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# A Comprehensive Review on Incremental Sheet Forming and its Associated Aspects

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## *Abstract*

Sheet metal forming belongs to that category of metal forming operations wherein flat metal sheets are plastically deformed to achieve the necessary product. Forming can be performed under compressive, tensile, bending and shearing conditions. There exists a wide array of forming operations utilizing different techniques, but with introduction of computers there has been a surge in the flexibility of manufacturing processes. With a growing need of complex designs in industry at low cost, the spotlight is now on incremental sheet forming (ISF). The ability to form non-symmetrical parts without the requirement of costly dies gives ISF an edge over other sheet forming processes. Process flexibility and higher formability are other aspects which makes ISF an attractive venture for manufacturing. In the last decades, sizeable amount of work has been done in this field to make it commercially viable; especially in automobile, aerospace and defence sectors. The present paper recapitulates the variety of research carried out in the concerned area in chronological fashion and discusses the areas where more attention is required.

*Keywords:* Incremental forming, Formability, Localised Deformation, SPIF, TPIF, AISF

## 1. Introduction

Incremental sheet forming owes its origin to conventional spinning, shear forming and flow forming processes. These processes are analogous to ISF as they can produce axisymmetric shapes without using expensive dies. Automation has been achieved in these above processes using computer numerical control (CNC), numerical control (NC) and programmable numerical control (PNC) systems, which have provided fast production with the necessity of skilled manpower. However, incremental forming methods have delivered the ease of producing non-symmetrical parts at low cost. Leszak [1] bears the credit for developing the idea of incremental forming, but it lacked technical feasibility during that time. Berghahn [2] from General Electric company also proposed another form of dieless forming, where the blank is rotated with respect to a numerically programmed roller following a spiral path towards the center. Mason's work is believed to be the origin of modern ISF, where he speaks of progressive development of a shape through a spherical roller with the essentiality of a backing material [3]. Iseki and his fellow workers did substantial amount of work, starting from simple setups to CNC machines. They worked on variety of shapes, different materials and manufactured non-symmetrical parts [4-6]. They also used water jet technology as a means to achieve forming [7]. Figure 1 describes Iseki's concept of incremental sheet forming.

Kitazawa put forward the concept of incremental stretch expanding by means of multiple passes [8] and two- path stretch expanding of hemispherical [9] and hemi-ellipsoidal shells [10]. Figure 2 depicts the theory of stretch expansion and the associated mechanism. The blank is rotated relative to the tool as in the case of spinning and it is limited to the forming of symmetrical shapes.

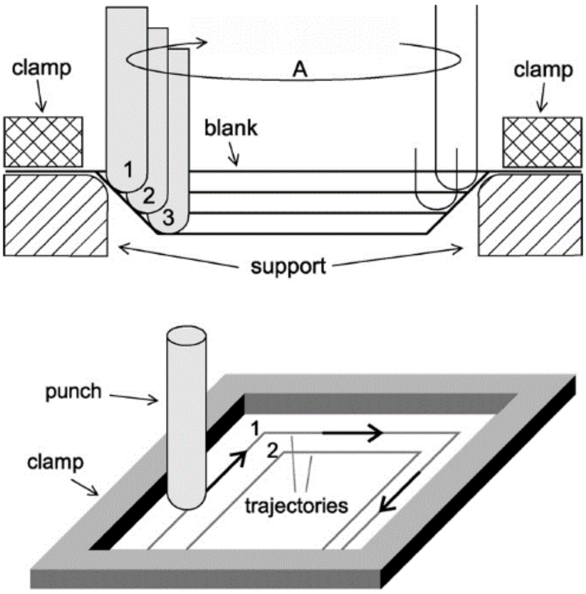

**Fig. 1.** ISF principle as given by Iseki [4], [5], [6]

Powell and Andrew [11] gave the initial concept of incremental backward bulge forming which Matsubara [12] utilised for producing low-volume non-symmetrical parts. Contrary to the earlier process, the blank remains stationary with a supporting center and forming occurs only due to tool motion as presented in Figure 4. This variant of incremental forming was later on termed as Two-Point Incremental Forming. Leach et al. [13] have presented backward bulge forming using a standard three-axis CNC milling machine. Jeswiet and Hagan [14] worked on forming concave shapes like automotive light reflector using CNC forming tool which was made to follow a contoured path with depth increments. It is well acknowledged that use of CAD/CAM made modifications of complex components easier.

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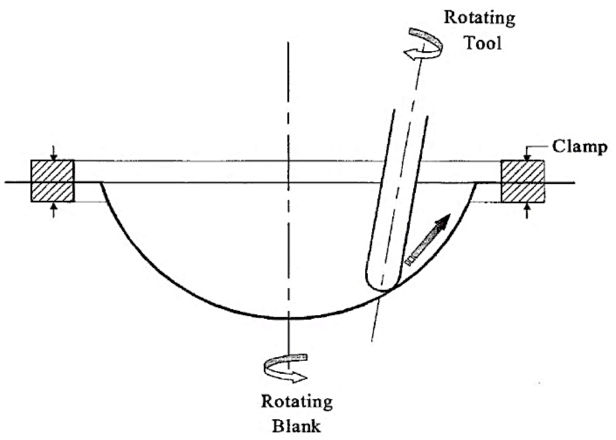


**Fig. 2.** Incremental stretch expanding apparatus [8]

Figure 3 illustrates the two forming stages involved in expanding of a hemisphere.

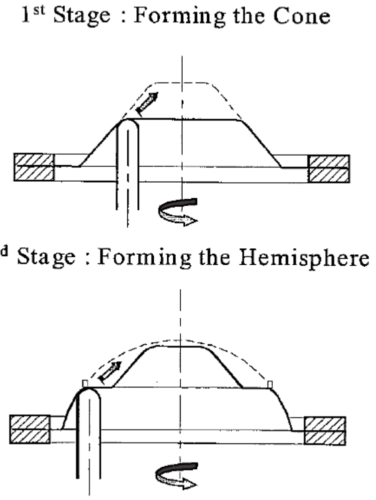


**Fig. 3.** Multi step formation of a hemisphere [9]

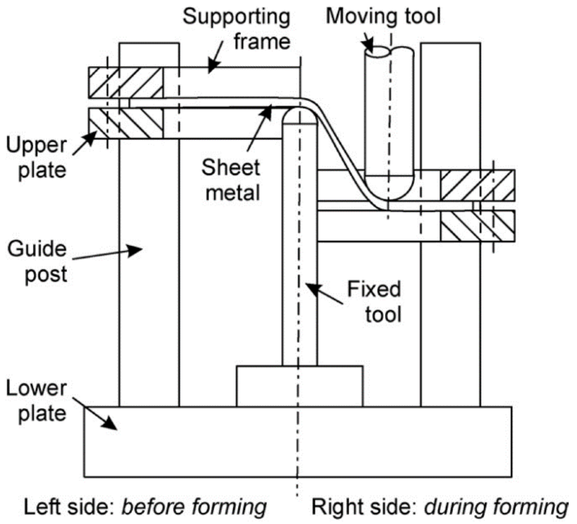


**Fig. 4** Backward bulge forming apparatus as proposed by Matsubara [12]

The beginning of 21st century saw tremendous progress in the field of incremental sheet forming. Presently, asymmetric sheet metal incremental forming (AISF) bears the following classifications, which is also shown in Figure 5.

- Single Point Incremental Forming (SPIF), which is defined by a single tool movement over the blank surface.
- Two-Point Incremental Forming (TPIF), where two tools (master and slave tool) are used.
- Two-Point Incremental Forming (TPIF) with Partial Die, where the secondary tool is replaced with a partial die to get the desired shape.
- Two-Point Incremental Forming (TPIF) with Full Die, which involves the movement of the tool over a full die to obtain the required design.

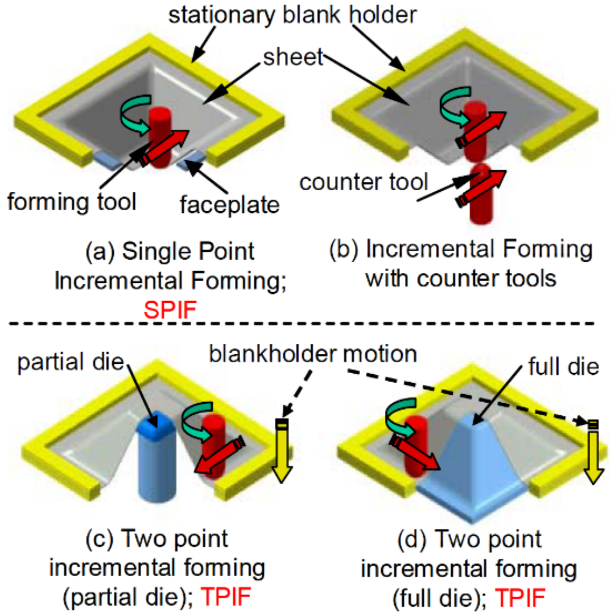


**Fig. 5.** Variants of asymmetric sheet metal incremental forming [15]

It is very essential to bifurcate the research work into different categories in order to make the discussion easier, as mentioned below:

- Formability and Forming Limits
- Deformation and Failure Mechanics
- Forming Methods
- Forming Materials and Tools
- Forming Forces
- Surface Quality
- Springback
- Process Accuracy
- Toolpath strategies
- Numerical approaches and Simulation

## 2. Formability and Forming Limits

Formability serves as an important indicator in determining the ease of a sheet metal to attain a desired shape before the occurrence of necking or fracture. Maximum draw angle ($\varphi_{max}$) can be defined as the largest angle up to which a sheet can deformed till it fractures. It is considered to be an important parameter in the assessment of formability [16-18]. In relation to the Sine law by Kobayashi [19], it is observed that as the draw angle increases material thickness reduces eventually leading to failure. Micari and Ambrogio suggested to use truncated cone as a benchmark specimen to yield formability results. Limit wall angle ($\varphi_{max}$) is derived when fracture occurs for a particular cone angle [20]. Limit wall angle is a crucial factor but it lacks clarity on complex strain state and formability behaviour. Hence, forming limit diagrams (FLD's) which are an effective way of representing the strains developed during the deformation process, are more suitable. Presently, forming limit diagrams are developed as per the methods prescribed by Nakajima [21] and Marciniak [22]. Forming limits are a characteristic of every material and their knowledge leads to optimization of the forming process. Figure 6 shows a characteristic forming limit diagram.

