Toward Understanding the Process Limits of Incremental Sheet Forming of Titanium Alloys

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Abstract
Incremental sheet forming (ISF) process is characterised by high flexibility at low cost, and short replacement time. ISF as a process has received global attention. Particular areas include the aerospace industries, customized products for biomedical applications and prototyping in the automotive industry. Most applications can become competitive due to the flexibility offered by this manufacturing process. In this work, a background study and review of state-of-the-art ISF have been undertaken with the aim of providing a better understanding of the process limitations. The critical factors of incremental sheet forming were discussed and the mechanical and thermal process demands were identified. This information provides the foundation for developing a forming optimisation map.

Keywords
Incremental forming, forming demands, process limits

1 INTRODUCTION

Innovative technologies of forming sheet metal are now at a stage where it is possible to produce either custom parts or small batch production quantities, with very short turnaround times from design to manufacture [1]. ISF process is characterized by high flexibility at low cost, and short replacement time. It allows for making of 3D complex sheet parts, while requires an available computer numerical control (CNC) machine, a simple rig, and universal tool. Thus, it is well - suited to meet agile manufacturing requirements for sheet forming of one-off component, prototyping or small production runs.

The ISF process makes use of a simple forming punch with its motion usually defined in terms of Cartesian coordinates [2]. ISF techniques can be distinguished into 'with-die' or 'without-die' also classified as positive and negative forming, respectively [1]. Although the ISF process can be die-less, it does need a backing plate to create a clear change of angle at the sheet surface and improve accuracy. Design changes, which may occur after initial design, can also be easily accommodated, giving the process a high degree of flexibility [3], [4].

The size of a component is rather limited by the working space of the machine than by forming forces. This is because forming forces do not increase since the contact zone and incremental step size remain small. There is also the possibility that the surface finish of the component can be improved [5].

ISF components can be used in minimally invasive surgery (MIS) and customized products in biomedical applications [6]. In the automotive industries ISF can be used in prototyping and conceptual modelling. Aerospace industries frequently require prototypes, and unique or small batches of components too. Other possible uses for ISF can be found in scoops for mining vehicles, water collection gutters, architectural components, and emergency air supply ventilation systems.

2 CRITICAL FACTORS OF INCREMENTAL SHEET FORMING

Incremental sheet forming is a relatively clean and efficient manufacturing technology, with the only waste typically resulting from the lubrication strategy. In most ISF operations, the lubrication fluid can be re-used and there are also no vapours or chips. Table 1 illustrates the ecological benefits using ISF technology for the forming of sheet components. The technology has low energy requirements, as the material is cold-worked with lower forces than used for hydroforming and conventional press using dies. Less energy-intensive machines can therefore be used. Results from published research [7], [8] showed that ISF has many advantages for prototyping and small batch production up to 300 parts from an environmental perspective.

Table 1- Ecological benefits of using the ISF process to form small batch [3].

Ecological benefit	Energy saving	Material saving
No die required	X	X
Reduction of transportation	X	

Reworking instead of reprocessing or scrapping	X	X
Lower forming forces	X	
Smaller machines	X	X

The process is suitable for unique products that are usually manufactured in small batches. High-volume production becomes economically unviable, as illustrated in Figure 1.

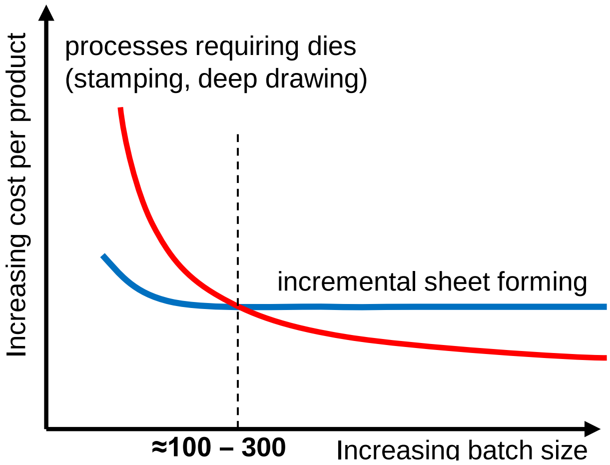

Figure 1- The inverse relationship between batch size and product cost, for ISF and traditional sheet forming (Not to scale – for illustrative purposes only) adapted from [3].

