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POSSIBILITIES OF APPLICATION OF INCREMENTAL SHEET-FORMING TECHNIQUE IN AIRCRAFT INDUSTRY

The article includes the characteristics of incremental forming of the sheet using the following two methods: Single Point Incremental Forming and Two Point Incremental Forming. The factors influencing the possibility of method application and the phenomena that limit the use of incremental forming of the sheet are presented. Based on the conducted experimental test, the disadvantages and advantages of single point incremental forming are specified. Possibilities for the use of the presented incremental forming technique for manufacturing elements in the aircraft industry are also included.

Keywords: aerospace industry, incremental forming, sheet metal forming

1. Introduction

Sheet metal forming is one of the most popular methods of obtaining finished products. Conventional methods of sheet forming are carried out at different temperatures, using stamping dies, usually on mechanical or hydraulic presses. The forming conditions depend on the temperature of the process in relation to the melting temperature of the metal. Cold forming is realized at temperature $T < 0.35\ T_m$, whereas hot forming is realized at $T > 0.55\ T_m$. To avoid high temperatures and forces, warm forming ($0.35\ T_m < T < 0.55\ T_m$) is used, which allows recovery but not recrystallization. In comparison to hot forming processes, warm forming requires higher forces because of the greater material yield stress [1]. During deep

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drawing, the yield strength of the sheet material is reached and the sheet metal is pulled through the punch into the die opening. The increase in the strength of the drawpiece is related to the strain hardening of the sheet material. In the case of drawing the drawpieces with complex geometry, the local strain and stress state change during the forming process. Furthermore, during the sheet metal forming processes there are areas of the workpiece in which the stress state, strain state, displacement speed, and friction conditions are different.

The occurrence of varied strain states is due to the influence of tools and technological factors that change the friction conditions. The correct selection of process parameters results in obtaining products with the desired shape and dimensional accuracy. The need to produce special tools adapted to the shape of the drawpiece, even in the case of manufacturing a series of elements types, is a disadvantage of conventional sheet metal forming processes. The high cost of stamping tools is related to the high degree of shape complexity of the dies that require the usage of precision machine tools and expensive tool materials. Therefore, the use of conventional deep drawing methods is suitable for medium- and large-scale production (Fig. 1). Incremental sheet forming ISF is typically cost-effective for 300–600 pieces [2].

However, the use of incremental forming (IF) methods is economically justified in piece and small-lot production [3]. Despite the low cost of the tools, incremental forming methods are cost-effective in small-lot production owing to the long forming time with respect to conventional extrusion time.

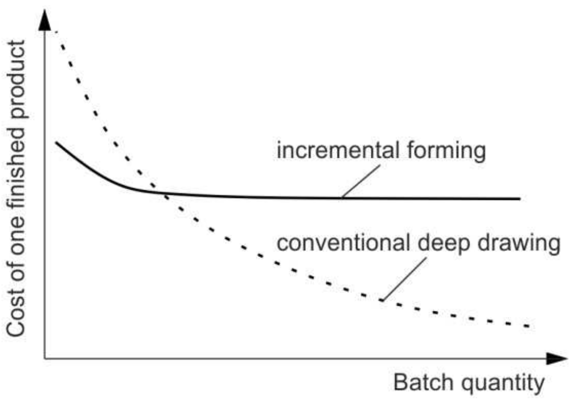

Fig. 1. Effect of batch quantity on cost of one product

In this paper the characteristics of the Single Point Incremental Forming (SPIF) and the Two Point Incremental Forming (TPIF) processes are presented. Furthermore, the factors influencing the possibilities for SPIF and TPIF application, and phenomena that limit the use of incremental forming of the sheet are presented.

2. Characterization of incremental forming

In order to reduce the set-up time of the element manufacturing and reduce the cost of production in piece and small-lot production, incremental sheet forming (ISF) methods have been developed. Initially, the SPIF methodology was based on conventional spinning, resulting in axisymmetric products. The widespread introduction of CNC machines allowed the development of spinning methods for the production of asymmetric elements [4]. The basis for the development of the incremental forming method is the patent developed by Leszak [5] in 1967.

SPIF methods have been used to make complex shell elements with a complex shape [5], and for rapid modelling of prototypes [6]. Application of the integrated CAD/CAM systems allows efficient design tool trajectories on a CNC machine, based on a CAD model of the drawpiece.