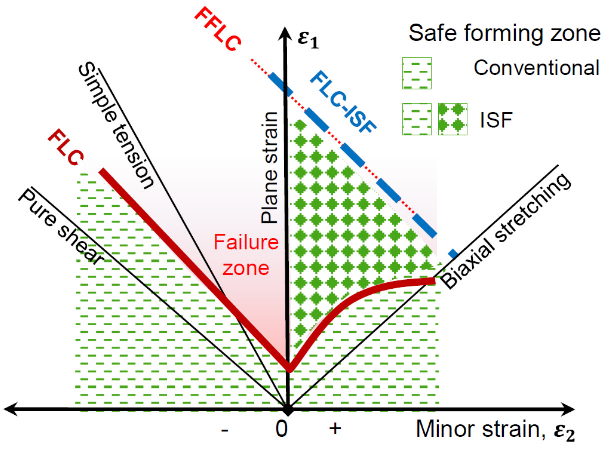


**Fig. 6.** Depiction of a forming limit diagram (FLD)

Iseki and Kumon [23] carried out initial research on forming limits and stated that incremental sheet forming has a greater degree of formability compared to traditional forming processes. Kim and Yang [24] assumed that shear deformation is instrumental in improving formability and proposed double-pass forming method to achieve the same. They also remarked that ISF needs a new FLD, owing to the difference in its process mechanics from the traditional sheet forming processes. Shim and Park performed dome stretching and ball stretching tests wherein the ball tests showed higher forming limits resulting in a negative sloped straight line. They stated that ISF is governed by localised deformation, with corners deforming more than the sides [25]. Figure 7 shows the forming limit diagram for various shapes.

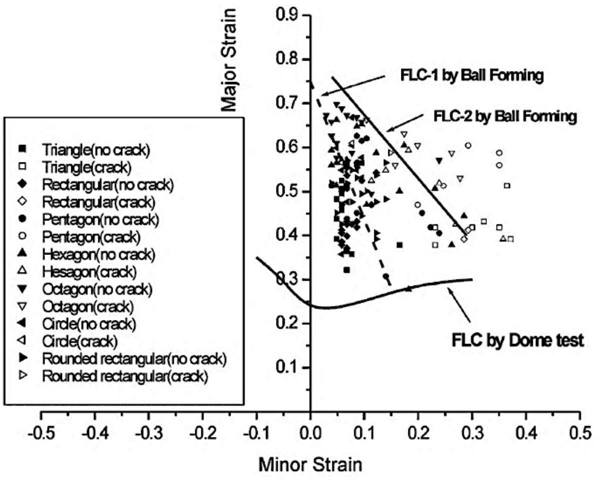


**Fig. 7.** FLD from various shapes [25]

Filice et al. reiterated that the forming limit curve carries the form of a negative sloped straight line located in the positive side of both the axes. With reference to the straining conditions, it was seen that biaxial stretching happens at corners and plane strain stretching between them. In a spiral toolpath, plane strain stretching changes to biaxial with decrease in diameter of the loop [16]. Kim and Park conducted straight groove tests and discovered that employing a low feed rate and minimizing friction proves effective in enhancing formability. Planar anisotropic factors cause formability to vary with tool movement variations [26].

Park and Kim mentioned that enhanced formability is obtained in case of plane strain stretching and the value of $\varepsilon_{max}$ + $\varepsilon_{min}$ can be considered as a measure of formability. Positive forming method was adjudged to better than negative forming, as the introduction of plane strain stretching increases the forming capability and makes it possible to achieve complex shapes [27]. Visioplastic evaluation and optical deformation measurements indicate that flat surfaces deform by plane strain mode [17]. Hirt et al. [28] specified that elastic deformation of the area around plastic deformation gives rise to hydrostatic pressure, which is the cause of higher strains in ISF. Fratini et al. assessed the correlation between formability and material properties by investigating on many materials. They used statistical analysis to conclude that material formability significantly depends on strain hardening and percentage elongation [29]. Jeswiet and Young found out maximum draw angles for different materials and determined forming limit diagram for a group of different shapes, as shown in Figure 8. They observed that high strains can be achieved by SPIF process [18].

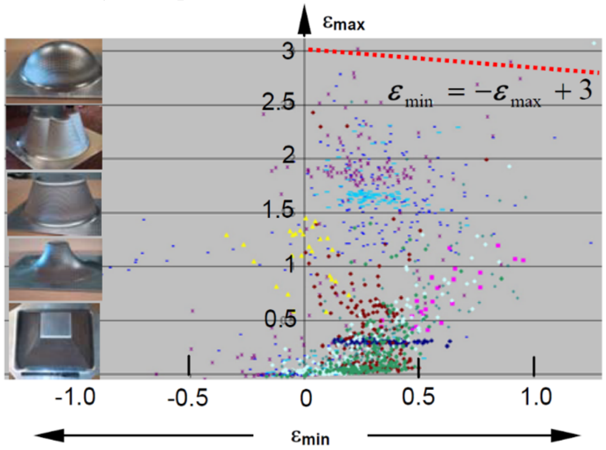


**Fig. 8.** Combined FLD of different shapes formed from 1.21mm thick 3003-0 aluminium [18]

Majority of researchers have found that formability increases with material thickness [18], [30-38]. In accordance with the sine law, it is considered that as more volume of material interacts with tool, it results in larger forming forces which explains for higher formability. It is worth noting that materials like aluminium, steel and polymer display similar trends. However, few authors have observed deviations from sine law and have considered optimisation in order to gain more formability. Optimisation involved modifying the interaction of material thickness with another parameter (e.g. tool radius) [39-41]. It can be pointed out that thicker sheets are more close to produce strong parts with desired final thickness, hence choosing a thicker sheet is more reliable. It is of general view that small diameter tools maximise formability, as the deformation zone becomes highly concentrated causing high strain [31-32], [35-36], [39], [42-46]. Also, some papers indicate that other parameters should be considered while assessing increased formability. It means tool diameter should be studied in combination with other parameters [26], [41], [47-50]. Large diameter tools have a bigger contact zone which is believed to increase forming forces and provide a better support of sheet metal. This has led to the conclusion of some authors that formability can be increased with large diameter tools [34], [37-38], [51-54]. Figure 9 shows the variation of strains with tool diameter for DC04. Smaller step size leads to better formability because of progressive deformation. The tool-sheet interface remains localised and there is minimal friction which leads to heavier deformations. Also, there is a decrease in the negative stress distribution at tool-sheet contact area and tensile stresses at the walls [26], [31], [36-37], [39], [42-44], [46], [51], [52], [55-56]. But, very small step sizes may result in tool wear, increase forming time and repeated application of stresses may lead to early material failure [47], [55]. Therefore, it is essential to select proper forming speed and formability values.

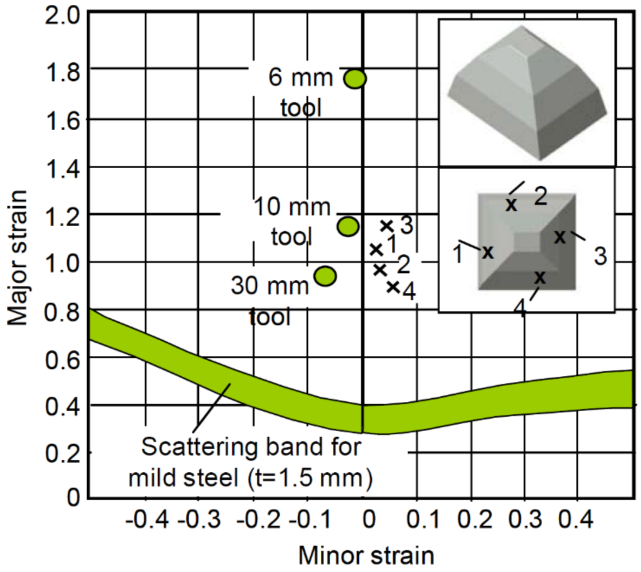


**Fig. 9.** Tool diameter effects on formability [17]

Feed rate affects formability to a very less extent, still research tells that formability is high at low feed rates. Localised heating or work hardening effect are believed to be the reasons [31], [42], [49], [52]. Optimum feed rates are better at maximising formability and reducing process time [56]. Higher spindle speeds result in heating of tool-sheet contact area due to friction, which in turn causes microstructural changes and formability is seen to increase [31], [38], [52], [57-58]. However, too high speeds can create high friction leading to surface damage. Few authors have found that optimum speeds can give better formability with decent surface finish [55], [59]. Obikawa et al. [55] and Durante et al. [44] performed experiments by rotating the tool in different directions and concluded that tool rotation direction does not affect formability.