Compared to traditional forming processes that requires dies ISF products become expensive with large batches as each component is individually formed. As the time and cost to produce a die is absorbed with larger batch sizes, the cost and speed per product becomes more feasible with traditional forming processes.

Interesting to note is that as the part complexity increases (more features), the viable batch size when using ISF technology also increases. Knowing this, it is also important to realize that there can be a loss of accuracy with the ISF process, when compared to the stamping of large batches [9]. Therefore, it is not easy to estimate the exact break-even batch size, without doing experimental studies. Another drawback of the ISF process is that the cyclic-time is much longer than competitive processes such as deep drawing. Therefore, the process is limited to small size batch production.

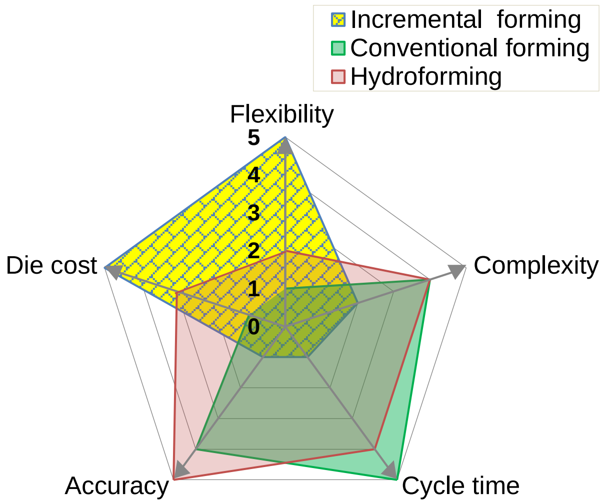

Figure 2- Conceptual comparison of different sheet forming technologies [8].

Figure 2, conceptually paints a comparison between ISF, hydroforming and conventional forming, using five weighting aspects (process flexibility, costs of required dies, processing time, and complexity of formed component and produced accuracy).

Evaluations from 1 for (poor) to 5 for (very good) are assigned to each of aspects mentioned. As it highlighted on the figure, every technology has its own strength and weaknesses. They cannot replace each other in all applications, however, trade-offs between them always exist [8].

Due to the applied tension stresses, sheet metal forming processes are limited by instability (necking), namely localised deformation over a small area (neck), while the adjoining area of the sheet stops deforming and any further stress will create a large strain, leads to sheet failure [10].

The analysis of deformation in sheet metal forming is often based on two principle membrane strains, ε_1 and ε_2. Most often, the maximum principle (major) strain, ε_1 is positive for the forming operation. The defination of positive and negitive strains are illustrated in Figure 3(a).

In the sheet metal industry the representation of the in-plane strain state, known as the forming limit diagrams (FLDs), together with forming limit curves (FLCs), are widely used to assess material formability and part manufacturability [11].The FLC in Figure 3(b) limits the boundary between the safe forming zone and the material plastic instability zone above the curve. Hence, the state of strain in forming must be such that it falls below the curve for particular material.

Practically, FLDs and FLCs are valid subject to certain restrictions, amongst others: a straight strain path (proportional loading); the situation of plane stress; absence of bending; and absence of through thickness shear [12], [10].

For ISF the relationship between strain limits plot on a straight line with negative slope in the area where minor strain $\varepsilon_2 > 0$. As shown on Figure 3(b), at a particular value of ε_2, (when $\varepsilon_2 > 0$), ε_2 for FLC-ISF (blue dashed line) is significantly larger than typical corresponding limit predicted for FLC as applicable to conventional forming processes, and close to material fracture limit [12], [13]. Previous studies on the morphology of the cracks and analysis of thickness variation of ISF formed components, revealed that material deforms by uniform thinning until fracture, without developing of necking [13]–[15].