Despite the economically unreasonable application of the SPIF method for large-lot production, it is used to manufacture elements which cannot be obtained using conventional sheet-forming methods. Figure 2 presents the relationship between the number of parts and component size serviceable by ISF for typical industrial applications. The application of ISF in the aircraft industry is well suited when the number of parts does not exceed approximately 100 [2].

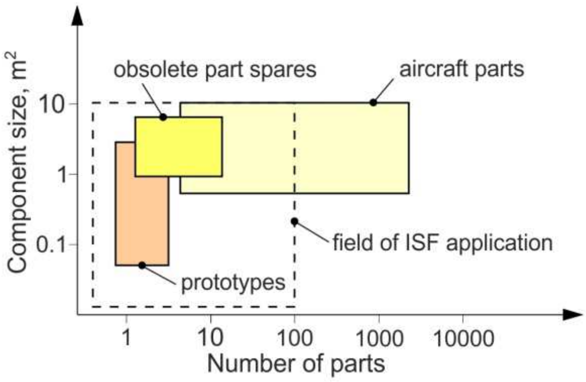

Fig. 2. Fields of application of ISF (prepared on basis of [2])

Regardless of the shape of the product, most of the incremental forming processes are conducted with a rounded tool, which is in direct contact with the sheet. The dimensions of the forming tool tip depend on the radius of the edge rounding of the drawpiece.

Among the many factors influencing the applicability of the SPIF methods, and the accuracy of the forming, the most important are:

– technological parameters (i.e. tool diameter, depth value between the two tool passages, tool rotational speed, friction conditions),
– material properties of the workpiece (ability for strain hardening, material anisotropy, Young’s modulus),
– design parameters (sheet thickness, geometry of the product).

3. Methods of incremental forming

Single point incremental forming (Fig. 3a) is a two point incremental forming, which can be conducted using a partial die (Fig. 3b) [7], or a specific die (Fig. 3c) [8]. The latter increases the geometric accuracy of the formed elements. In TPIF methods (Fig. 3b,c), there is an additional movement of the fixing grip of plate, which increases the accuracy of the obtained drawpieces [7].

In incremental forming with counter tool (IFWCT), an additional forming tool located opposite the forming tool moves according to the adjusted trajectory of the main tool (Fig. 3d). Among the mentioned methods, TPIF using the specific die is called positive incremental forming (PIF), whereas the other methods are known as negative incremental forming (NIF). One of the variants of SPIF is Water Jet Incremental Sheet Metal Forming (WJISMF), in which the frictional metallic contact of the forming tool with the workpiece is eliminated. In the case of WJSPIF, the available force of the tool (a high-velocity water jet) is defined mainly by the water pressure and the diameter and type of the nozzle. Petek et al. [9] concluded that SPIF is more appropriate in cases of bigger wall angles and smaller horizontal steps, whereas WJSPIF performs better for larger horizontal steps and smaller wall angles.

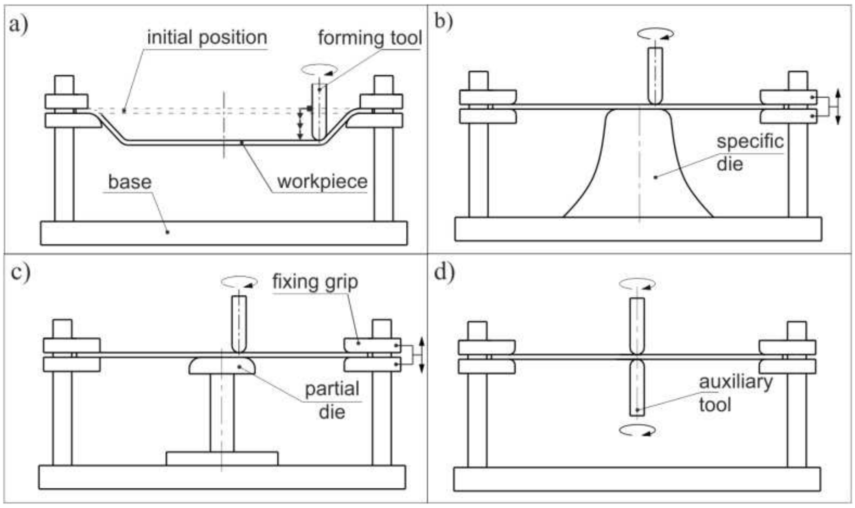

Fig. 3. Incremental forming processes: a) single point incremental punching, b) two point incremental punching with specific die, c) two point incremental forming with partial die, d) two point incremental forming with counter tool

4. ISF in aerospace applications

The application of lightweight components is a challenge in modern transportation engineering. Mass reduction of aircrafts is necessary for ecological and economic reasons, as well as to improve product properties [10]. Aerospace components are composed of lightweight materials such as titanium magnesium, and aluminium alloys.