Temperature has a major influence on formability. Duflou et al. [60] used a laser based heating system to form titanium and showed an increase in formability. Göttmann et al. [61] also presented a new form of laser forming and got improved formability results for titanium. Ji and Park [62] carried similar work with magnesium. The use of electric assisted forming was also done by Fan et al. [63] and Liu et al. [64] with hard to form materials. Adam and Jeswiet [65] used similar techniques and observed enhanced formability.

Maximum forming angle is a significant parameter in the assessment of formability limits of a material. This angle is determined by forming constant wall angle parts each with a steeper wall angle until material failure [25]. Another way is to form shapes with variable wall angles where only one test is required. Variable wall angle tests provide more accurate results than constant wall angle tests [66]. Ham and Jeswiet [31] found that material thickness and tool diameter affect maximum forming angle whereas step size has no effect. Bhattacharya et al. [67] showed that forming angle decreases with increased tool size, incremental depth and decreased sheet thickness. Fritzen et al. [68] observed that spiral toolpaths could achieve higher forming angles as compared to traditional toolpaths.

Both formability and forming limits are crucial for predicting and preventing part failure while ensuring dimensional accuracy in ISF. Achieving a balance between these factors is essential for optimizing the process and producing high-quality formed parts. One must include material properties, process parameters, and tooling considerations while optimizing the process in order to ensure the successful fabrication of high-quality formed parts.

## 3. Deformation and Failure Mechanics

It is widely accepted that ISF offers more stretching of sheet metal as compared to conventional stamping operations. Iseki et al. [69] conveyed through his work that the formability for ISF is well above the common forming limit curve. Localised deformation is the general analogy derived, but better explanations have been provided for the enhanced formability. Sheet metal failures can happen due to nucleation and agglomeration of voids or shear band formation or necking instability [70]. In ISF, stabilisation of necking is the prime reason of high fracture limit. Martins et al. [71] have described various modes of deformation like, plane strain stretching conditions in flat surfaces (A) as well as rotational symmetric surfaces (B) and equal bi-axial stretching conditions at corners (C). These are shown in Figure 10.

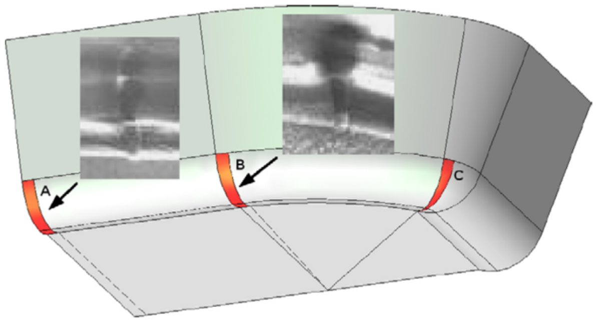


**Fig. 10.** Zones of deformation with specifications of tool-surface contact area [71]

Sawada et al. [72] did a numerical analysis about through-thickness shear with respect to punch movement. Similarly, Bambach et al. [15] through FEM simulations projected that the amount of shear is influenced by punch head diameter and the vertical pitch. Jackson et al. [73] experimentally showed the effect of through-thickness shear by measuring the relative displacement between two sandwich panels. Allwood et al. [74] related through-thickness shear to be the reason for enhanced formability. Eyckens et al. [75] did an MK-type analysis and established that orientation dependent shear phenomenon can elevate the FLC. Fracture occurrence in SPIF is influenced by “through-the-thickness” shear and local deformation of the sheet in the vicinity of the tool, as described by Malhotra through finite element analysis [76], [77]. Xu et al. [78] conducted both experimental and numerical studies on aluminium AA5052-H32 sheet to explain the through-the-thickness shear phenomenon. Additionally, he compared the simulation of a cone having an angle of 70° by SPIF and deep drawing; the conclusion being that the concerned phenomenon is more relevant in SPIF. The phenomenon is given in Figure 11.

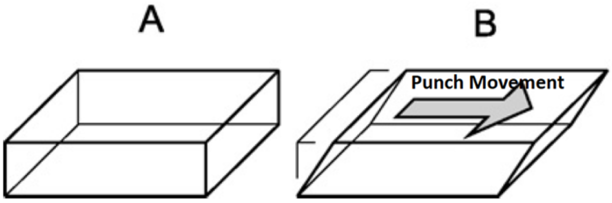


**Fig. 11.** (A) Initial sheet condition (B) Visualization of Through-thickness shear

Smith et al. [79] developed an analytical model that indicated an increase in FLC due to contact stress. Banabic and Soare [80] observed similar results through a MK-type analysis. Based on Smith's work, Huang et al. developed a direct relation between the presence of contact stress and enhanced formability [81]. High levels of contact stress was seen, but suitable derivations were not made [15], [82]. Silva et al. [83] explained about the reduction of tensile yield stress by contact stress through membrane analysis. He mentioned that bending of the material adjoining to punch causes contact stress. Martins et al. [71] achieved similar results based on the membrane analysis model. Bending-under-tension speaks of concurrent bending and stretching of a sheet, wherein stress state is unchanged. Sawada et al. [72] proposed about the mechanism on the basis of simulations. Emmens [84] also made a similar proposal based on the proportionality relation between formability and sheet thickness. Emmens and van den Boogaard [85] studied the mechanism and reported elongation up to 430% for mild steel. Bambach et al. [15] indicated that cyclic straining may have effect on material behaviour and stated the need for further investigations. Eyckens et al. [86] did a MK-type analysis on similar grounds and found an increase in formability. This mechanism required better analysis so as to establish its relevance for formability.

Martins et al. [71] put forward a theory taking membrane analysis and ductile damage mechanics into consideration. They suggested that fracture limits formability due to tensile meridional stresses that arise under stretching conditions. Similarly, Silva et al. [83] also gave a model that considers meridional tensile stresses as the initiators of cracks. Decultot et al. [87] showed that fracture occurs in uniaxial stretching area through experiments using a surface 3D digital image correlation approach. Fang et al. [88] gave an analytical model which suggested that deformations primarily occur in a meridional direction and to some extent in the circumferential direction. Fracture is also seen to occur in transition zones. Fracture forming limit diagram was established for accurate prediction of fracture in SPIF, as conventional FLCs are inapplicable [89-92].

During ISF, the sheet material undergoes complex deformation involving stretching, bending, and shearing. The distribution of strain across the sheet depends on factors such as tool geometry, feed rate, spindle speed, and material properties. Numerical simulation techniques, such as finite element analysis (FEA), help in predicting strain distributions and optimizing process parameters to achieve desired part geometries. Material flow in ISF is influenced by the interaction between the forming tool and the sheet surface. The tool applies localized forces that induce plastic deformation, causing the material to flow along the tool path. Controlling material flow is critical for achieving uniform thickness distribution and minimizing defects such as wrinkling and thinning.

## 4. Forming Methods

Single Point Incremental Forming (SPIF) and Two Point Incremental Forming (TPIF) are the basic diversifications of incremental sheet forming. Lot of work has been done with respect to SPIF and as such, many novelties have been conceptualized in order to enhance the process limits. Iseki [7] materialised the idea of using a high speed water jet for forming. It possesses the advantage of applying a uniformly distributed and customizable force on the sheet. Jurisevic also worked on the feasibility of water jet as a tool and presented the advantages and shortcomings. He also initiated a simulative study on the impact of a high velocity on a flat rigid surface [93-95]. However, the technology needs a detailed exploration.

Laser is an attractive option as a forming tool, especially where precision and accuracy is highly desirable. The bending of sheet occurs with respect to the resident stresses. Geiger inculcated the idea of laser forming into ISF [96-97]. Analysis and process effectiveness in relevance to industrial applications and achieving complex shapes was done by Hennige et al. [98]. Based on similar concept, Male et al. [99] proposed the use of plasma arc for forming. He cited that it incurs less cost than laser forming.

Yoon and Yang [100] manufactured sheet metal using a movable setup which involved multiple stages. They believed that deformation can be controlled by relating experimental parameters with the radius of curvature of the sheet. Additionally, FEM simulations were carried out along with the development of an equation to predict the radius of curvature. Meier et al. [101] introduced duplex incremental forming which talks about the use of dual motion forming tools positioned on both sides of the sheet to create superimposed pressure. This will help in achieving increased maximum draw angle, better surface quality and geometrical accuracy. An analytical model incorporating membrane analysis, incorporating bi-directional in-plane contact friction forces, was employed to systematically examine both quantitatively and qualitatively the crucial process parameters and their interrelations. Experiments depict an increase in maximum formability, minor increase in geometrical accuracy whereas surface roughness is dependent on different parameters.

Material formability increases with elevation of forming temperatures. This aspect was exploited by many researchers to develop new variants. Ji and Park [62] used hot air blowers to form magnesiumAZ31 sheets at different temperatures. Forming limit was observed to increase, but accurate control of forming temperature was difficult. Ambrogio et al. [102] formed the same material by placing a heater band on the external surface of the fixture. The process was not energy efficient as it did not focus on localised heating. Duflou et al. [60] achieved dynamic local heating by using a laser source which moves in synchronisation with the forming tool. Göttmann et al. [61], [103] implemented the same in both SPIF and TPIF using a coaxial rotating optics. Process costs are quite high for lasers. High rotational speeds can generate heat due to friction. It can be easily implemented without additional costs, however tool wear and ineffective control of forming temperature put it at disadvantage [57-58], [104]. The concept of electric hot incremental sheet forming was given by Fan et al. [63], who studied the effect of various process parameters on the formability of AZ31 magnesium. Ambrogio et al. [105] tested the formability of an aluminium alloy AA2024-T3, a magnesium alloy AZ31B-O and a titanium alloy Ti6Al4V. Microstructural observation showed diverse grain structure and the reason can be attributed to both electrical heating and induced strain. Adams and Jeswiet [65] said that proper current density range is essential to improve formability. Forming temperature can controlled by adjusting input current [103]. Improvement of accuracy and reduction of springback effects in E-ISF was approached by Van Sy and Nam[106]. Palumbo and Brandizzi [107] preheated the sheets using electricity and then utilized frictional effects to further elevate the temperature. Valoppi et al. [108] developed an electrical double-sided incremental forming to fabricate Ti6Al4V sheets wherein less forming force was required without any spark formation. It also lead to enhancement formability and geometric accuracy. while decreasing the forming force. Min et al. [109] formed advanced high strength steel (DP1000) using EISF and noticed reduced forming force. Forming temperatures are required to be controlled to obtain optimum results.

