	Reduction in the forming forces and lower hardening exponent was concluded.	[56]
Electrical Heating					
G. Ambrogio et.al.	2008	Electrical heating	Magnesium alloy – AZ31	Maximum formability has been reported, globally heated sheet at 250ºC.	[60]
G. Fan et.al.	2008	Electrical heating	AZ31 magnesium and TiAl2Mn1.5 titanium alloys	Grater values of electrical current rise the heating can improve the formability.	[59]
G. Ambrogio et.al.	2012	Electrical heating	AA2024-T3 aluminium alloy	Formability has improved compared to cold forming but the surface finish deteriorated.	[61]
G. Palumbo et.al.	2012	Electrical heating	Titanium alloy Ti6Al4V	The Combined effect of electric heating and friction heating can help to the onset of necking.	[62]
D. Adams et.al.	2014	Electrical heating	6061-T6 Al	Current density plays an important role to enhance formability.	[58]
B. Saidi et.al.	2020	Electrical heating	Ti–6Al–4V titanium sheet	Forming wall angle 55º was achieved with increased temperature range	[63]
Induction Heating					
A. Al-Obaidi et.al.	2016, 2017	Induction heating	advanced high-strength steel (AHSS)	Forming forces requirement reduced significantly.	[30] [64]
G. Francesco et.al.	2017	Induction local heating	carbon steel, titanium alloy Ti6Al4v	Materials with lower formability at room temperature can be formed.	[65]

G. Ambrogio et.al.	2017	Induction heating	Ti-6Al-4V	Superior temperature control and good surface quality and lower spring back achieved compared to electric heating.	[66]
Halogen Lamp Heating					
S. W. Kim et.al.	2007	Halogen lamp heating (Local heating)	Magnesium alloy – AZ31	Fracture height can be increased with an increase in temperature up to 300^{O}C	[68]
M. Okada et.al.	2018	Halogen lamp heating	Fiber-reinforced thermoplastics (CFRTP)	An increment in temperature reported as the worksheet thickness increases lead to improved formability.	[67]
Hot Fluid & Hot Air Heating					
Y. H. Ji et.al.	2008	Air blower heating	Magnesium alloy – AZ31	Increased forming angles can be achieved through the progressive method of forming	[73]
Y. H. Ji et.al.	2008	Air blower heating	Magnesium alloy – AZ31	An increment in formability has been reported.	[72]
L. Galdos et.al.	2012	Heated hot fluid	AZ31B magnesium alloy	Full recrystallization of the component at 250 °C enables to achieve the highest angle 60^{o} through forming.	[69]
Al-Obaidi et.al.	2019	Hot air heating	PA6GF47 (GFRP)	Composite has successfully formed greater than 50° wall angle	[74]
S. Zhang et.al.	2020	oil bath heating	AZ31B magnesium alloy	The highest forming angle of 68.144^{o} can be achieved with optimised conditions at 250^{o}C	[70]
H. Wang et.al.	2020	Hot fluid	AA2024	The improved tendency in forming limits has been reported.	[71]

4.2 Lubrication Assisted SPIF

The selection and application of appropriate lubrication are necessary for the metal forming processes to ensure high quality and lower cost of the product. Lubrication-assisted SPIF may have the capability to improve surface quality, forming force requirement, and tool life [75]. Different researchers have studied the effects of various types of lubricants on the performance and formability of the sheet metal during the SPIF process. N. Azevedo et.al. [75] have applied two types of mineral Oil (Repsol SAE 30, total finarol B 5746) and three types of greases/ pastes (moly slip AS 40, weicon AL-M, moly slip HSB) during SPIF of DP780 steel and aluminium 1050. It was concluded that greater surface finish can be achieved with SAE 30 oil and AL-M grease for AA1050 and Finarol B5746 oil and AS-40 grease for DP780. Lower friction ranges can be obtained by applying AS-40 for both the sheet materials. Furthermore, higher viscosity lubricant applied to the material with lower hardness and lower viscosity lubricant applied to the material with higher hardness can result in good surface finish. K. Jawale et.al.[76] has investigated lubrication assistance during the forming of copper sheets considering the maximum forming angle, fracture strain, and surface roughness for different lubricants like copaslip, AS40, weicon Ni, special weicon montage, Castrol magnaglide D68, and without lubrication. It was concluded from the study that mineral oil-based lubricants prove to be good for surface quality during the incremental forming of copper. While forming copper, no significant effect resulted in formability improvement. K. Jawale et.al. [77] have investigated the effect of lubrication assistance for SPIF for surface roughness from the microstructure point of view using Scanning Electron Microscopy (SEM) analysis. A significant difference was found on the lower and upper face of the blank after forming. An increment in surface roughness has been reported due to the developed valley along the grain boundary. No significant difference was reported on grain size and shape during forming with lubrication assistance with different lubricants named Copaslip, AS40, Weicon Ni Special, Weicon montage, and Castrol Magnaglide D68.

