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Deformations and forces analysis of single point incremental sheet metal forming

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ABSTRACT

Purpose: In this paper the experimental equipment and design of the system for deformation and forming force measuring by single point incremental sheet metal forming are described. Beside this the analysis results of the impact of the wall angle, tool rotation, vertical step size, tool diameter and lubrication on the magnitude of forming force and plastic logarithmic strain are presented.

Design/methodology/approach: The incremental sheet metal forming process was performed on the CNC controlled milling machine Moiri Seiki with the FANUC MSC-521 control system. The forming forces were measured using specially designed force measuring system which is connected with the milling machine. In contrast to force measuring, the deformations of the specimen were measured by using the graphometric analysis based on the size and direction investigation of the major strains of the particular sheet metal area.

Findings: The results show that the forming force is very small in comparison to the deep drawing process and it does not depend on the product size. That is why the production of very large products is absolutely appropriate for forming. Beside this, the deformations and forces distribution are mostly dependent on the size of the wall angle of forming, tool diameter and vertical step sizes of the tool.

Research limitations/implications: The deformations and forces analyses are researched only for the steel DC05 of 1 mm in thickness.

Practical implications: The analysis results will help to improve the choice of the appropriate equipment and to setting of the optimal process parameters on the strain distribution and the size of needed forming force. By this the production time of the product could be reduced, which is otherwise by this process very long.

Originality/value: A detailed deformations and forces analyses of single point incremental sheet metal forming for some combinations of process parameters used are original.

Keywords: Plastic forming; Single point incremental forming; Strain; Force

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Incremental sheet metal forming is a modern method, which brings new possibilities of sheet metal forming. Nowadays a lot of attention is focused on the single point incremental sheet metal forming, where the dedicated die is not needed. This method is very flexible, has a large number of adaptable process parameters influencing the forming results and is manly used for small batch production and prototype production of sheet metal components.

Comparing this technology to the conventional sheet metal forming in one or more steps with complex tool geometries (e.g. deep drawing [11], extrusion, hydroforming [10], etc.) in incremental sheet metal forming a simple tool geometry is used for incrementally form the workpiece into the final part shape.

Incremental sheet metal forming with a rigid tool is actually not a new methodology of sheet metal forming, because some conventional processes may be also called incremental processes. The typical example of conventional ISMF is spinning. This process involves a roller and a mandrel on which the specimen is clamped. The mandrel is designed for a particular shape of a product, while the roller is universal. The roller is pushed against the rotating mandrel whereby the sheet metal is deformed. With this method only axi-symmetrical parts could be formed according to the shape of the mandrel. The next example is hammering, where a set of hammers and simple-shaped dies are used at the process of forming. These two processes are traditional and were mainly used for art products manufacturing. However, they have also been employed for prototyping of various shapes in automotive and ship industries. Often the small batch and prototype production were manufactured with traditional technologies, which are very expensive and demanding for manufacturing when compared to incremental sheet metal forming.

At the moment the development of incremental forming is focused in modernizing conventional procedures and into the development of new procedures of sheet metal forming. Therefore, in current scientific literature numerous articles presenting the incremental sheet metal forming can be found.

Iseki and Naganawa [4] presented in their article the forming of vertical thin wall surface with the use of multistage incremental forming. Formability of incremental sheet forming was also analyzed by different authors [7-9, 14]. Park [14] developed a tool with a free rotating ball. Test results were analyzed with the mesh measurement and finite element analyses. The forming limit curve was determined. The article shows the large difference between the forming limit curve and the curve obtained using conventional procedures. The result is that the limit curve in incremental forming is a straight line with the negative slope positioned on a positive area of the forming limit diagram. The curve is also higher as in the usual forming procedure. The fracture on specimens usually appeared at the edge of the surface due to a larger deformation on this area. Kim and Park [7] were analyzing the influence of the process parameters on the tools size, feed rate speed and plane anisotropy on formability. They also analyzed the formability of aluminium under different forming conditions [7]. Strano [15] pays special attention to the rotating incremental sheet forming of cone shape. In his articles, Hirt et al., [2] investigates the surface quality, geometric accuracy, thinning, economical efficiency, etc., of the two point incremental sheet metal forming. In contrast Jeswiet and Hagan [5], Ambrogio et al., [1], Petek et al., [13] and Hussain and Gao [3] show in their articles the principle and the influence parameters of single point incremental sheet metal forming. In comparison to the above mentioned papers, Junkar investigates incremental forming using high-speed water jet instead of a solid tool with defined geometry [6].