Taleb et al. [110] conceived the idea of combining ISF and stretch forming. Forming time is less and uniform thickness distribution is achieved. Cui et al. [111] developed an electromagnetic incremental forming where the punch is substituted for an electromagnetic coil that had no mechanical interaction with the formed sheet. Repulsive forces make the sheet to adapt the shape of the mould. Better surface quality and less forming time are the benefits. Ultrasonic vibration was implemented by Vahdati et al. [112] and Amini et al. [113] on aluminium sheets. Improved accuracy, better surface finish, higher formability and less forming forces were observed. Vanhove et al. [114] formed aluminium alloys in a cryogenic environment. There is no visible improvement in formability, however increase in hardness is noted. Wen et al. [115] conceptualised Multi-Directional Incremental Sheet Forming (MISF) which implements forming through means of cylindrical tools. Complex thin-walled parts which deviate from biaxial stretching are accomplished using this technique.

## 5. Forming Materials, Tools used and Tool Wear

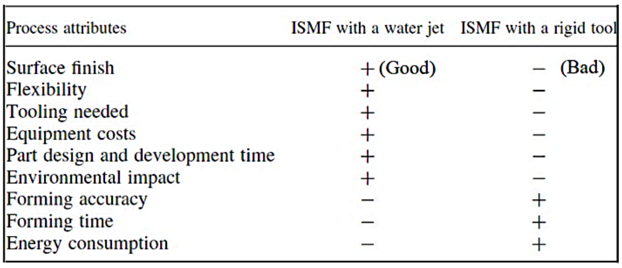
Table 1 briefly presents the investigated materials and tools. An array of materials such as aluminium, copper, stainless steel, titanium, alloys, and plastics are examined. These studies investigate how each material can be shaped through distinct tooling techniques, which include balls tools, punch sets, hemispherically-tipped instruments, spherical head tools, straight edge tools, along with several customized equipment. By exploring these unique combinations of materials and shaping methods, researchers aim to enhance their comprehension of substance performance during metalworking activities.

**Table 1**. Summary of materials and tools used

| Paper | Materials | Tools |
|---|---|---|
| Shim and Park [25] | AA1050-O | Ball tool |
| Yoon and Yang [100] | AA1050-O | Punch set |
| Matsubara [116] | Commercially Pure Aluminium | Hemispherical head tool |
| Kim and Park [26] | AA1050-O | Ball and Hemispherical head tool |
| Jeswiet et al. [30] | AA3003-O | Hemispherical head tool |
| Filice et al. [16] | AA1050-O | Hemispherical head tool |
| Iseki and Naganawa [117] | Aluminium | Spherical and Cylindrical rollers |
| Park and Kim [27] | Aluminium | Ball tool |
| Ceretti et al. [118] | Cu DHP and AISI 304 | Spherical head tool |
| Ambrogio et al. [119] | AA1050-O | Hemispherical head tool |
| Fratini et al. [29] | Copper, Brass. High speed steel, Deep drawing quality steel, AA1050-O, AA6114 T4 | Hemispherical head tool |
| Ambrogio et al. [120] | AA1050-O | Hemispherical head tool |
| Kopac and Kampus [121] | Aluminium | Rounded and Ball tool |
| Jeswiet and Young [18] | AA3003-0, AA5182-0, AA5754-0, A1011 steel | Hemispherical head tool |
| Jeswiet et al. [122] | AA3003-0 | Hemispherical head tool |
| Strano [51] | AA1050-O | Semi-spherical head tool |
| He et al. [123] | AA3003-0 | Spherical head tool |
| Duflou et al. [60] | AA5182 | Laser |
| Hussain et al. [66] | Aluminium | Hemispherical head tool |
| Ham and Jeswiet [39] | AA5754, AA5182, AA6451 | |
| Eyckens et al. [86] | AA3003-0 | Hemispherical head tool |
| Duflou et al. [124] | AA3003-0, AA3103-O | |
| Lasunon and Knight [125] | AA5052-H32 | |
| Allwood et al. [74] | AA 5251-H22 | ‘Paddle’ tool |
| He et al. [126] | DC01 carbon steel | Spherical head tool |
| Governale et al. [127] | AA6016 T4 | Semi-spherical head tool |
| Minutolo et al. [128] | AA7075-T0 | Hemispherical head tool |
| Maidagan et al. [129] | Stainless steel | |
| Silva et al. [130] | AA1050-H111 | |
| Ji and Park [62] | Magnesium AZ31 | Hemispherical head tool |
| Verbert et al. [131] | AA3003-O | Spherical head tool |
| Hussain et al. [132] | Commercially Pure Ti | Hemispherical head tool |
| Alves et al. [133] | AA1050-H111 | Hemispherical head tool |
| Skjoedt et al. [134] | AA1050-H111 | Semi-spherical head tool |
| Franzen et al. [53] | PVC | Spherical head tool |
| Petek et al. [43] | DC05 steel | Hemispherical head tool |
| Bambach et al. [135] | DC04 mild steel | |
| Martins et al. [32] | POM, PE, PA, PVC, PC | |
| Durante et al. [136] | AA 7075-T0 | Hemispherical head tool |

| | | |
|---|---|---|
| Fan et al. [137] | Ti-6Al-4V | Hemispherical head tool |
| Decultot et al. [87] | AA5086-H111 | Hemispherical head tool |
| Hussain et al. [49] | AA2024-O | |
| Cavaler et al. [138] | AISI 304L | Hemispherical head tool |
| Manco and Ambrogio [33] | AA6082-T6 | |
| Ziran et al. [48] | AA3003-O | Flat end and Hemispherical head tool |
| Bouffioux et al. [139] | AlMgSc alloy | |
| Dejardin et al. [140] | AA1050-O | Hemispherical head tool |
| Durante et al. [44] | AA7075T0 | Hemispherical head tool |
| Gottmann et al. [61] | Ti Grade 2, Ti-6Al-4V | Spherical head tool |
| Marques et al. [35] | PET, PA, PVC, PC | Hemispherical head tool |
| Palumbo and Brandizzi [107] | Ti-6Al-4V | |
| Ambrogio et al. [105] | AA2024-T3, AZ31B-O, Ti6Al4V | Hemispherical head tool |
| Malhotra et al. [77] | AA5052 | |
| Fiorentino et al. [141] | Ti Grade 2 | Spherical head tool |
| Xu et al. [78] | AA5052-H32 | Spherical head tool |
| Fritzen at al. [68] | Brass 70-30 | Semi-spherical head tool |
| Liu et al. [142] | AA7075-O | |
| Shanmuganatan and Senthil Kumar [36] | AA3003-O | Spherical head tool |
| Cawley et al. [143] | AA3003-O | Angle, Flat, Parabolic, Hemispherical tools |
| Daleffe et al.[144] | Titanium F67 grade 2 | Spherical head tool |
| Hussain et al. [41] | AA2024-O | |
| Buffa et al. [58] | AA1050-O, AA1050-H24, AA6082 | Hemispherical head tool |
| Xu et al. [57] | AA5052- H32 | Spherical head tool |
| Ambrogio et al. [145] | Ti Grade 2, Ti-6Al-4V | Hemispherical head tool |
| Bagudanch et al. [146] | AISI 304 | |
| Hmida et al. [147] | FPG Copper foil | |
| Golabi and Khazaali [37] | AISI304 | Hemispherical head tool |
| Adams and Jeswiet [65] | AA6061-T6 | Hemispherical head tool |
| Novakova et al. [148] | Ti Grade 2, Ti-15-3-3-3, Ti-6Al-4V | Ceramic wheel |
| Homola et al. [148] | Ti Grade 2, Ti-6Al-4V | Tungsten Carbide roller |
| Devarajan et al. [149] | AA2024-O, AA5083-H111, AA7075-O | Hemispherical head tool |
| Lu et al. [150] | AA1100, AA2024, AA5052, AA6111 | Oblique roller-ball tool |
| Kurra and Regalla [151] | Extra-deep drawing steel | Hemispherical head tool |
| Oleksik [152] | DC04 | Hemispherical head tool |
| Martínez-Romero et al.[153] | AISI 304 | Hemispherical head tool |
| Katajarinne et al. [154] | AISI 301 LN, AISI 316 L, AISI 304_1, AISI 304_2 | |
| Davarpanah et al.[59] | PLA, PVC | |
| Mohammadi et al. [155] | AA5182-O | Hemispherical head tool |
| Min et al. [109] | DP1000 | Semi-spherical head tool |
| Reddy [156] | Phosphorous Bronze alloy | |
| Al-Ghamdi and Hussain [50] | AA2024-O, AA2024-T6, AA1060-O, AA1060-H24, AA5083-O, Steel DS, Cu H59 | Hemispherical head tool |
| Centeno et al. [46] | AISI304 | Hemispherical head tool |
| Pereira Bastos et al. [157] | AA1050-H111, DP600, DP780, DP1000 | |

Echrif and Hrairi [158] compared water jet with rigid tools, the details of which are shown in Figure 12.



| Process attributes | ISMF with a water jet | ISMF with a rigid tool |
|---|---|---|
| Surface finish | + (Good) | − (Bad) |
| Flexibility | + | − |
| Tooling needed | + | − |
| Equipment costs | + | − |
| Part design and development time | + | − |
| Environmental impact | + | − |
| Forming accuracy | − | + |
| Forming time | − | + |
| Energy consumption | − | + |

**Fig. 12.** Comparsion between water jet ISF and tool based ISF.

Kim and Park [26] used straight groove test to show that roller ball tool gives better formability than stationary solid hemispherical tool. Similar observations were also recorded by Li et al. [54] and Lu et al. [150]. Durante et al. [44] however found no difference in formability when they made the same comparison in a VWACF (variable wall angle conical frustum) test. Ziran et al. [48] showed that lower forming forces, higher accuracy and formability can be achieved by using flat end tools in comparison to hemispherical end tool.