To form hard-to-form materials at ambient temperature, especially magnesium and titanium alloys, hot incremental forming has been developed [11]. Incremental forming can be considered an alternative to the hot stamping of lightweight alloys. Magnesium alloys require a forming temperature higher than room temperature and are usually worked at a temperature ranging between 200 and 300°C. These temperatures permit the activation of new sliding planes, and dramatically increase material formability. As shown by Ambrogio et al. [12], maximum formability of AZ31magnesium alloy occurs at 250°C. AZ31 magnesium alloy and TiAl2Mn1.5 titanium, having low formability at room temperature, were successfully formed by Fan et al. [11]. They found that an increase in the electric current can increase the temperature and formability of hard-to-form sheet metals. In contrast, an increase in feed rate, tool diameter, or step size can decrease the temperature and formability.

Titanium is utilized extensively in the aircraft industry owing to its better strength-to-weight ratio compared to steel and aluminium, and high strength at elevated temperatures. The main titanium parts in aircraft are elements formed in bending process; i.e. stringers and ribs. Titanium is the main material used for manufacturing the engine of the Airbus A330 [13]. High temperatures in the contact area (up to 700°C for TiAl2Mn1.5 alloy) requires the use of forming tool made of YG8 titanium carbide.

Among aluminium alloys, AA2024-T3 alloy is typically used in the aircraft industry owing to its high formability and high fatigue. AA2024-T3 is difficult to weld by fusion techniques, but some investigations [e.g., 14] indicated that friction stir welding can be used successfully for safety welding. Hussain et al. [15] investigated the formability of annealed and presaged AA2024 alloy in the SPIF process. They found that the interaction of feed pitch and tool radius is very significant for the formability. It was also noticed that a variation in the forming speed does not affect the formability of the annealed AA-2024 sheet. Furthermore, an increase in forming speed decreases the formability of a pre-aged AA-2024 alloy sheet. Three lightweight alloys, typically utilized in the aircraft sector – i.e. aluminium AA2024-T3, magnesium AZ31B-O and titanium Ti6Al4V alloy – were studied using SPIF, by supplying a continuous current in order to generate local heating [10]. It was found that local heating of the sheet and induced strain lead to changes in the microstructure. The different grain distributions are directly dependent on the material properties [10]. However, the

AA7075-T0 aluminium alloy can be successfully formed using SPIF at room temperature [16].

5. Technological parameters of SPIF

In the single point incremental forming process, a forming tool with a rounded shape gradually forms the sheet by performing an integrated movement around the blocked edge of the shaped object. A sheet is placed in the tooling, and is clamped at the edges. Then a tool moves following the required shape in space under CNC control, using a succession of „planar" contours or a single „spiral" contour, so that the part is obtained as the result of accumulated, localized, plastic deformations [17]. In the next stage, these movements are repeated until the desired shape of the element is obtained (Fig. 4).

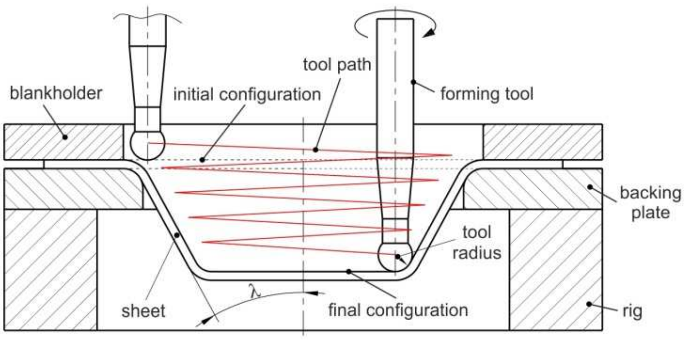

Fig. 4. Schematic of single point incremental forming

The essence of the process is to form the element by the integration of two tool movements: the horizontal one along the closed trajectory; and the inward transition to the next horizontal forming path. Therefore it is necessary to use a CNC machine controlled on at least three axes. In SPIF and TPIF processes there is local contact of the forming tool with the sheet. So, the degree of sheet deformation in the areas exposed to excessive forming limit strains can be controlled. The rotational speed of the tool can reach up to 20,000 rpm [18]. However, in most SPIF methods, the rotational speed of the forming tool with a rounded tip is in the range of 200 to 800 rpm. The rotational speed, as well as the linear motion of the forming tool, depend on the geometry of the drawpiece and the technological characteristics of the process, and are usually in the range of 300-2000 $mm \cdot min^{-1}$ [11, 19]. Parallel investigations have also been conducted on the use of a free-rotating [19] or non-rotatable tool [18].