Q. Xu et.al. [78] have applied molybdenum disulfide lithium base grease as a lubricant and Cr/C coated treated forming tool during SPIF of 1060 and 2024 aluminium blank. The reduction in friction due to lubrication and coating leads to delay the fracture and hence the formability improves significantly. J. Diabb et.al. [79] have studied the significance of lubrication and wear resistance in SPIF of aluminium 6061 sheets alloys when 0.0125, 0.025, 0.05, and 0.1 wt% of SiO2 nanoparticles are mixed with vegetable oil-based lubricants developed from sunflower and corn oils. The formation of SiO2 clusters was restrained due to nano-particles dispersion in the oil, which resulted in good anti-wear properties. The 0.025 wt% composition provided better lubrication in both corn and sunflower oils. This composition resulted in the highest surface finish compared to pure vegetables and other compositions (0.0125, 0.05, and 0.1 wt%).

M. Vahdani et.al. [9] have concluded that the application of lubrication has a major significant impact on formability while forming titanium alloy blank of Ti–6Al–4V. While applying graphite powder, sparks formation was not evident, resulting in a better surface finish with the highest formability. Graphite-based anti-seize mixture with grease as the carrying medium results in even distribution of graphite particles which leads to greater surface finish. G. Hussain et.al. [80] have experimented with different lubrication proportion, tool material, coating, and application methods to incrementally form the commercially pure titanium (cp-Ti) sheet. The combination of 4:1 proportion of paste of MoS_2 powder with white petroleum jelly and hardened HSS tool was found to improve the surface finish significantly. N. Sornsuwit et.al. [81] have investigated the role of lubrication assistance with formability and roughness, various materials like SUS304, SUS316L and TiGr2 were tested with machine oil, MoS_2, and air as a lubricant. It has been found in the tested materials that the minimum depth at which the sample ruptured, the value of the surface roughness was reported to be the maximum. The highest forming depth and surface quality can be attained by applying MoS_2 as a lubricant for titanium sheet and air as a lubricant for stainless sheet. Q. Zhang et.al. [82] have applied MoS_2, graphite, $K_2Ti_4O_9$, and graphite as lubricants with and without PAO (pulsed anodic oxidation) for warm negative incremental forming of magnesium alloy AZ31. It was concluded that a good surface finish with lower friction can be obtained through MoS_2, graphite with PAO coating.

Table 3 Summary of Lubricants used in SPIF

Author	Year	Lubricant used	Sheet Material	Research Findings	Reference
G. Hussain et.al.	2008	MoS_2 powder with white petroleum jelly	CP-Ti sheet	MoS_2 powder mixed with white petroleum jelly in 4:1	[80]