It has been postulated that the extremely small deformation region as compared to the sheet size, leads to a plastic zone always surrounded by elastic material that effects the development of necking.

Furthermore the combination of: serrated strain baths arising from cyclical, local loading; dynamic bending and unbending under tension of sheet around the forming tool; stretching; and through thickness-shear, are proposed to describe these special forming conditions that lead to stabile deformation and the suppression of sheet necking [12].Therefore, all the above-mentioned forming conditions to generate a FLD are violated in ISF.

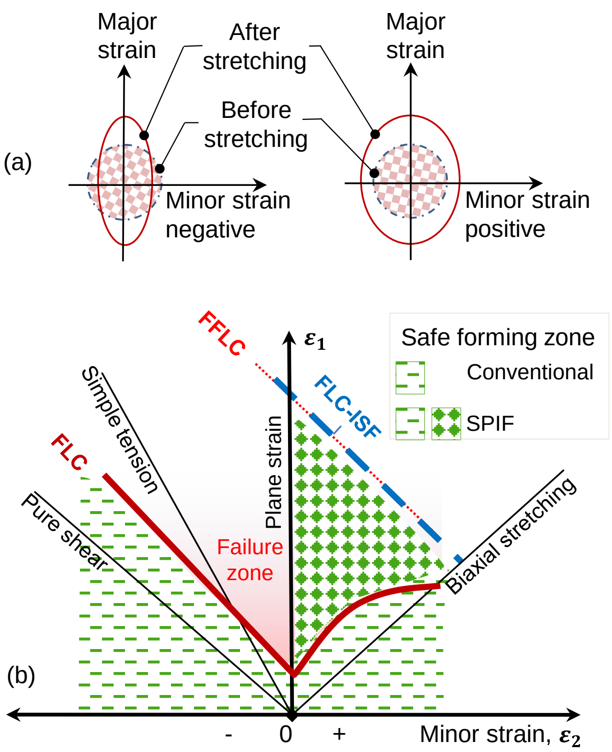

Figure 3- Schematic presentation of the principal strain space showing: (a) the definition of positive and negative strains [16]; (b) the necking limit (FLC), the fracture limit (FFLC), extended strains in ISF

Consequently, standard FLDs and FLCs of sheet metal, which presume necking as the failure mode, are inapplicable to assess the instability and describe failure in ISF process. Instead, formability limits by fracture and fracture forming limit curves (FFLCs) are recognized as characteristic of process formability and predicting material failure [15], [17].

The large reachable levels of strain before fracture in ISF has been regarded as very beneficial for the environment and cost saving. It enables using of less sheet material and still being able to manufacturing required component, makes ISF more appropriate for processing of high cost lightweight alloys. This is also characterized by the so-called buy-to-fly ratio or the relationship between the money invested for the resources of a certain product and the price of the final product [8], [18].

3 RESEARCH METHODOLOGY

ISF entails process variations and differing equipment configurations. Among these, single point incremental forming (SPIF), utilising three-axis CNC machine tools, appears to be the most flexible, simplest, and low cost approach. However, more efforts need to be directed at improving process accuracy and utilising its potential on a broader scale for manufacturing applications. Authors' main interest is focussed on investigating the capability of the SPIF process in the forming of medical implants, using titanium alloy sheets and a triple-axis CNC milling machine.

As illustrated in Figure 4, a background study and review of state-of-the-art ISF have been undertaken with the aim of providing a better understanding of the process limitations. In this review and background study, significant data on each forming condition from more than 100 relevant research articles and studies were analysed and documented.