Lubricants used in SPIF correspond to those used in conventional sheet forming and are adjusted mainly according to the pressure values, the material of the friction pair and the speed of the forming tool. The phenomenon that limits the formation of titanium sheets used in the aerospace industry by SPIF is the adhesion of titanium particles to the tool surface, which intensifies the worsening of the sheet metal's surface quality. Forming commercially pure titanium sheets requires the use of Molybdenum Disulphide (MoS_2) powder and white petroleum jelly mixed in proportion of 4:1, and a high-speed steel tool with a hardness of 62-65 HRC [20]. The results of investigations by De Bruyn and Treurnicht [21] show that MoS_2 exhibits favourable characteristics for the SPIF process, as the mean surface roughness for this lubrication strategy is the lowest. In the case of forming aluminium alloy sheets, the optimum condition for achieving high deformation levels of the sheet and high-quality drawpiece surfaces is the use of a high-speed steel mandrel without lubrication [22].

Higher tool rotational speeds allow increased plastic deformations of the sheet and are used to form thin sheets or foils with limited ability to plastic deformation. The size of the tool tip is determined by the shape and minimum radius of the rounding of the drawpiece edge. An increase in the size of the tool tip increases the contact area between the tool and the sheet [19].

6. Experimental tests of SPIF

Pilot-phase experimental investigations to form conical drawpieces (Fig. 5) were carried out on a 3-axis HAAS TM1P milling machine. The slope angle of a truncated cone was 45°, and drawpiece height was equal to 20 mm. 2024-T3 precipitation hardenable aluminium alloy sheets with a thickness of 0.4 mm were used for the fabrication of drawpieces. The mechanical properties of the used sheets determined in the uniaxial tensile test are as follow: yield stress $R_{p0.2}$ = 302 MPa, ultimate tensile strength R_m = 449 MPa, Young's modulus 72.85 GPa and Poisson ratio ν = 0.33. The edge of the workpieces was fixed using a blankholder. The tests were conducted on hard-to-form material under cold forming conditions. The tool with a rounded tip with a radius r = 3.5 mm (see Fig. 6) was made of high-speed steel. The clamping of the tool in a head of the machine was realized through the „ER" collet system, developed and patented by Rego-Fix in 1973, which allowed the tools to be mounted with a cylindrical shank.

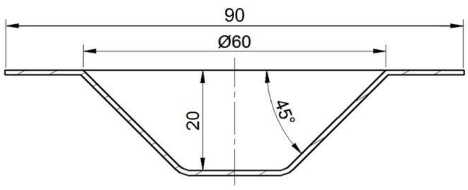

Fig. 5. Profile of drawpiece

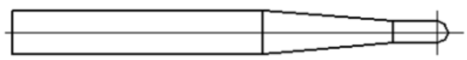

Fig. 6. Forming tool used in SPIF

The extruded model was designed using the INVENTOR system, as well as the processing technology and EDGECAM program based on the geometric model. The result of the processing stage of the CNC code evaluation is shown in Fig. 7. After the control program was created, the forming device and the tool (Fig. 8) were mounted on the HAAS TM1P 3-axis milling machine. Then, the control program created in the simulation mode was validated in the test mode. During machining, the following processing conditions were applied: feed rate f = 800 mm·min^{-1}, the tool rotational speed n = 37 rpm and the feed pitch a_p = 0.3 mm.