				proportion improves the surface finish.	
Q. Zhang et.al.	2010	MoS_2, graphite, $K_2Ti_4O_9$ and graphite	Magnesium alloy AZ31	Good surface finish with lower friction can be obtained through MoS_2, graphite with PAO coating.	[82]
N. Sornsuwit et.al.	2014	Machine oil, MoS_2	SUS304, SUS316L, and TiGr2	The highest forming depth and surface quality attain by applying MoS_2 for titanium sheet and air for stainless sheet.	[81]
N. Azevedo et.al.	2015	Mineral Oil - Repsol SAE 30, Total Finarol B 5746 and pastes (Moly slip AS 40, Weicon AL-M, Moly slip HSB	DP780 steel, aluminium 1050	Higher viscosity lubricant applied to the material with lower hardness and lower viscosity lubricant applied to the material with higher hardness helps to achieve a good surface finish.	[75]
K. Jawale et.al.	2016	Copaslip, AS40, weicon Ni, special weicon montage, Castrol magnaglide D68	Copper	Mineral oil-based lubricants prove to be good to improve surface quality.	[76]
J. Diabb et.al.	2017	SiO_2 nanoparticles are added to sunflower and corn oils	Aluminium 6061 sheets alloys	The 0.025 wt% compositions of SiO_2 nanoparticles mixed with sunflower and corn oils produced better lubrication.	[79]
K. Jawale et.al.	2018	Copaslip, AS40, Weicon Ni Special Weicon montage, Castrol Magnaglide D68	Copper	An increment in surface roughness has reported due to the developed valley along the grain boundary	[77]
Q. Xu et.al.	2018	Molybdenum disulfide lithium base grease	2024 Aluminium	The lubrication and Cr/C coated tool delay the fracture and hence the formability improves.	[78]
M. Vahdani et.al.	2019	Graphite powder	Ti–6Al–4V Titanium alloy	Lubrication produces a significant impact on material formability after the electric current.	[9]

5. Formability of Different materials

Material properties play an important role to define the forming limit of that material. Material's ability to form also depends on mechanical properties affecting the deformation mechanism. The percentage reduction of the area proved to be an influencing factor for formability in SPIF [83]. The formability study of some important materials is discussed below.

5.1 Aluminium & its Alloys

The aluminium and its alloys have lower formability compared to steel and its alloys, although the higher strength to weight ratio attracts the automotive industries. To improve the formability of aluminium and its alloys, incremental forming has been employed instead of conventional forming. L. Filice et.al.[84] have reported during the forming of AA 1050-0 with SPIF that the process was distinguished by local stretching deformation, which was different from the conventional process. The FLC of the process shows a straight shape with a negative inclination in the positive e_{minor} side indicating that the higher strain values can be achieved through SPIF. V. K. Barnwal et.al. [85] have highlighted that the plain strain is a major cause of deformation in the forming of AA6061. The orientation of the major principal strain is at the right angle to the tool travel, which encourages the flow of the material, at the right angle to the tool travel path. It was concluded that the maximum deformation resistance was experienced in the ID direction during the experiments. During hole flanging operation of AA707-O metal sheet with SPIF, Martinez-Donaire et.al. [86] have reported that numerically evaluated hydrostatic stress during SPIF was much smaller than conventional sheet forming operation. Furthermore, enhancement in formability can be better explained with the help of hydrostatic stress. P. Eyckens et.al. [87] have reported that non-monotonic, serrated strain paths were evident while processing AA3003-O through SPIF, which results in higher formability compared to monotonic loading conditions in conventional loading. As the tool moves, the sheet is repeatedly bent and unbent resulting in serrated strain paths. X. Song et.al. [88] have found that ductile failure has been evident in the form of radial and circumferential cracks during fracture analysis of soft-temper foils (Aluminium 1145) in micro incremental sheet forming. Galling on the surface resulted in dull surface and peel-off from the surface, which resulted in crack formation in the later stage leading to decreased formability. C. Raju et.al. [89] have reported that while forming multiple sheets of pure (cp) aluminium, the value of true strain was decreased from the upper sheet to the bottom sheet while forming two, three, or four sheets together in all conditions. The values of the minor true strain were independent of the sequence. It had been concluded from the experiments, that failure was evident in the bottom-most sheets in all trials after significant plastic deformation. T. J. Kim et.al. [90] have concluded that even thickness strain distribution can be attained with the double pass forming method and higher formability can be achieved. M. Shamsari et.al. [2] have found that using hybrid deformation strategy considerably improved forming depth and sheet thinning for AA1050. Enhancement in forming depth has been achieved due to the equi-biaxial forming of the entire blank with the hydraulic bulging in a two-stage SPIF strategy.