The lifespan of a tool plays a vital role in assessing the viability of any manufacturing method, and the movement of the forming tool across the secured metal sheet in ISMF markedly impacts tool deterioration. Oraon et al. discovered that reducing the step size (P = 0.021) and altering the thickness of the sheet metal (P = 0.005) have a notable impact on the wear experienced by 440C steel tools [159]. They also used image processing technique for tool wear prediction and found out that the maximum predicted tool wear was 0.0663 mm with an error of 0.0104 mm [160]. In incremental sheet forming, common factors contributing to tool wear encompass the friction between the tool and the forming sheet, tool rotation which enhances surface quality but also accelerates wear, the influence of tool size on defect occurrence and management in the forming procedure, and the plastic deformation of metal sheets executed by a basic forming tool. Moreover, variables such as step reduction, sheet metal thickness, and the material composition of the forming tool, such as 440C steel, play significant roles in determining tool wear within incremental sheet metal forming processes [161].

## 6. Forming Forces

Force measurement is essential in order to avoid any sudden tool/material failure. The design of CNC milling machines is such that, high forces perpendicular to spindle axis are not sustainable [162]. Due to lack of an inbuilt force measurement system, many authors have investigated analytical, semi-analytical, empirical and numerical approaches. Jeswiet et al. [122] measured the forces encountered during single point and two point incremental forming. The objective was to determine the capacity of the equipment suitable for the above processes and for the development of appropriate models. They used a cantilever type of sensor as shown in Figure 13.

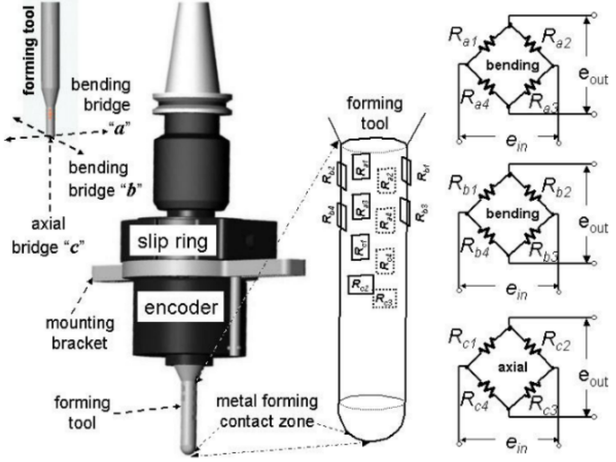


**Fig. 13.** Single Point Incremental Forming Sensor [122]

Duflou et al. [163] conducted experiments using a six-component force dynamometer and stated that vertical step size, tool diameter and wall angle affect the total forces on the forming tool. Increase in tool diameter increases the forces substantially. Petek et al. [43] noted that in ISF forming force was small as compared to the deep drawing process and it is independent of product size. The deformation and force distributions are generally reliant on the wall angle of forming, tool diameter and vertical step size.

Ambrogio et al. analysed the pattern of forming force to decide about the safety of the process and suggested strategies to avoid failure. The force applied during the forming process between the tool and the sheet was measured by a piezoelectric dynamometer situated beneath the sheet clamping frame. They said that using an online force monitoring system, the reasons for failure can be noted and thus effective process parameters can be built to achieve safer process conditions. Punch diameter reduction and Tool depth step change are the chief parameters which are modified for the above process. The authors state that the present strategy is beneficial when complex shapes are involved [47]. Filice et al. devised a monitoring and control system that will provide the process parameters during the operation of SPIF. The complete clamping setup was secured onto a Kistler piezoelectric dynamometer, connected to a data acquisition system through a charge amplifier for capturing the vertical component of the total force. Process parameters were systematically adjusted to observe the trends in tangential force, and a relevant statistical analysis was applied to illustrate the impact of experimental parameters on force trends. The tangential force gradient serves as an indicator for detecting process stability. Both the force peak and the gradient after the peak are closely associated with material failure. The system continually compares current values with critical ones, enabling the adjustment of process parameters to ensure the production of defect-free parts [164].

Aerens and his co-workers developed a force prediction model with an empirical equation that embodied important process parameters. The equation supplies a relation between the tensile strength of the material and the force in the axial direction [82], [165], [166], [167]. The model has been a part of study of many researchers who have conducted experiments to validate the same [168], [169]. This model holds no consideration for strain hardening and sheet anisotropy. Similarly, spindle speed which plays an important role in forming temperature and formability is avoided [107]. These factors cause a change in the forming forces leading inaccurate measurements. However, analytical model gives a quick estimate of the forces in comparison to finite analysis where the strain hardening is considered. Eyckens et al. [170] and Henrard et al. [171] carried out numerical simulation to predict forming forces in SPIF. They suggested the requirement of an accurate model based on Through-Thickness Shear (TTS) for estimating forces. Li et al. [172] considered the deformation modes of stretching, bending and shearing to propose a model for the tangential force. Figure 14 shows a force variation graph occurring in SPIF.

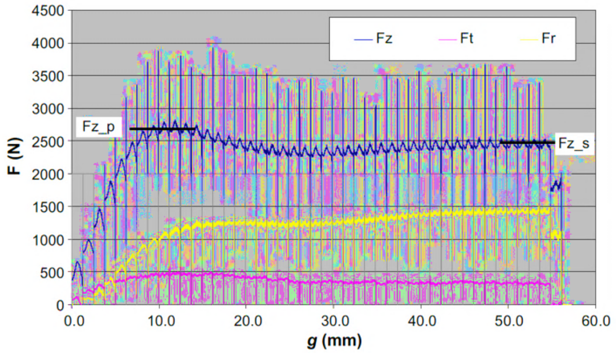


**Fig. 14.** Graph showing three components of force [165]

Contact forces between the forming tool and the sheet material are the primary contributors to forming forces. Friction between the tool and the sheet surface opposes the movement of the tool and affects the distribution of forming forces, hence the need for proper lubrication. As understood from the various works, bending and stretching of the sheet material contribute to the overall forming forces. Materials with higher strength require higher forming forces to induce plastic deformation. Most importantly, parameters such as feed rate, spindle speed, step size, and toolpath strategy influence the dynamics of forming forces.

## 7. Surface Quality

The quality of a formed surface is an assessment of its texture. It is referred to as the vertical deviation from its typical form. ISF utilizes parameters like average roughness ($R_a$) and maximum roughness ($R_z$) to evaluate roughness values. Surface roughness is dependent upon certain parameters e.g. tool rotation, forming tool, tool path, step size and forming angle, that has been investigated by many researchers.

Rotating tools give best surface finish at optimum speeds. Lower RPMs and static tools deteriorate the surface. Surface quality can be improved by decreasing the relative motion between tool and workpiece [173]. Silva et al. [174] analysed both tool rotation and step size. He found that higher speeds gave acceptable roughness with lesser time. Yamashita et al. [175] performed numerical analysis and observed that deeper products display less roughness due to a stronger stretching force delivered by the movement of the tool. Cerro et al. [176] on the basis on experimental and numerical work reported lower roughness values in the direction of tool advance but not in the vertical direction. Reducing axial step size can decrease roughness values as depicted in Figure 16. Durante et al. [136] mentioned that rotating tools present less surface roughness values in comparison to non-rotating tools as depicted in Figure 15.

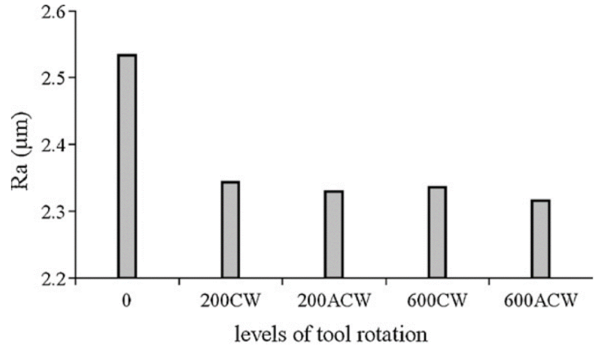


**Fig. 15.** Surface roughness measurements for various tool rotation configurations [136]

Hamilton and Jeswiet [177] studied the effects of forming at high feed rates and tool rotational speeds in SPIF. Higher step size causes more roughness. For thickness distribution, there is no adverse influence owing to higher forming speeds. One can aim to reduce forming duration by operating at high feed speeds without affecting the surface quality.