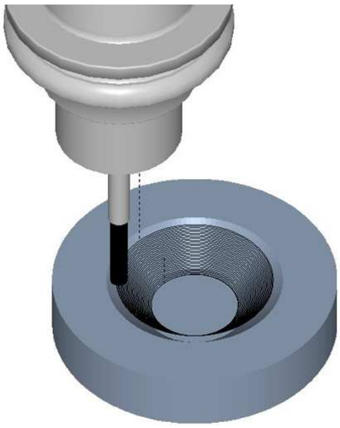

Fig. 7. Generated tool paths performed in EdgeCAM software for 3D milling

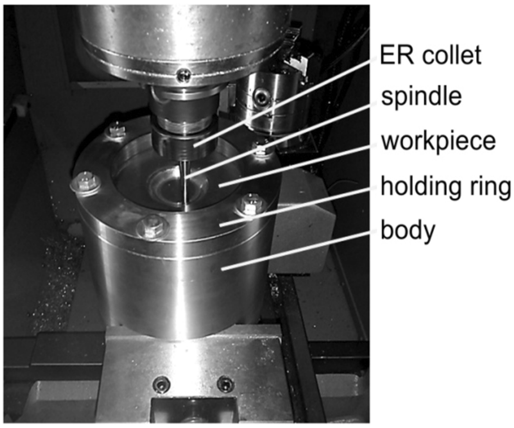

Fig. 8. SPIF device

During forming, machine oil lubricant was applied. Owing to the conical shape of the formed drawpiece, the oil accumulated at the lowest surface of the drawpiece, allowing continuous treatment in the presence of a lubricant. The trials to form a 1 mm thick AA2024-T3 aluminium alloy sheet metal were unsuccesful under different feed rates and feed pitches. Cracks were observed at a forming tool depth of about 5 mm. Although limit strains of the AA2024-T3 sheet are not higher, trials of forming the stiffening ribs (Fig. 9) in the 0.4-mm-thick AA2024-T3 Alclad aluminium alloy sheets were conducted. The aim of the investigations was the determination of influence of the forming parameters on the quality of stiffened ribs and compression strength. This material has been extensively used for highly loaded constructional elements in aircraft structural components. The incremental sheet metal forming process was performed on the CNC HAAS TM1P 3-axis milling machine. The profile tool-path trajectory was generated using the EDGECAM software. The experiments were carried out using a tool rotation speed of n = 36 rpm. The feed rate was f = 800 mm/min. The vertical pitch was equal of 0.5 mm. The forming equipment is shown in Fig. 10. Longitudinal U-shaped stiffening ribs of 20 mm wide and 120 mm long (Fig. 10). The forming of the stiffening ribs is stopped at depth of crack occurring.

Fig. 9. Rib-stiffened sample

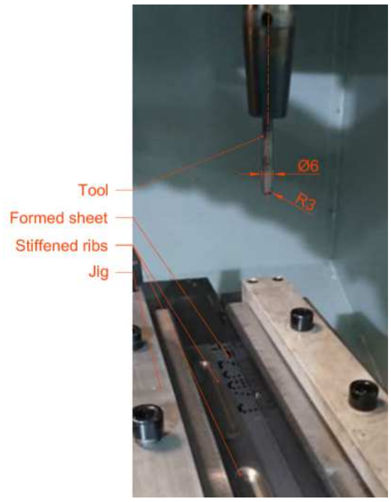

Fig. 10. Incremental sheet forming equipment

The tool path plays also a vital role in the homogeneous thickness distribution and geometric accuracy of the part. Both outward and inward strategies were studied. In the outward strategy the tool travel outward without moving down and forms another loop of the undeformed material to the specified incremental depth, thus causing the previously formed shape to be displaced by rigid body motion in the direction normal to the in-plane motion of the tools [23]. In the inward strategy the forming tool moves around the edge of the rib, from the top to the bottom. It covers the component level by level, in the predefined vertical increment and incrementally deforming the blank until the desired shape has been formed.

The highest depth of rib (about 6 mm) at the moment of crack indication is found for the outward strategy. The height of rib for the inward stategy was about 5 mm. The corner of the rib is the most strained region of the sheet due to the complex stress state. The region of crack initiation of the sheet (region of local sheet thinning) in the rib region depends on the tool path strategy used. The crack initiation was observed in the vicinity of rib bottom and propagates along the bottom of the rib (Fig. 11a). The main parameter influencing the surface finish of the sheet during the ISF process is the vertical pitch and friction phenomena. In the ISF the sheet is deformed locally and as the contact area is small, high pressure contact and consequently high frictional resistance occur. This may result in poor surface finish (Fig. 11b). The localized plastic deformations in the sheet deform the workpiece with higher formability than compared to conventional forming techniques.