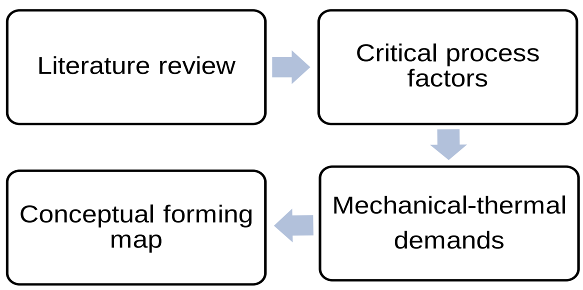

Figure 4- Schematic roadmap of the sequential steps of the applied Research Methodology.

Suitable values and their process limits for the various operating factors and parameters were obtained and summarised from both the abovementioned review and background study.

In selecting these values and their limits for the various parameters, the following conditions were set. It must satisfy: the maximum wall angle (θ_{max}), the minimum load, and good surface quality requirements. Taking account of the conclusions presented by several authors, the suggested optimum values together with their applicable upper and lower limits will be used in order to focus the number of experiments required. Using this data narrows the space when characterising SPIF design factors. This information provides the foundation for developing a forming optimisation map.

4 MECHANICAL AND THERMAL DEMANDS

Unlike in traditional forming technologies, the forming forces in ISF operations are not preselected by the designer or the operator. Instead, forces are generated as a reaction to (or a consequence of) the forming operation. These loads are determined to a large extent by the applied forming strategy, the process kinematics and tool/sheet interaction [19]-[21].

4.1 Mechanical demands

The type and thickness of a material have a direct bearing on its mechanical properties and deformation behaviour during forming. Selecting range of working parameters, loads generated, and thickness of final product all are subjected to the initial thickness and strength of its material. Figure 5 highlights the common range of sheet thickness and types of materials as sourced from the literature. The majority of these materials are soft and ductile metals, like aluminium, particularly the 3xxx series, and deep drawing steel. Some studies included forming of hard-to-form alloys, for example titanium, and titanium alloys, stainless steel, magnesium and high strength-aluminium. Few other studies also uncovered the possibility of expanding the materials capability window of SPIF beyond metals, such as forming of polymer plates [22].

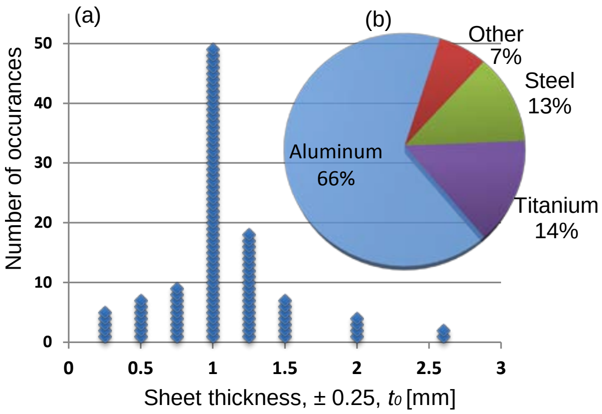

Figure 5- The occurrence of (a) sheet thicknesses, and (b) type of material commonly cited in the literature [2], [5], [7], [9], [13]–[15], [17], [19]–[21], [23], [26]–[110].

Although the ISF process requires high formability, it must be noted that the suitability of this process to effect deformation, is clearly associated with material type used. Forming loads are strongly depending on formed material strength and thickness. Also, the maximum wall angle θ_{max} that can be achieved in single-stage forming of high-strength metals such as titanium, remains lower than 45°. For aluminium and mild steel on the other hand, this angle exceeds 75°.

A strong relationship exists between formability and initial sheet thickness, t_0; matching a suitable tool-tip diameter to the sheet thickness used, rendered the best results [29], [45], [56]. If however the sheet thickness is increased without adjusting the tool-tip diameter, forming loads will also increase [53], [85].