Tool size and material also influence surface finish. Ham et al. [178] compared the effects of two tools on surface quality. In comparison to the carbide tool, the acetal tool presented a consistent qualitative surface without any burnishing effect. Oleksik et al. [179] while working with titanium observed that roughness of the tool and tool-surface friction are more major parameters than tool diameter. The external surface remains unaffected during the process. However, Bhattacharya et al. [67] reported decrease in roughness values at all incremental depths with increase in tool diameter as shown in Figure 17. Lu et al. [150] stated that the use of an oblique roller ball tool leads to a superior surface finish. Low step size values give lesser roughness. This was confirmed by the work of Hagan and Jeswiet [173] who defined a relationship between incremental depth and peak-to-valley roughness. Attanasio et al. [180] noted a decrease in surface waviness with less step sizes. On the other hand, Bhattacharya et al. [67] noted an initial decline in surface quality with an increase in step size depth up to a specific angle, followed by an subsequent improvement.

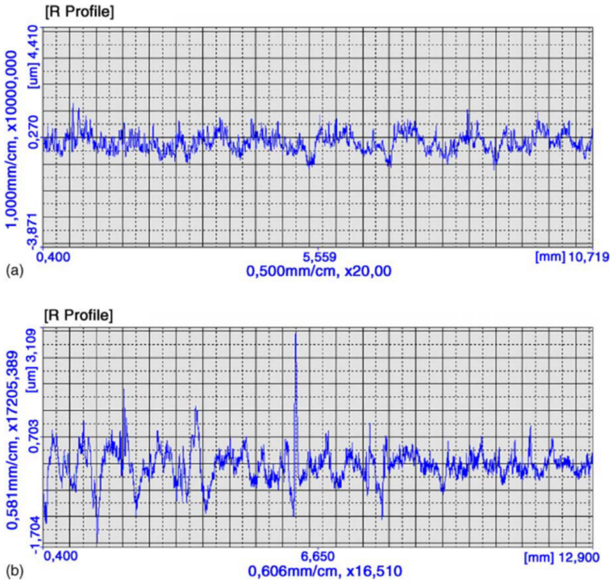


**Fig. 16.** Roughness graphs of: (a) forward tool direction; (b) perpendicular direction [176]

Bhattacharya et al. [67] pointed out that surface quality is directly dependent on wall angle. Change in forming angle cause more stretching which improves surface finish. Ambrogio et al. carried out hot forming of light weight alloys and observed more roughness at higher angles. Daleffe et al. [144] tested both external and internal roughness for a titanium sheet for 3 different angles. With increase in angles, the external roughness increases whereas internal roughness decreases. Cavaler et al. [138] investigated the surface roughness of components produced from AISI 304 austenitic stainless steel, utilizing various process conditions. The finishing roughness parameter Rz was measured, revealing that roughness is greater in the slipping region compared to the rolling region. Additionally, there was a reduction in roughness with an increase in vertical depth. Notably, coated tools and those with larger diameters exhibited lower roughness levels. Suresh et al. [181] estimated surface roughness using Artificial Neural Networks(ANN), Support Vector Regression (SVR) and Genetic Programming (GP) optimisation models. The results depicted a good prediction behaviour which was further utilised for experimental verification. Azevedo et al. [182] experimented on the use of lubricants in SPIF process with emphasis on aluminium and steel sheets. A wide range of lubricants were tested and roughness tests were carried put to measure surface quality. Lubricants showing good results for aluminium shows prove to detrimental in case of steel and vice versa. The harder the material, the lesser is the required viscidness. Greases generally provide a good finish but not as good as oils. Steels require higher process forces, but they offer better surface finish in comparison to aluminium components.

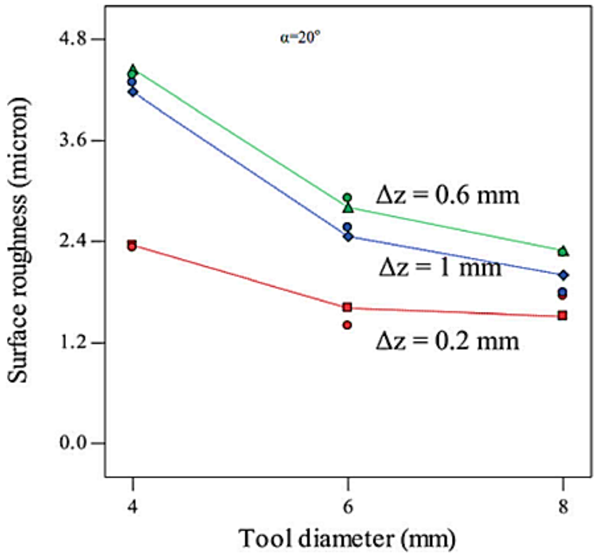


**Fig. 17.** Surface finish variation at different incremental depths [67]

## 8. Springback

Springback can be defined as the elastic recovery of sheet metal after the removal of forming forces. It causes deviations in the final shape. In ISF, owing to minor contact area between tool and sheet springback is not severe. Jeswiet et al. [183] classified springback in ISF into 3 types; a constant local springback which occurs at every step of tool movement, an overall springback that is evident after the material is released from all forces and a global springback after trimming.

Ambrogio et al. [119] carried out experiments on AA1050-O sheet specimens with variation in tool diameter and tool pitch to study the effect of springback. FEM was utilized to numerically the study the similar parameters of experiments. Moreover, the deformed geometry was determined through a laser-based scanning technique to highlight disparities between the actual part and the intended product. A comparison between the experimental and ideal geometry revealed variations, particularly at the intersection of the oblique walls and the major base of the pyramid, attributed to the lack of support. This issue can be addressed by introducing a proper counter-die at the edge. Distortion along the oblique walls arises from elastic springback, and mitigating errors is achievable by opting for a smaller punch diameter and a reduced tool path pitch. The speaker also suggested employing modified tool paths to circumvent springback effects and stiffness reduction. This modification involves adjusting the tool path at the current point based on the distance between the previous deformed point and the ideal one. Numerical analysis was conducted using an implicit model grounded in the static equilibrium equation [120]. Similarly, Dejardin et al. [140] utilised a well-defined toolpath for precise prediction of springback by using shell elements. Han et al. [184] developed a closed-loop algorithm by integrating wavelet transform with fast Fourier transform. This algorithm proved to be effective in predicting an optimal toolpath and reducing errors. Based on similar transforms, Fu et al. [185] developed an algorithm which took springback after unloading into account.

Oleksik et al. [186] while forming Cp Ti sheet observed that with increase in tool diameter and decrease in step size and sheet thickness, a rise in global springback value occurs. Vahdati et al. [187] suggested an analytical model demonstrating that springback diminishes with an increase in tool diameter, feed rate, spindle speed, and sheet thickness, while decreasing with a reduction in vertical step size. Junchao et al. [188] stated that springback increases in multistage forming. Wall angle had no role to play. Duflou et al. [60] mentioned that use of heat can help in reducing springback and stress levels.

It is essential to understand the elastic properties of the sheet material which is crucial for prediction and compensation for springback. Optimizing tool geometry can help in minimization of localized deformation and stress concentrations leading to lesser springback. Also, controlling material flow through toolpath optimization and process parameter adjustments can help mitigate springback effects. Heat treatment processes can also turn out to be effective in reducing springback.

## 9. Process Accuracy

Dimensional accuracy is a prime aspect for any manufactured product. Deviations are observed between CAD geometry and real product dimensions. Bramley reported accuracy values of ±1.5 mm for symmetrical and ±2 mm for asymmetrical parts. The use of a support plate can reduce the deviations which otherwise are observed to be higher [189]. Jeswiet et al. [183] state that ISF products have higher inaccuracies due to absence of a supporting die and stiffness of the machine. Other than equipment errors, springback, distortion due to stress are other factors for deviations. Ambrogio et al. [190] reported minimal deviation with the implementation of smaller tool diameter and pitch size. Duflou et al. [191] discovered that employing a double pass toolpath strategy, with an upward contour finishing pass, yielded the highest overall accuracy. Hirt et al. [192] suggested to use an iterative model and use real time data to build a corrective toolpath. The data will be based on difference of measured points between the actual geometry and target geometry. However, it is applicable only for small batches. Ambrogio et al. [120] designed a discrete point contact measurement system to calculate the deviations which are used to correct the toolpath. Finite element methods have been used mostly to predict dimensional accuracy. Long computation time is a major limitation [171], [193-195]. Guzmán et al. [196] performed numerical studies and linked accuracies to springback and elastic strains caused by structural elastic bending.

Enhancing accuracy is achievable through the implementation of various measures, including the use of flexible support, counter pressure, multipoint and back drawing incremental forming, and the utilization of optimized trajectories [197-198]. Bambach et al. [135] addressed the limitation of geometrical accuracy in asymmetric incremental sheet forming and proposed a solution involving a combination of multi-stage forming and stress-relief annealing before the trimming process to overcome this challenge. They have shown that multi-stage forming can yield a better accuracy than single-stage forming. Trimming of as-formed part can cause loss of accuracy, so stress relief annealing is done prior to it. Some authors have also suggested reprocessing or reverse finishing of planar shapes to improve accuracy. The process is however time consuming and lacks good surface quality [191], [199]. Rauch et al. [200] developed an online toolpath optimization methodology, although it lacks the capability to analyze depth accuracy and the overall structural accuracy.