Knowledge about the magnitude forming force and deformation distribution in ISMF is very important especially in the case of determining the appropriate equipment and optimal process parameters for sheet forming. The present article shows six different process parameters affecting the size of forming force and deformation. These parameters are wall angle, tool diameter, vertical step size, tool rotation speed and lubrications.

2. Experimental procedure

2.1. Process description and tooling setup

Single point incremental sheet metal forming, also known as dieless forming, is a new and innovative method of sheet metal forming. The sheet metal is formed in a complicated unsymmetrical shape without dedicated die (Figure 1).

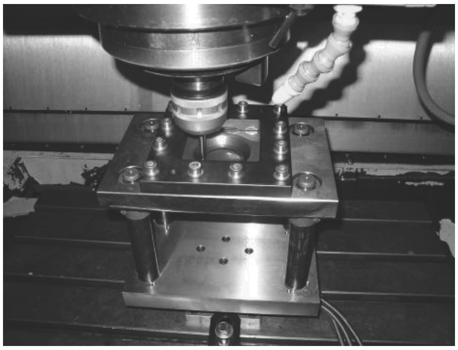

Fig. 1. Single point incremental forming

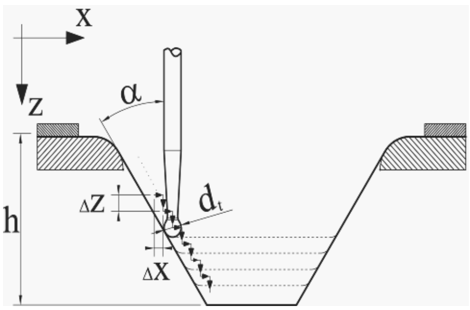

Fig. 2. Steps of SPIF

The rod-shape forming tool with a smooth hemispherical head is clamped into the spindle of the milling machine. It was made of cemented carbide, which enables the forming of numerous materials as well as the stainless steel. The sheet metal is fixed and positioned with the upper blank holder, which is pressed onto the lower blank holder in which the simple die is placed. The whole support tool was inserted and fixed onto the worktable of the milling machine. While the punch presses and locally deforms the sheet directly under the punch head with a very small value of deformation, the blank holder and die remain fixed during the entire forming process. The punch follows to the predetermined tool path and gradually forms the sheet metal in a series of incremental steps until the final depth is reached. The steps of single incremental sheet metal forming are shown in Figure 2. They are defined as Δx, Δz and h, representing increment in x and z direction and finite forming depth, respectively.

The tests for the analysis of influential parameters at single point incremental sheet metal forming were carried out on the CNC controlled milling machine Moiri Seiki with the FANUC MSC-521 control system for three-axis positioning and linear interpolation as well as two-axis circular interpolation.

It is evident from available literature [7] that the lubricant between forming tool (punch) and specimen and between die radius and specimen is needed. For this reason the SYLAC 80-05 lubricant oil, which does not contain chlorine, was used.

2.2. Material

Simple cone specimens were used for determination of material formability. Due to its frequent use in sheet metal forming industry, steel DC05 of 1 mm in thickness was used as specimen's material. Material properties obtained by a uniaxial tensile test are shown in Table 1.

Table 1.
Material properties of steel DC05

C = 531.5 MPa	E = 210 GPa
n = 0.23	ρ = 7850 kg/m^3
r_0 = 1.59	ν = 0.3
r_{45} = 1.06	t_0 = 1 mm
r_{90} = 1.76	

where the parameters are:
C…..strength coefficient [MPa]
n…..strain hardening exponent [11]
r…...material anisotropy [11]
E…..Young's modulus of elasticity [MPa]
ρ…..density [kg/m^3]
ν…..Poisson's ratio [11]
t_0…..initial specimen thickness

Table 2 presents the reference ISMF process parameters obtained from the preliminary tests and attainable literature sources. During the study there was only one process parameter from Table 2 which varied while all other parameters remained unchanged.