The material of which tool is made, is of crucial importance due to the severe tribological interaction during the ISF process, where tool-tip is in continuously sliding contact with the sheet. High mechanical and thermal loads at the tool/sheet interface cause tool deterioration and premature wear. Thus far carbide, high speed steel, and cold-workable tool steel hardened and tempered to 60 HRc, have been found to exhibit sustained high mechanical and thermal stability, making them suitable materials for tool-tips. Their strength and wear resistance allow them to maintain their forming surface for a longer time [111]. However, for biomedical use, like body parts, contamination of the surface of the component by chemical elements harmful to health (such as Mn, Si, Ni, and Cr) may occur [112]. Thus, a new tool-tip material, which is compatible with health requirements, needs to be identified. Titanium might be a suitable material.

The diameter of the tool-tip, $\emptyset_{t,}$ has a pivotal role in affecting several process aspects like deformation, forming loads and processing time. Small tool-tip diameters increase material formability and generate minimum loads, while dramatically increasing forming time. They produce rough surfaces and exhibit reduced stability under severe forming conditions. Moreover, very small diameters result in material squeezing out from under the tool/sheet contact zone, causing penetration of tool into the sheet and removal of material from work piece surface [45], [113].

By contrast, large tools distribute stresses better over the contact area, reduce processing time and produce a more desirable surface quality. But they significantly increase forming loads. In the production of satisfactory work, there is a strong relationship between tool-tip diameter, $\emptyset_t$ used, and the initial sheet thickness, t_0 [14].To maximise formability and avoid the evolution of forming defects, the appropriate $\emptyset_t$ can be selected so that the threshold ratio, $\emptyset_t/t_0 > 4.7$ [45].

As per the collected data from the literature and depicted in Figure 6, the range of too-tip diameters predominantly applied are between 8 and 15mm.

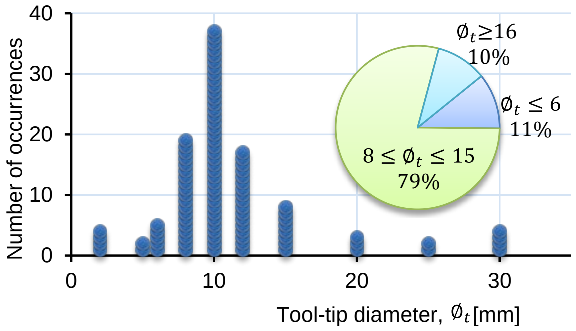

Figure 6- The occurance of tool-tip diameter, $\emptyset_t$, cited in the literature [2], [5], [7], [13]–[15], [17], [19]–[21], [23]–[50], [52]–[110].

In the process of forming, the magnitude of the forming loads acting on a sheet surface is dependent on the relative position of tool-tip to the plan area of the sheet, as well as the nature of the tool-tip/sheet interaction. In ISF, trajectories of the forming tool are defined by numerical control codes generated by a CAM system, based on the CAD model or target geometry. Standard helical and contour milling toolpaths are frequently adopted when performing ISF. Using helical tool paths generates surface qualities better than from simple z-level contours. The latter leaves marks (scarring) on sheet surface and causes force peaks [47], [55]. Other important factors related to ISF toolpath design are listed below.

Step depth is the vertical distance (Δz) between successive contours or is the amount of material deformed for each single pass of the forming tool. The step depth is comparable to the depth of cut in machining. It is selected mainly with regard to $\emptyset_t$ of the applied tool-tip, the target shape and the demands of surface quality. The interaction of step depth and tool-tip diameter significantly affects the formability process in terms of the generated loads at tool-tip, execution time, and produced component quality. In general, large Δz substantially reduce processing time. However, when using small tool-tips, a high surface roughness occurs [26], [28]. Furthermore, a large Δz implies large deformation of the sheet on each pass, and so intensifies the forming forces due to the extension of the tool/sheet contact area [88]. Figure 7 displays experimental values of Δz, as found in the literature consulted. The figure highlights the range of Δz most frequently used is form 0.25 – 0.5mm.