5.2 Steel & its alloys

Higher acceptance of steel and its alloys in different industries makes it favourable for the research. Steel with different alloying elements possesses different properties as per the requirement, however the higher strength to weight ratio requirement for the different applications encourages the researcher to form the material with advanced metal forming processes like incremental forming. J. Li et.al. [50] experimented on the DC04 sheet with an incremental forming process concentrated on thickness variation and mechanical properties while forming a truncated pyramid. It was highlighted that minimum thickness was largely dependent on tool diameter with conventional tool path and the location was decided by the step depth. It was concluded from the tensile test specimen extract from the formed pyramid that with increment in strength, the plasticity of the material has dropped suddenly. D. T. Nguyen et.al. [91] have reported while forming cold-rolled steel for maximum wall angle, that the maximum wall angle of 68.2^{o} was achieved on the final shape of the part. Moreover, the corresponding deformed height was to be located below the obtained forming limit in the cases where the maximum wall angle was more than 68.2^{o}. The evolution of cracks and corresponding strain paths indicated that the strain path for the process was not linear. P. Verleysen et.al. [92] have found that the uniaxial tensile test results of the S235, DC04, AISI904steel, and TRIP steel grades exhibited the impact of strain rate on the forming limit. Prediction of onset of necking in steel sheet based on the M-K model subjected to multi-axial strain state was achieved. At higher strain rates, the downward shift in the forming limit diagram reflected reduced ductility in the S235 and DC04 steel grades. In the case of TRIP steel, the reverse trend has reflected and for AISI409 steel, no considerable effect has been reported. J. Li et.al. [93] have found that compared to single-pass incremental forming in DC56 sheet, more uniform thickness distribution in double pass incremental forming due to the increase of the total plastic deformation zone. It was also reported that as the number of stages during forming increased, it led to more uniform thickness distribution in addition to that with the increased value of $\Delta\alpha$ (increment in angle in two nearby stages), major thickness decrement falls at the beginning and then increased with the $\Delta\alpha$ value [94].

5.3 Other material & its Alloys

Materials like titanium and magnesium are much more difficult to form at room temperature than conventional metal forming processes. Higher formability can be achieved by SPIF as compared to convention forming during the forming of a material having lower ductility at room temperature. R. Araújo et.al. [95] have reported that FFL (failure by fracture) can be predicted by the straight line declining from left to right and the intersection of major strain axis and FLC at a point of equivalence to the strain hardening exponent. The gap in the middle of neck formation (FLC) to failure by fracture (FFL) points out the inadequate workability of grade 2 titanium material due to the interaction between instability and rupture close to biaxial tension. M. Vahdani et.al. [9] have investigated Ti–6Al–4V titanium alloy workpiece forming with resistance heating assistance along with different lubricants. It was concluded that the lubrication was the most significant factor to improve surface finish and formability. Maximum formability can be achieved by applying graphite powder as a lubricant and a great surface finish can be achieved by applying a graphite-based anti-seize compound. Heating and lubrication assistance during the process helps to improve formability. Y. H. Ji et.al. [72] have reported an increment in formability of magnesium alloy AZ31 achieved with heating assistance from a hot air blower. Major strain values in plane-strain stretching and axisymmetric stretching reached a maximum at 150^{o}C. C. Raju et.al. [96] have applied hybrid optimization using grey relational analysis and response surface methodology while forming several commercially pure copper sheets. It has been concluded that the feed rate proves to be the most influential parameter followed by vertical feed and tool diameter. It was concluded from the reviewed articles that difficult to form materials at normal room temperature can be formed successfully with heating and lubrication. Improved formability has also been reported during the forming of multiple sheets together.