Malhotra et al. [201] introduced an automatic spiral toolpath generation technique that considers geometric accuracy, forming time, and scallop height as input parameters. The methodology measures the formed scallop heights and compares them with the specified maximum permissible scallop heights. He also tested a mixed toolpath approach to prevent stepped feature generation in multi-SPIF and deliver a smooth product [202]. Laser assisted SPIF can produce stiff regions which minimizes interaction between different features to give higher accuracy [203-204]. A cognitive system built on iterative learning control was demonstrated by Fiorentino et al. [205]. Khan and others have promoted the concept of data mining and surface representation to understand springback [206-207]. However, these have not been utilised in real manufacturing processes.

## 10. Toolpath strategies

Toolpath is an essential way of defining the movement of a tool. The shape and features of the part, in addition to accuracy and processing time is largely dependent on the type of toolpath. Toolpath is generally classified into contour and spiral/helical types. Contour toolpath has fixed $\Delta z$ increments and leaves a mark during its movement which is not desirable [13-14]. Spiral toolpath has a continuous incremental descent which avoids any descent marks [16], [192]. Skjoedt et al. [208] proposed a helical toolpath suitable for any shape to nullify the limitations of contour toolpath. The mentioned toolpaths have represented in Figure 18. With respect to the direction of movement, we have unidirectional clockwise, unidirectional anticlockwise, and mixed/bidirectional suggested by Shankar [209] shown in Figure 19.

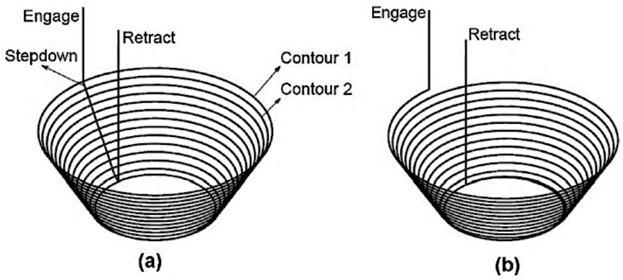


**Fig. 18.** (a) Contour toolpath (b) Helical toolpath

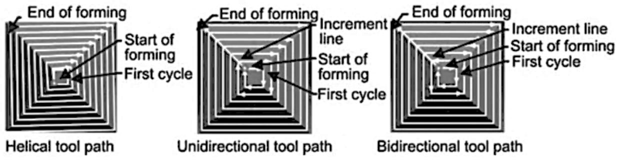


**Fig. 19.** Forming path strategies [209]

Bidirectional toolpath reduces the effect of twist and improves the accuracy. This toolpath was modified with distributed increments by Jadhav [210]. Kitazawa [211] started the concept of multistage forming and compared different strategies by analysing the formed components. Junk et al. [212] used trial and error approach to optimise a multistage strategy for producing a rectangular pyramidal frustum with right wall angles using TPIF. Hirt et al. noticed that the previous strategy is time consuming and thus suggested modifications based on bending and stretch deformation [213]. Kim and Yang [24] formulated a double – pass forming method to achieve a more uniform thickness strain distribution. Giardini et al. [214] in his methodology preformed the material with a tool of larger diameter and used a smaller tool to complete the final steps.

Dai et al. [215] proposed to increase the degree of evenness of deformation through optimization of forming locus. Optimization of forming locus is done by loading the area of small stiffness and minor deformation and simultaneously easing the area of large stiffness and major deformation. In addition, the system of forming of the particles is interchanged. They stated that an even strain distribution can be obtained by careful balance of tool motion between areas of varying stiffness. Strain distribution is also dependent on toolpath direction [134]. Verbert et al. [131] dealt with the multi-step approach and found that material relocation is the answer to obtain higher wall angles. They found that the approach led to shifting of material from bottom. There is significant decrease in radial strains but tangential strains are on rise. Bambach et al. [216] defined several strategies to evaluate thickness distribution. Two strategies were meant for z-movement and another two for in-plane movement. FEM was used with different optimization algorithms which identified genetic algorithm as a better approach. Yamashita et al. [175] also studied various toolpaths and their effects on deformation behaviour through numerical simulations.

Attanasio et al. [180] combined response surface method (RSM) and sequential quadratic programming (SQP) algorithm with finite element analysis (FEA) to formulate an optimal strategy. They noted that a toolpath with a variable step depth produced superior results. Rauch et al. [200] used real time process data and specific constraints to make the process effective. Li et al. [217] introduced a finite element model (FEM) to assess the thickness distribution and mechanical properties of a truncated pyramid. The toolpath proposed by the authors included incorporating displacement constraints, mirroring the actual process. Their findings indicated that a spiral trajectory, coupled with an appropriate step depth and a larger tool diameter, resulted in a more uniform thickness distribution. Azaouzi and Lebaal [218] have discussed about optimizing the toolpath in order to cut processing time and regulate thickness distribution of an asymmetric part. The idea revolves around dual utility of RSM and SQP in FEA, aided by Kriging interpolation that delivers an optimal tool path after 27 iterations at a faster rate. Ambrogio et al. [219] utilized a combined approach involving a numerical procedure and the Taguchi method to optimize the tool trajectory with the ultimate goal of minimizing maximum thinning. They presented an optimization model based on the "Decremental Slope" concept, which involves applying over-bending in areas where the sheet is typically less stretched [220].

Paniti and Somlo [221] discussed about two-sided ISF (TSISF) variants, the tool-path essentials which also involves a new process methodology. They created a device based on TSISF that has a pronounced accuracy of products through stable and consistent guiding of the forming tools. Malhotra et al. [201] developed a methodology wherein 3D spiral toolpaths can be automatically generated. There exist certain constraints on preferred geometric accuracy and maximum specified scallop height, but the forming time is expected to decrease. Suresh et al. [222] used CAM software to generate the required toolpath for simulations from the NC part program. They experimented with various geometries and found satisfactory results.

Behera et al. [223] used an optimisation technique known as Multivariate Adaptive Regression Splines (MARS) to produce continuous error response surfaces for individual features and feature combinations. The tool possesses the ability to limit the deviations which help in improving the accuracy of the toolpaths. Response surfaces are projected based on data collected from training sets, which aid in designing compensated tool paths. Malhotra et al. [202] explored the mechanism responsible for creating stepped features in Multi-Pass Single Point Incremental Forming. The accurate prediction of stepped features demanded a combination of analytical and experimental operations. The outcomes facilitated the development of a toolpath strategy aimed at preventing the generation of stepped features. Subsequent experiments demonstrated that the proposed strategy resulted in a smoother component base. Asghar et al. [224] worked on minimization of dimensional deviations using an analytical model. The predicted values of the model were used for defining the toolpath. Experimental results provide a satisfactory note on the used methodology.

## 11. Numerical approaches and Simulation

The deformation behaviour exhibited by ISF is cyclic and localised. Due to constant change in tool-sheet contact area, there exists high nonlinearities. Additionally, material behaviour is not constant throughout and the presence of non-monotonic strain paths make finite element analysis (FEA) a complex and time consuming process [86], [225]. Accurate prediction is essential to ensure feasibility of operation and safe use of equipment. Sine law has a simplistic approach and it can give thickness distribution. Kim and Yang [24] considered the use of a triangular mesh with the assumption that deformation occurs by shear to formulate the deformation mechanism. Iseki [226] suggested an approximate deformation analysis utilizing a plane strain deformation model. In the finite element method (FEM) calculations, the approximations involved treating the ball roller as a hemispherical tool with zero friction. Also, it is assumed that the sheet material follows von Mises criterion and $J_2$ theory of plasticity. Ambrogio et al. [120] carried out numerical simulation using experimental data based on an implicit model. The optimised trajectory was tested to validate its suitability. Bambach et al. [227] attempted modelling of non-conventional ISF strategies through FEM. The authors have proposed optimization methods to counter limitations such as sheet thinning and geometrical accuracy. They aimed at optimizing the tool path to facilitate the production of steep angles and to reduce geometric deviations. Ceretti et al. [118] used a bidimensional plane strain model to estimate the loads acting on the punch. Hirt et al. [192] used FEM to predict the sheet thickness distribution for the forming of tailor rolled blanks and the influence of process parameters on the limit strains using a damage model. Lievers et al. [228] conducted finite element method (FEM) analysis employing Gurson–Tvergaard–Needleman (GTN) constitutive softening equations, calibrated based on experimentally measured changes in material density. The analysis resulted in the creation of large regions of homogeneous deformation, contributing to a deeper understanding of the significance of void nucleation in determining forming limits. Bambach et al. [229] utilised three constitutive laws (i) von-Mises plasticity with isotropic hardening, (ii) von-Mises plasticity with combined isotropic and kinematic hardening and (iii) Hill’48 plasticity with isotropic hardening. Mixed hardening law gave more accurate results, however kinematic hardening is required for better prediction of geometry. Hussain et al. [230] carried out FE analysis for better understanding of forming defects. It was seen that defects occur due to undue stresses in the tool/blank contact and in the bottom of part. Stress ratio is an important parameter to control defects. Yue et al. [231] conducted a simulation study employing an extended fully coupled ductile damage model that incorporates mixed isotropic and kinematic nonlinear hardening fully coupled with isotropic ductile damage. This model also incorporates distortional hardening, enhancing its capacity to model metallic material behaviour under complex loading paths.