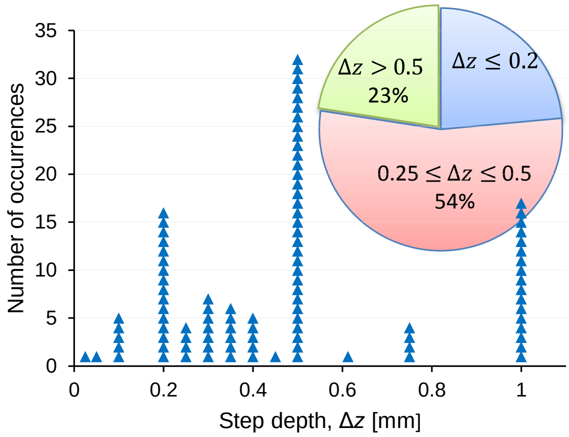

Figure 7- The occurrence of step depth, Δz, cited in the literature [2], [5], [7], [13]–[15], [17], [19]–[21], [23], [26]–[55], [57]–[84], [86]–[110], [112]–[116].

4.2 Thermal demands

Elevated temperatures are an enhancing factor in metal forming. They help soften the work piece material, reduce the required loads, and minimise springback. In different conventional metal forming operations, particularly, when forming of lightweight alloys, thermal energies from external sources are usually integrated with mechanical loads in at least one stage (before, during or after) the forming process, to increase formability and relieve residual stresses. And ISF is no exception, as the researchers have developed few hybrid versions of the ISF process referred to as heat-assisted incremental forming. In this heat-assisted process, localised dynamic thermal energy from an external source is applied and integrated into the forming zone; the energy is either from a high ampere DC current running through the forming tool onto the sheet, so-called electrically-assisted forming [8], [30], [46], [110], or from a directed laser beam, referred to as laser-assisted forming [45], [47], [102], [115], [116]. Applying external energy to the forming zone leads to significant benefits in terms of increased formability and a decrease in the forces required, however in expense of process complexity and increased cost.

Conversely, in cold SPIF operations, too much heat due to friction could lead to negative effects on the forming tool or workpiece surface at the contact zone. Oxidation of formed surface, tool failure due to deflection, or severe wear of the tool, and evaporation of the lubricant are all the major concerns.

The scope of this research is limited to studying of process demands of SPIF at room temperature. The thermal demands considered are only those related to heat generated due to tool/sheet interaction and plastic deformation.

In SPIF heat is generated at the contact zone due to relative motion between tool-tip and work piece surface. Unlike mechanical loads, the effects of thermal loads can to an extent be controlled by tuning the process parameters, so that formability is only marginally affected [58].

Considering friction heat generated in SPIF operations, tool exposure and its speed are the main influencing factors. Forming speed or simply speed, V_f, is the rate at which the outer edge of tool-tip moves along the tool-tip/sheet interface (this is similar to cutting speed in machining). Equation 2 designates that, V_f m/min is directly proportional to tool-tip diameter and its rotation speed. By adjusting spindle rotation ω_t controls the heating of contact zone.

$$V_f = \frac{\pi \cdot \emptyset_t \cdot \omega_t}{1000} \quad (1)$$

As shown in the diagram of the tool/sheet interface in Figure 8, during the course of deformation only a fraction of tool-tip is in direct contact with sheet surface. The tool/sheet interface area can be simplified as a ribbon of constant width.

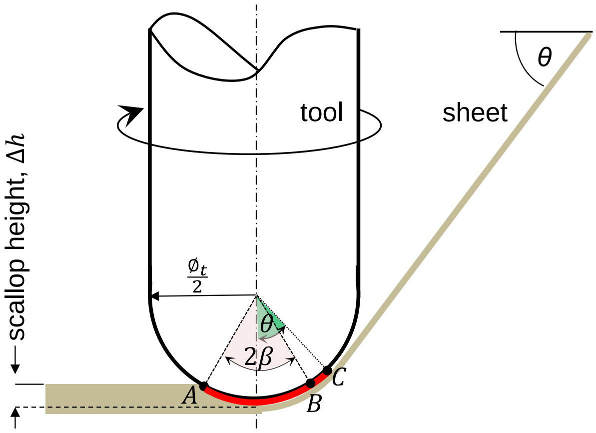

Figure 8- Enlarged diagram of tool/sheet interface

Length of the ribbon l_c equals the arc length $\widehat{ABC}$ is function of tool-tip diameter and two angles in meridional direction; the wall angle, θ ; the half-angle of groove β also known as scallop angle.