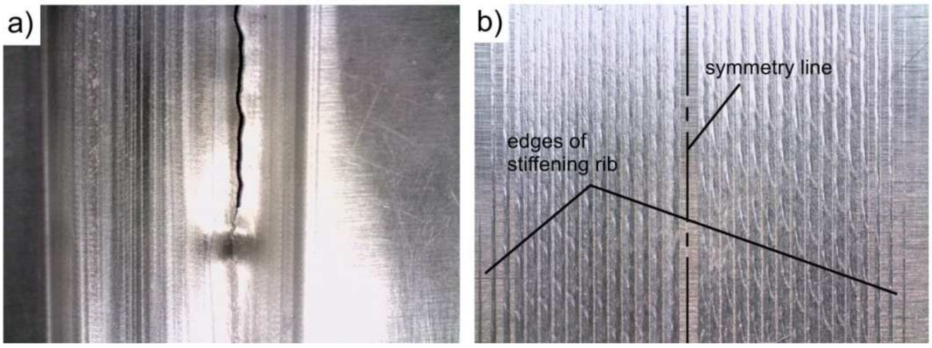

Fig. 11. Fracture at bottom of the rib (a) and stratch bands on the rib surface (b)

In the future research of SPIF for AA2024-T3 aluminium alloys, electric static heating in the forming process should be assured. Consideration should also be given to the possibility of using high rotational speeds of the tool. The combination of heating by both electric bands and high tool rotation speed has been revealed to be a feasible solution for manufacturing hard-to-form lightweight materials such as Ti alloys [24].

In SPIF methods, the outer edge of the workpiece is locked, which introduces tensile stresses in the plane of the sheet which eliminate the wrinkling of the drawpiece walls. Correction of the tool path combined with reverse engineering allows the almost completely elimination of sheet springback. The changes in the final element shape only require a 3D model change, and the generation of a new control program. By using SPIF processes, we can accelerate the prototype time and reduce the cost of the forming process instrumentation. It is also possible to use formed parts in piece and small-lot production without incurring a significant cost for tools.

7. Forming limit diagram

Excessive drawpiece wall thinning leading to cracking and wrinkling is the major defect in cold sheet metal forming processes; i.e.: deep drawing, spinning, and related methods. The possibility of a certain limiting phenomenon occurring depends on the sheet-forming method, the forming conditions and the mechanical properties of the sheet. Realizing the sheet deformation process at different strain states allows the determination of the forming limit curve. The Forming Limit Curve (FLC) is generally governed by localized necking, which eventually leads to ductile fracture. FLC can be represented as a curve of the major strain (ε_1) at the onset of localized necking for all values of the minor strain (ε_2), and the full graph is called the forming limit diagram (FLD) [25].

The suppression of localized necking in single point incremental forming is due to the inability of necks to grow [26]. If a neck was to form at the small plastic deformation zone in contact with the forming tool, it would have to grow around the circumferential bend path that circumvents the tool. If the conditions for localized necking are met in the small plastic deformation zone, growth is inhibited by the surrounding material, which experiences lower stresses [26]. Stress-strain states existing in conventional deep drawing, which cause the conditions for the suppression of localized necking mentioned above, do not occur owing to uniform loading and deformation conditions. The differences between neighbouring plastically deforming regions in SPIF are much larger than in conventional deep drawing. So, the stress-strain states in SPIF cause easy growth of necking. The FLD determined for conventional deep drawing is not appropriate to describe failure in single point incremental forming. According to Martins et al. [26], the fracture forming limit diagram (FFLD) better describes the limiting strains in SPIF, rather than FLD.

Predicting sheet deformation based on the FLD is based on the assumption of a plain stress state in the sheet; i.e. sheet deformation corresponds to the crack moment, and only depends on the value of the major strains in the sheet plane. The FLC at SPIF represents a straight line falling in the direction of increasing values of ε_2 (Fig. 12). The measure of the limiting strains of the sheet is the appearance of localized deformation in the form of a groove, directly preceding the crack. Below the line of limit strains for SPIF (line 1, Fig. 12) there is a safe area with respect to the cracking of the sheet material. Above line 1 there is a loss of sheet metal stability, which leads to fracture. The values of limit strains in the incremental forming are higher than in the case of conventional forming (line 2, Fig. 12). So, in SPIF larger plastic deformations can be induced without the risk of fracture. Typical values of indicator r/g (where r is the tool tip radius, and g is sheet thickness) in SPIF are in the range of 2-10. So, according to the formula developed by Martins et al. [26], the slope of the FFLD line (Fig. 12) varies between –0.7 and –1.3. However, in the case of a conventional deep drawing FFLD diagram the slope is often about –1 [26]. The fracture forming limit in single point incremental forming can be expressed as $\varepsilon_1 + \varepsilon_2 = m$ (Fig. 12), where $m = -\varepsilon_t$ is the thickness strain at the onset of the fracture in plane strain conditions.