5.4 Polymeric Materials

Polymeric materials are largely produced by the moulding process; however, intricate shapes can be generated by the specialised incremental forming. Traditional and incremental forming can be the secondary process to generate complex shapes which were difficult to be generated by the moulding process. Durante et.al. [34] have found that in incremental sheet forming of metal sheets, the onset of necking is evident along the circumference on the tool-path while forming a cone shape. In the case of forming a polycarbonate sheet, the crack propagation starts immediately and in the direction opposite to the tool movement, after the necking has been evident. The formability of the polycarbonate can be increased by the adoption of ATP (alternate spiral tool-paths, alternating the spirals in anti-clockwise and clockwise directions). M. Davarpanah et.al. [97] have investigated that during forming of amorphous PVC and a semi-crystalline polyamide, the ductility and toughness were enhanced while elastic stiffness and the yield stress were compromised. For the application purpose, the requirement of higher toughness is more important than stiffness for polymeric materials that can be achieved through SPIF. I. Bagudanch et.al. [98] have reported in the case of polymer materials (PVC- polyvinyl chloride and PC- polycarbonate) that formability has increased with an increase in forming tool speed and the mode of failure was found to be ductile fracture without previous necking. The part failed in twisting if the process temperature was very close to or greater than the glass transition temperature. In the case of materials with a glass transition temperature below room temperature, no significant effect has been reported with increased spindle speed. Material with a low melting point temperature, the formability may reduce with increment in temperature. It was evident that PVC had the highest formability followed by PCL (polycaprolactone) and PC. I. Bagudanch et.al. [44] have highlighted that the fracture strains were closer to the maximum strain which indicated that the fracture did not happen due to unstable processes such as necking. It has also concluded that plane and biaxial strains measured and calculated theoretically, were identical. It indicated that PVC samples acted like an incompressible polymer. The formability of the PVC material can be increased with increment in spindle speed. V. Franzen et.al. [99] have concluded that the SPIF process on commercial PVC sheets at room temperature is capable of form up to the high depth and can be applied for complex components. It was reported that the forming limit can be increased with higher spindle speed because of friction between work-piece material and the forming tool, which elevates the heating phenomenon.

5.5 Composite Materials

Composite materials consist of two or more physically and chemically dissimilar materials separated by a distinct interface. Higher-strength to weight ratio and the other desirable qualities like higher strength, toughness, and design flexibility of the composite material gain the attention of industries and researchers. Forming of the composites with incremental forming improves the forming limit of the material which attracts the researcher to adopt the SPIF for such materials. M. Okada et.al. [67] have reported that during the forming of carbon fiber reinforced thermoplastics (CFRTP) with spot forming process, forming limit was found to improve with increment in sheet thickness and punch radius. Evidence of fracture was recorded during excessive thinning in the sidewall portion is simple spot-forming and two-dimensional sheet-fed forming. S. L. Clavijo-Chaparro et.al. [100] observed that in plasticized and reinforced poly (methyl methacrylate), PMMA, C-30B, and the PMMA chains, mechanical interlocking effect was apparent. It resulted in improved performance of material while forming. The material plasticized with 20 wt% of triacetin and reinforced with 2 wt% of C-30B was found to be the best for manufacturing cranial implants.

K. A. Al-Ghamdi et.al. [101] concluded that with raising annealing temperature, the formability improves in both stampings and the SPIF process for steel-Cu roll-bonded composite sheets. Higher formability can be achieved with SPIF compared to the stamping process for the steel-Cu roll-bonded composite sheet. However, the formability is compromised with the increase in annealing temperature in SPIF. M. Fiorotto et.al. [11] have experimented with glass fiber reinforced epoxy/aluminium alloy FML, which has developed in three plies of kevlar/glass/kevlar fabric woven with epoxy resin. A wrinkle-free part was formed with the assistance of aluminium sheet as a diaphragm and using a vacuum bag during the forming of the material. It was concluded that significant improvement was noticed in strength and specific stiffness while forming FML with SPIF. Z. Liu et.al. [5] have investigated the Cu-Al composite sheets for different layer arrangements by varying the thickness of both layers. It has been concluded that compared to Cu/Al layer, Al/Cu layer structure shows higher formability in both GR(Groove) and TCG (truncated cone with variable generatrix) tests irrespective of the incremental step sizes, rate of feed, and tool radii. However, forming force requirement is higher in Al/Cu arrangement compared to Cu/Al layer arrangement. K. P. Jackson et.al. [102] have formed the sandwich panels of MS (Mild Steel)/PP (Polypropylene) /MS (Mild Steel) and Al (AA5182) /PP (Polypropylene) /Al (AA5182) with ISF. However, panels being ductile had an incompressible core, which can survive a local impression in incremental forming without the core failure. The investigation reveals that similar variations can be reported with vertical tool force, step depth, and tool diameter. The blank thickness variation along an angular wall can be described with sine law.