Table 2.
The reference ISMF process parameters

Wall angle α	65°
Forming depth h	60 mm
Rotation speed v_r	40 r.p.m.
Tool diameter d_t	10 mm
Tool path	by steps - CW
Feed rate	1700 mm/min
Vertical step size Δz	0.5 mm
Lubricant	SYLAC 80-05

2.3. The deformation measurements

The knowledge about deformations on the sheet metal is very important at the forming processes. It is necessary to define where the critical areas of necking and fracture are. If the forming limit for a particular product is known the process can be optimized. In this way time is saved, costs are reduced and the quality of products is improved. Therefore

The deformations of the specimen were, by experimental test, measured by using the graphometric analysis based on the size and direction investigation of the major strains of the particular sheet metal area [12]. The measure grid is printed on the specimens before the forming process. In case of circular grid, circles are distorted into ellipses after deformation, and strains are measured in major (along the cone surface from apex to base - 1) and minor (on the cone surface perpendicular to 1 direction - 2) directions of the ellipses. The circular grid method was used to evaluate local deformation at a prescribed position but is inappropriate for measuring global distribution of deformation and strain. In this case it is more convenient to use square grid pattern, which requires special equipment.

Circle grid measuring was made by an optical measurement system with accurate x-y coordinate table (Figure 3). The results were further used for the calculation of the first principle strain φ_1, which is major in the plane of the sheet metal, and the second principal strain φ_2, which is minor in the plane of the sheet metal.

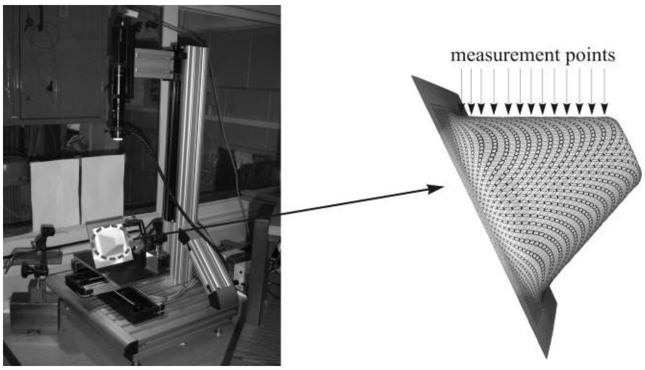

Fig. 3. Contactless x-y measurement system (x-y table with CCD camera) and measurement points

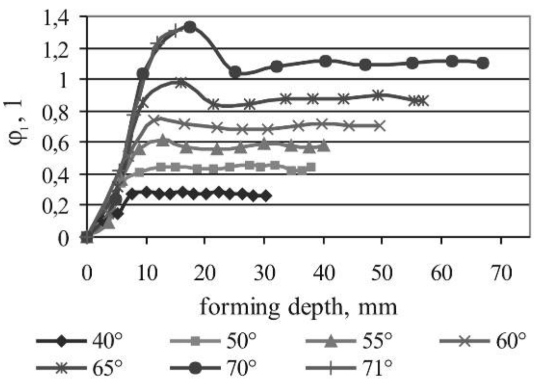

Fig. 4. Logarithmic strain φ_1 versus forming depth

Influence of the wall angle

The analyses were carried out at the wall angle of 40°, 50°, 55°, 60°, 65°, 70° and 71°, respectively. For each parameter variation the logarithmic strains were measured up to the specimen's final depth. Except for the wall angle, the process parameters correspond to their reference value according to Table 2. Figure 4 shows the magnitude of plastic logarithmic strain (φ_1) in dependence on the forming depth by variation of wall angle α (see Figure 2).

At the beginning of forming, the strain curves increase to their maximum values of strain. These appear in most cases at the forming depth from 10 to 20 mm. At the steeper part's wall angle the deformation peaks become higher, while at smaller wall angles (bellow 50°) the deformation peak could not be seen. These can also be explained with the fact that the bigger the wall angle of the specimen is, the bigger the deformations on the sheet metal are. It was established that the maximal attainable wall angle by forming of the cone-shaped part prior to the crack occurrence is 70°. At the wall angle of 71° the fracture already occurs at the forming depth of 18.5 mm (see Figure 4). To avoid any coincident results in such a small change of the wall angle (1°) all important tests were repeated three times and the finite results were always the same. It can thus be concluded that the ISMF is a process with high reproducibility.