$$l_c = \frac{\emptyset_t}{2} \cdot (\theta + \beta) \quad (2)$$

The tool-tip/sheet contact area (tool exposure), is found to be mainly affected by the tool diameter, and to a lesser degree by wall angle and scallop angle which is a function of step depth Δz [15], [33].

In SPIF, different values of tool feed rates, f_t, are testified to have only minor effects on the finish of the sheet surface, the thickness distribution, or the material micro structure of the formed component. Thus, employing high feed rates can considerably reduce manufacturing time without materially affecting component quality, making SPIF more attractive to manufacturing. Figure 9(a) shows the range of process feed rates from the cited references. It is presumed that the upper limit of the practical forming rate is governed by the maximum feed rate achievable by the CNC machine [5], [27], [45]. Of course the rigidity of applied machinery and its tooling setup are critical variables and could be regarded as limiting constraints.

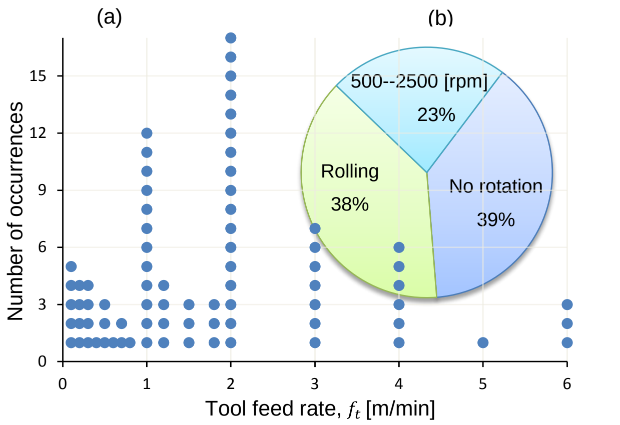

Figure 9- The occurrence of (a) feed rate, f_t , and (b) tool rotation, ω_t, cited in the literature [5], [7], [14], [15], [17], [19]–[21], [23], [26]–[30], [32], [34]–[44], [47]–[51], [53]–[59], [61]–[65], [67]–[73], [75], [77]–[80], [82], [84]–[86], [88]–[100], [103]–[105], [107]–[110].

The mechanism of interaction between tool-tip and sheet is of the utmost importance. As illustrated on Figure 9(b), based on the assigned spindle speed (ω_t) the following four varieties of tip/sheet interactions have been explored in the cited literature:

Fixed tools indent the sheet without rotation; indenting the sheet without rotation increases the heat generated at sheet surface due to sliding friction, and contributes to better formability. However, extreme sliding friction creates high bending loads on the tool-shank, and the applied equipment; raises the generated heat, which increases the wear and surface degrading at the tool-tip; and lowers surface quality.

In another way of interaction, forming tool rolls over the sheet surface with almost no sliding, and deformation occurs by the imposed forces and the rolling friction. This reduces both the relative motion between tool-tip and work piece, as well as the heat generated at the tip/sheet interface. Though, it employs using of inventive tool with freely rotating hardened sphere as tool-tip and pressurised fluid to operate, thus, increases tooling cost [40], [117].