Table 4 Formability Limitations of SPIF for various materials

Author	**Year**	**Material**	**Parameters studied**	**Outcomes/ Research Findings**	**Limitation**	**Reference**
T.J. Kim et.al.	2002	Aluminium	Thickness strain, formability	Formability improvement was reported with the double-pass forming method.	Thickness strain distribution limits formability.	[90]
P. Eyckens et.al.	2007	AA3003-O	Strain path	Serrated strain paths are resulted due to a change in direction of the tool path.	Complex, non-uniform strain path are generated	[87]
K. P. Jackson et.al.	2008	MS/PP/MS and Al/PP/Al sandwich panels	Tool forces, through-thickness deformation	Vertical tool force shows identical modifications with step depth and tool radius.	Limiting wall angle was less compared to sheet	[102]
Y. H. Ji et.al.	2008	AZ31 sheet	Formability of free surface	Maximum formability achieved at 150ºC due to the highest value of major strain.	-	[72]
V. Franzen et.al.	2009	Commercial PVC (polyvinyl chloride-rigid) sheet blanks	Formability	Successfully manufactured parts with good formability.	-	[99]
M. Fiorotto et.al	2010	Fiber Metal Laminates (FML) kevlar/glass/kevlar	Surface Quality, Formability	Successful wrinkle-free components can be formed with aluminium sheets as a diaphragm and using vacuum bag technique.	FML with aluminium sheets and a composite core is difficult to form without wrinkles.	[11]
P. Verleysen et.al.	2011	CMnAl TRIP steel, S235, DC04 and AISI 409	Strain rate	Downward shifting of forming limit diagram reported at higher strain rate in S235 and DC04.and reverse trend reported in TRIP steel.	Strain rate would be considered as the limiting factor for formability	[92]
L. Filice et.al.	2012	AA 1050-0	Tool path, different straining conditions	FLC of the process clearly shows that higher strain values can be achieved through SPIF	-	[84]

J. C. Li et.al.	2012	DC04 sheet	Thickness distribution, tool path	Thickness variation depends on tool trajectory and location depends on step depth.	Work hardening in ISF parts increases strength and decreases plasticity.	[50]
J. Li et.al.	2012	DC56 sheet	Thickness distribution	Uniform thickness distribution achieved through double pass forming due to increment in a total plastic deformation zone.	Non-uniform thickness distribution will result in premature failure of the part	[93]
D. T. Nguyen et.al	2013	Cold-rolled steel	Maximum wall angle, forming depth	The final shape formed by cold-rolled steel produces a maximum wall angle of 68.2º	Deformation height has compromised if the maximum wall angle is higher than 68.2º	[91]
J. Li et.al.	2013	DC56 sheet	Number of forming stages, incremental wall angle, thickness variation	More number of forming steps produces uniform thickness distribution.	Larger amount of spring back in multi-stage forming.	[94]
R. Araújo et.al.	2014	Titanium grade 2	Formability	The maximum permissible drawing angle is 60°	It is difficult to form extreme angle.	[95]
I. Bagudanch et.al.	2015	Polyvinyl Chloride (PVC)	Forming force, forming depth, temperature	Increased spindle speed results in reduced forming forces and increases the formability	-	[44]
C. Raju et.al.	2016	Pure copper sheets	Spindle speed, feed rate, step depth, tool diameter	Rate of feed is the most influential parameter succeeded by vertical pitch and tool radius	-	[96]
K. A. Al-Ghamdi et.al.	2016	Steel-Cu roll-bonded composite sheet	Formability	Compared to stamping, much higher formability can be achieved through SPIF.	As the annealing temperature increase the formability decreases in SPIF	[101]
C. Raju et.al.	2017	Pure(cp) aluminium	Strain distribution	The bottom-most sheets failed first during all the trials after undergoing a considerable amount of plastic deformation when two, three, or four sheets were formed together	Minor true strain values are difficult to predict.	[89]