At the corners of rectangular drawpieces formed by SPIF there is a strain state which corresponds approximately to biaxial uniform stretching, and deformations in the sheet plane are equal to ($\varepsilon_1 = \varepsilon_2$). Along the flat walls of the rectangular drawpiece there is a state corresponding to stretching in the plane strain state ($\varepsilon_1 \neq 0$, $\varepsilon_2 = 0$). An increase in the diameter of the forming tool and the feed speed reduces the formability of the sheet [22].

The phenomenon which particularly limits the formation of drawpieces in SPIF with the required geometric tolerance is the springback phenomenon, which is observed particularly in the case of stainless steel [27]. The values of elastic sheet deformation depend mainly on the shape of the drawpiece and the mechanical properties of the sheet material. The heat treatment of the element to eliminate internal stresses [27] is one of technological methods for eliminating sheet metal springback.

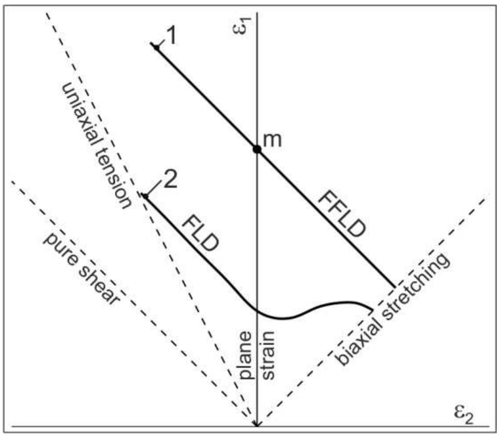

Fig. 12. Comparison of forming limit diagram for conventional sheet forming and SPIF (prepared on the basis of [27])

8. Summary and conclusions

The aim of presented experimental results was to verify the basic parameters that are to be used in forming of thin-walled structures with complex shapes likes isogrid systems. The ISF becomes very attractive to make stiffening ribs in aircraft structures made of hard-deformable aluminium alloys. The formability of the sheet in ISF is defined in terms of five parameters: a radius of a tip of forming tool, a sheet thickness, a size of the vertical step down, a tool rotation speed, and a feed rate. The rotational speed of the forming tool direct influences the frictional conditions at the tool-sheet interface. It was found that the tool path strategy has a direct influence on the surface quality and an amount of limit strains prior to fracture. The depth of the stiffened rib is higher in the case of using the outward strategy compared to the inward strategy.

The main advantages of single point incremental forming are: (i) no need to manufacture the dies, (ii) the ability to shape elements on a conventional CNC milling machine, (iii) much less forming force compared to conventional deep drawing, (iv) higher value of the sheet deformation in relation to die forming, (v) constructional changes in formed elements can be quickly and easily taken into consideration. However, the SPIF has a number of disadvantages, that is: (i) longer duration of forming times compared to conventional sheet-forming methods, (ii) only economically justified for use in piece and small-lot production, (iii) low geometric accuracy of elements, especially in areas with small rounding radii, (iv) significant springback of the drawpieces, which can be minimized using appropriate tool path correcting algorithms.

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MOŻLIWOŚCI ZASTOSOWANIA METOD KSZTAŁTOWANIA PRZYROSTOWEGO BLACH W PRZEMYŚLE LOTNICZYM

Streszczenie

Artykuł zawiera charakterystykę metod kształtowania przyrostowego blach z wykorzystaniem dwóch odmian: kształtowania jedno- i dwupunktowego. Zaprezentowano czynniki wpływające na możliwość zastosowania omawianej metody oraz zjawiska ograniczające zastosowanie kształtowania przyrostowego blach. Na podstawie przeprowadzonych eksperymentalnych badań pilotażowych przedstawiono również wady i zalety jednopunktowego kształtowania przyrostowego. Zawarto również wybrane przykłady zastosowania technik kształtowania przyrostowego do wytwarzania wyrobów dla przemysłu lotniczego.

Słowa kluczowe: przemysł lotniczy, kształtowanie przyrostowe, kształtowanie blach

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