Simulation algorithms have been configured into explicit and implicit schemes. Explicit codes take longer computation time if springback is involved. Implicit methods provide better accuracy but at the cost of time. Explicit methods deliver reasonable accuracy with time that allows the provision of optimisation. Wong et al. [232] compared different formulations in terms of efficiency. They pointed out that explicit code in FE gives better results compared to implicit code. Different aspects of ISF was numerically investigated with a comparison between experimental and simulation results. ABAQUS and Lagamine were used to ascertain the final geometry, thickness distribution of the product, strain history, strain distribution during deformation, and reaction forces. FEM results revealed an elongation-type deformation in the radial direction, compression in the thickness direction, and a form of bending and unbending behaviour in the circumferential direction [123], [195], [233]. Henrard et al. [234] constructed a finite element method (FEM) model utilizing a dynamic explicit time integration scheme. The model is grounded in the utilization of the actual contact location instead of fixed positions. It carries the advantage of incorporating bigger elements or coarser mesh. The algorithm delivers accurate geometrical results, but is slower than the classic implicit algorithm. Eyckens et al. [82] utilised a standard implicit code in a sub-modelling strategy as an improvement. However, they used a simple constitutive model and finer mesh size to obtain accurate force values. Yamashita et al. [175] used a dynamic explicit finite element code to study the effect of various toolpaths on deformation behaviour. Forces and strain distribution were effectively predicted. They found out that smoother surface is obtained where sheet is subjected to stronger stretching force. Movement of tool in spiral manner helps in obtaining more uniform thickness distribution in the product.

Sena et al. [235] performed implicit based solid and solid-shell FE analysis including a comparison between various types of FE simulations. They also tried to study the impact of assigning different layers in thickness direction on simulation results. They showed that their proposed logic of RESS finite element gives better results. Malhotra et al. [236] have considered the use of solid continuum elements combined with the implicit method for numerical simulation of SPIF process. The effects of the yield criterion, element size, and element type on the predicted forming force were examined. Additionally, a new damage model was proposed for use in finite element method (FEM) simulations to predict the force curve, fracture location, and maximum thinning. Solid elements are able to give better thickness predictions but the force predictions are not reasonable. Isotropic yield criterion gives better accuracy than anisotropic yield criterion. Ayed et al. [237] presented a simplified numerical methodology for accurate analysis of ISF process and reduce computational time. Constitutive equations and tool-sheet contact factors were assumed. They utilised a shell element DKT12 in their calculations that significantly reduced time and gave better results. Upon comparison with experimental values, a good correlation was noticed. Li et al. [172] used fine solid elements for modelling and analysed the deformation behaviour. The outputs were crucial in designing an analytical model, which takes into account various deformation modes. Experimental study of forming forces depict a correlation with numerical results. Furthermore, the model is processed with complex geometries to note its effectiveness.

Robert et al. [238] introduced elasto-plastic material behaviour for computation which involves flow rule theory of plasticity and incremental strain method. Ma and Mo [239] highlighted the challenge in employing a symmetrical model for numerical simulations of ISF due to the absence of symmetric load and geometry conditions, leading to suboptimal results. To address this, they utilized brick elements to construct a simplified model, which was then employed to simulate the SPIF process under various parameters, allowing for the study of incremental forming principles. Ambrogio et al. [240] devised a FE model for analysing complex geometries having variable wall inclination angle which is compared with experimental findings. Their conclusion emphasized that despite ISF exhibiting localized deformation, the formation of the product is not contingent on process conditions or material properties. Rather, the behaviour of the sheet is directly influenced by the 3D profile. Han and Mo [241] adopted a 3D elasto-plastic finite element model to analyse ISF process. The influence of various parameters was discussed and it was observed that they maintain similarity with experimental values. Nguyen et al. [242] suggested an amalgamation of CAM and FEM to accomplish forming of complex shapes. CAM and CAE was used to generate an input file by processing it through MATLAB. Taguchi method was inculcated to improve the process parameters. Subsequently, simulations were run as per Taguchi orthogonal array in ABAQUS to identify the best combination of parameters for achieving better formability.

Thibaud et al. [243] developed a numerical methodology to simulate micro-shapes and forming of thin sheets. The methodology is in a form a toolbox, which not only allows numerical simulations but also helps in comparison with experimental data. The process yielded significant success in forming small parts with less thickness. Gómez-López et al. [244] attempted numerical simulation of Single Point Incremental Forming (SPIF) process using SOLIDWORKS software. They convincingly demonstrated that the mentioned software can be utilized for accurately defining process variables and material properties, particularly in terms of plastic behaviour. Mirnia et al. [245] proposed a modelling technique employing sequential limit analysis, demonstrating its ability to predict thickness distribution more efficiently than an equivalent finite element model. The model was then applied to assess the influence of various deformation paths on thickness distribution. Suresh and Regalla [246] investigated the outcome of element size and adaptive re-meshing technique in FE simulation. They minimized the computational time without compromising the accuracy. Naranjo et al. [247] carried out simulation of SPIF process in ANSYS environment. Simulation results are governed by mesh element size and therefore smaller values are preferred.

Suresh and Regalla [151] have performed FE analysis of extra deep drawing steel. Designed conical and pyramidal geometries with varying wall angles, incorporating circular, elliptical, parabolic, and exponential generatrices. The principal strain values obtained from numerical simulations indicate that conical frustums deform under plane strain conditions, while pyramidal frustums experience bi-axial stretching. Senthil and Gnanavelbabu [248] numerically studied AZ61A magnesium alloy as a part of numerical simulation. The obtained results provide significant insights into workpiece deformation and strain distribution. The models effectively identified areas in the workpiece that would undergo thinning. Ambrogio et al. [249] designed a FEM model to predict material behaviour during a high speed process using a thermomechanical model by confirming substantially experimental evidence. The ability of the numerical tool to obtain convergence at the expense of time without mass scaling has been showcased, however lesser time can be achieved by including mass scaling factor which makes the analysis complex. Sebastiani et al. [250] proposed a decoupling algorithm which separates deformation zones. They are analysed alternately in stepwise manner where results of one model supplies data for another. This saves computational costs. Similarly, Hadoush and Boogaard [194], [251] formulated a substructuring method which inculcates implicit code. FE mesh is differentiated into various areas. They considered using Newton’s method owing to strong linearity in the undeformed parts of the sheet. However, the same method is not suitable in case of a large elastic deformation part. Figure 20 derives a comparison of experimental and numerical predictions.

Investigators involved in this field should dedicate efforts towards optimizing multiple factors related to production procedures, including but not limited to: feed pace, rotation velocity, tool movement plans, and lubricant approaches. Tailoring material properties and microstructures to improve formability and reducing springback can be a focus. Moreover, exploring unconventional materials like lightweight alloys and high-strength steels for ISF applications needs more attention. Material models which can accurately predict material response, including strain hardening, anisotropy, and temperature effects, under dynamic loading conditions are needed. New tool designs geared towards increasing operational effectiveness, product excellence, and tool durability similar to multipoint forming instruments, flexible tooling configurations, and ingeniously devised toolpath schemes can be explored. Also, the use of coatings and surface modifications can be exercised since they enhance wear resistance and prolong tool lifespan. Integration of ISF with other manufacturing processes can further help in generating intricate shapes while achieving enhanced precision and superior surface texture. Also, automation of ISF processes through robotic systems and machine learning algorithms can enhance productivity, repeatability, and flexibility.

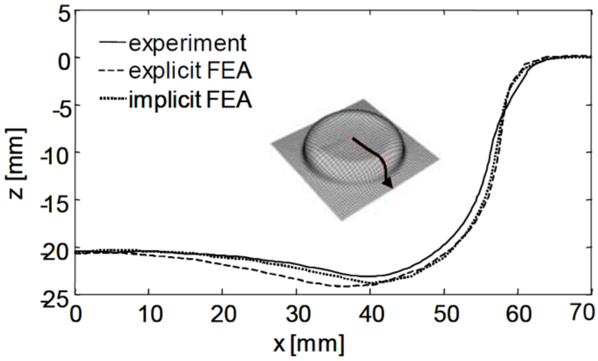


**Fig. 20.** Comparative plot of experimental and FEA results [227]

## 12. Conclusion

Incremental sheet forming (ISF) emerges as a transformative approach for achieving rapid and cost-effective manufacturing of intricate designs. Despite substantial progress in this field, certain challenges persist. Notably, the time factor stands out as a significant bottleneck, wherein the quest for improved accuracy and quality shares equal importance. This detailed overview aims to shed light on the intricacies of the incremental sheet forming process, emphasizing the pivotal role of formability.

Efforts to enhance ISF include the incorporation of a multistep strategy, utilization of heat-supported techniques, and the meticulous control of various process parameters. Recognizing the critical nature of accurate failure prediction, there is a concurrent emphasis on the development of hybrid processes. Optimized toolpaths have proven effective in reducing forces, although the demand for improved algorithms for swift force analysis remains a priority.

A range of multiple toolpath strategies has been devised to facilitate efficient forming, with certain adaptations specifically addressing the springback effect. From an accuracy standpoint, the pursuit of models capable of handling real-time data is advocated, enabling immediate rectification during the forming process. Accuracy and precision are fundamental to delivering a high-quality product, prompting advancements such as feature-based compensation, regression tools, and matrix-based predictions.

To expand the limits of the ISF process, considerations involve the integration of stiffness elements in calculations, coupled with error-correcting functions. Despite the progress, simulation tools are yet to achieve substantial predictive abilities, with simple shapes being easier to predict than more complex geometries, which demand more time for accurate predictions. Constitutive laws can be tailored to achieve better results, and tools must possess the versatility to simulate a diverse array of process parameters. As ISF evolves, accommodating new variants requires a profound understanding to achieve the desired outcomes. The existence of various modes of deformation and failure underscores the need for a unified model. Notably, the interplay between formability and wall angle is contingent on numerous factors, emphasizing the importance of establishing a nuanced relationship between these parameters for successful incremental sheet forming.

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