M. A. Davarpanah et.al.	2017	Amorphous polyvinyl chloride (PVC), semicrystalline polyamide sheets	Incremental depth, tool rotation speed	Ductility and toughness increase but the elastic stiffness and the yield stress decrease.	A clear trend of the incremental depth and tool rotation was not evident.	[97]
I. Bagudanch et.al.	2017	PVC, PC, and PP – polypropylene, PCL – polycaprolactone, and UHMWPE	Formability, spindle speed	Raising tool rotation enables to achieve higher formability in PVC and PC	No significant effect has reported with the increased spindle speed, with a glass transition temperature below room temperature	[98]
V. K. Barnwal et.al.	2018	AA-6061 aluminium alloy	Forming Behaviour, Strain distribution, and tool path	The flow of the material, at a right angle to the tool travel path.	Maximum deformation resistance experienced in the ID direction during SPIF	[85]
A. J. Martinez-Donaire et.al.	2018	AA7075-O	Strain path and hydrostatic stress	Hydrostatic stress numerically evaluated during the SPIF process was considerably smaller than those in conventional sheet forming operations.	Pre-cut hole diameter should put the limitation on formability	[86]
X. Song et.al.	2018	Aluminium 1145 soft-temper foils	Deformation mechanism and formability	Cracks are observed both in the circumferential and radial directions which indicates ductile failure	Existence of gall results in poor surface finish and lower formability	[88]
M. Shamsari et.al.	2018	AA1050 aluminium sheet	Forming depth, thickness distribution	Two-stage SPIF results in higher formability due to biaxial deformation of the sheet at hydraulic bulging.	The difference in the strain path was not evident.	[2]
M. Durante et.al.	2018	Polycarbonate sheets	Formability, forming forces, sheet thinning, surface roughness	ATP tool path with a fixed end tool proved to be best	The negligible effect found with the rotating tool.	[34]
M. Okada et.al.	2018	Carbon fiber reinforced thermoplas	Forming height	Increasing punch radius and sheet thickness formability have improved.	Fractures were evident on the sidewalls.	[67]

		tics (CFRTPs)				
S. L. Clavijo-Chaparro et.al.	2018	PMMA composite	Formability	Material plasticized with 20 wt% of triacetin and reinforced with 2 wt% of C-30B has proved to be the best in SPIF	-	[100]
M. Vahdani et.al.	2019	Ti–6Al–4V titanium alloy	Formability, surface finish	Enhancement in formability was reported with resistance heating along with lubricating with graphite powder and grease.	Too high local heating resulting in the sheet burning.	[9]
Z. Liu et.al.	2019	Roll-bonded Cu-Al composite	Forming ability, surface irregularity, thickness distribution, and force required for forming	Layer arrangement creates a significant effect on formability.	Different layer arrangement exhibits variation in thickness distribution.	[5]

6. Conclusions

Based on the review, SPIF can be considered as a promising and novel material forming method for rapidly manufacturing prototypes and small batches. With proper understanding of the formability phenomenon of the materials, it is possible to select the proper set of parameters, the SPIF has the potential to replace the costly traditional methods of forming by minimising the rejections due to poor accuracy and surface finish, and defective parts. Moreover, it can provide a solution to manufacture single or few parts, which otherwise is not economically viable through conventional forming processes. Network analysis maps of the review indicate that incremental forming of metals for improved surface finish and dimensional accuracy is the major research trend in metal forming area. in order to enhance the formability

The surface finish and dimensional accuracy are the most important criteria for defining the quality of the SPIF parts. Because of the distinctive research findings about the impact of various tool parameters on surface irregularity and geometrical accuracy of the material, it needs to be investigated systematically. Moreover, the effect of lubrication and heating on accuracy and surface finish related to different tooling designs for different materials should be studied analytically.

Formability analysis of aluminium and its alloys, steel and its alloys, polymeric materials and different other hard to form materials with conventional forming methods have been studied using the SPIF process. From the reviewed work, it can be concluded that with the proper selection of the process parameters with their suitable range can help to improve the acceptance of this process in the industries. However, very limited work has been carried out focusing on systematic investigation of the formability analysis of composite materials and hence, there is a research need to carry out a detailed investigation of formability evaluation for different types of composite materials.

7. Recommendation for Future Work

From the above reviewed literature, it can be seen that research has been carried out on performance and optimization aspects of the SPIF process, but very limited research was focused on the formability analysis of composite and other specialised materials. Some potential areas have been identified for further research as listed below.

1. Accuracy and surface irregularity improvement: Accuracy along with the surface irregularity of the formed part is to be properly related and modelled with the formability of the material.
2. Process improvement: For the process improvement, novel tool path strategies, the lubricating method along with the new tool designs may be considered.
3. Forming of novel and specialised materials: The study of composite and specialised material is the key area to be focused on considering influential parameters along with heating and lubrication assistance, which necessitates substantial considerations for the future study.

Availability of data and material:
All the data generated or analysed during this study are included in this review article and have been given appropriate citation and included in the reference list. The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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