For typical tools with hemispherical head, rolling interaction requires the feed rate to be equal to average edge of tool in contact with sheet multiplied by the spindle speed. As described by Equation 1, the optimum rotational spindle speed, ω_t , is proportional to feed rate, f_t, the tool radius ($\frac{\emptyset_t}{2}$) and wall angle θ of the component being made [1].

$$\omega_t = \frac{f_t}{\pi \cdot \frac{\emptyset_t}{2} \cdot \sqrt{\frac{1}{2}(1 - \cos(2\theta))}} \quad (3)$$

Another widely used interaction employs free (un-driven) tool movement, which leads to a reduction of slide friction, bending and horizontal loads. When generated friction at tool-tip escalates, tool responds and upholds the load by passive rolling over the sheet.

In contrast, while tool-tip moves onto the sheet, the high tool rotation ω_t, reduces friction forces. At very high ω_t, however, the tool slides more often on the same point. The occurring hot forming phenomena can result in chemical attrition at the tool/sheet contact zone [27], [58].

4.3 Towards understanding process demands

Manufactring process must exhibit a feasible space of operating conditions, often referred to as the "Process Window". A conceptual process window is shown in Figure 10. The illustrated window identifying several process concepts of the SPIF process for two main process states; X_1 and X_2.

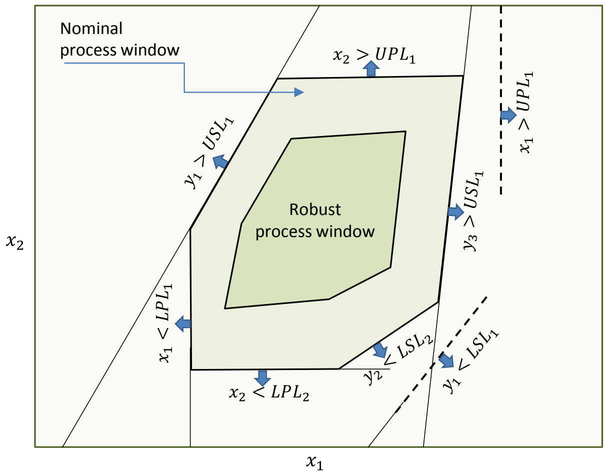

Figure 10- Process map formation (adapted [117])

Each one-sided constraint applied to either a process input (design variable), x_i or quality attribute, y_j, eliminates a region of the process from the overall process operating space. The process outputs, y_i, may also be modeled as a function of x_i in process objective function, $f(x_i)$. In the optimisation process, the goal is to minimise the objective function, $f(x,y)$. Subject to a set of constraints in the region of interest:

$$LPL_i \leq x_i \geq UPL_i$$
$$LSL_j \leq y_j \leq USL_j \quad (4)$$

Where; LPL_i and UPL_i are the lower and upper process limits for the process design variables, x_i, LSL_j and USL_j are the lower/upper specification limits for the process outputs, y_j [117].

Establishing SPIF process window is complicated and requires characterisation of operable range of several interacting process factors.
Process non-operable boundaries are usually identified using the DOE, which can be very demanding in time and resources. The adequate operating region for the process factors can be narrowed from identified process characterization. A proposed method will employ the data documented from previous work in literature as references when characterising of feasible region of SPIF. Therefore allows future research to be focused on process optimisation and high model fidelity inside the characterised space.

5 CONCLUSION

In this work, an extensive review of state-of-the-art ISF was conducted on the data from previously accomplished research efforts. This data has been classified and documented. The documented data and acquired knowledge will then be employed as references when characterising the SPIF key design factors and their variable limits.
In this paper, wherever possible, these limits and their effect on SPIF have been visually presented in the form of charts and tables, with related deductions and conclusions provided in the adjoining text.
Tool-tip diameter and step depth (as adjustable variables) together with sheet thickness and wall angle (as geometry dependent variables) were understood to be the main design factors in the planning for SPIF processes.
In addition to their individual effects, the role of the interaction between these variables needs to be considered. Alternation of the horizontal and rotational speeds has a minor impact on the magnitude of mechanical loads, but it significantly changes the thermal loads. A high feed rate is favourable for improving execution time and a high rotational speed reduces sliding friction and enhances the quality of formed component.

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