The comparison of the magnitude of the main plastic logarithmic strain (φ_1) was made to find out how the forming depth influences the strain distribution of the specimen. The measurements were made at the depth of 42 mm and at the maximum depth reachable with the used die. In case of the wall angle of 65°, the final depth reachable is 60 mm.

The increase of the forming depth to the maximum value does not significantly influence the size of the maximum attainable deformation at forming up to the depth of e.g. 42 mm, as presented in Figure 5.

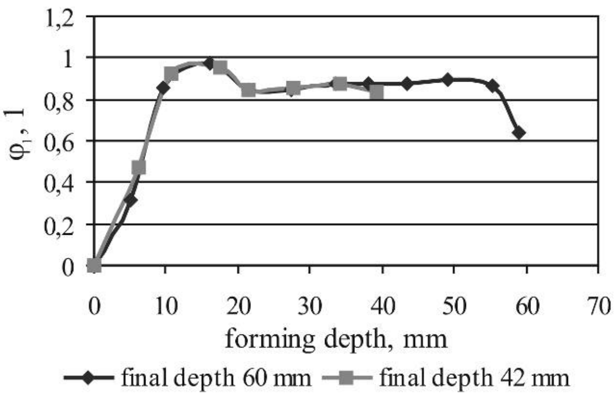

Fig. 5. The influence of the forming depth on the distribution and size of maximal strain (φ_1)

It could be concluded that at the ISMF process the sheet metal is only locally deformed and does not influence the already deformed parts of the work piece. The points obtained with the strain measuring of the cone-shaped specimen after the forming appeared around the axes of main logarithmic strain in transversal direction ($\varphi_1, \varphi_2 \approx 0$).

Figure 6 shows maximal main deformations of the specimens at forming with various wall angles until the maximum depth is reached.

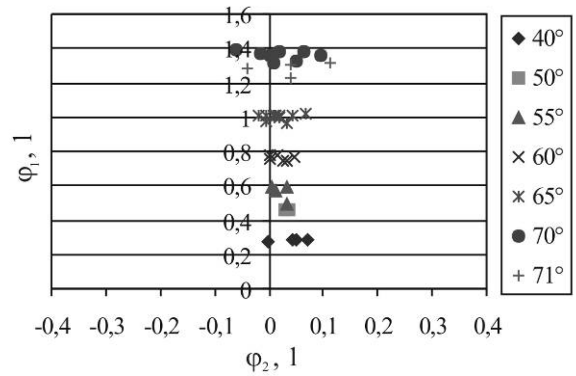

Fig. 6. The points of two maximal main deformations in dependence of the wall angle

Influence of the tool rotation

The experiment was performed for a fixed tool, free tool rotation and tool rotation of 40 rpm. Other process parameters were fixed according to the reference values presented in Table 2. The tool rotation speed of a free spindle was determined. It was established that the tool rotates around 60 rpm despite the oiled surface. Figure 7 shows the influence of forming tool rotation, placed in a spindle jaw, on size and distribution of two main logarithmic strains, (φ_1) and (φ_2).

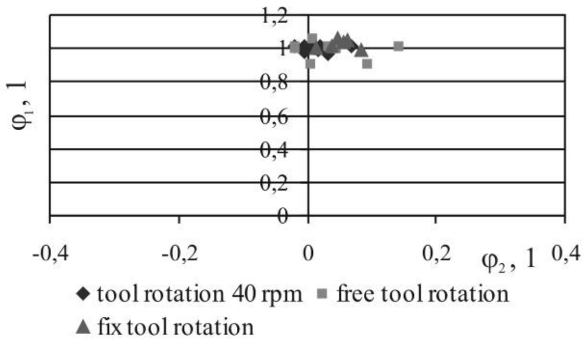

Fig. 7. Influence of tool rotation on the maximal main logarithmic strains, (φ_1) and (φ_2)

Despite the negligible influence of the tool rotation on the strains the visual review of specimens shows bigger tool trace in the case of fixed tool rotation. That is the consequence of the friction caused by a tool sliding along the specimen's surface. In the other two cases with a rotating tool the cylindrical contact friction between the tool and the specimen appears and improves the surface quality.

Influence of the vertical step size

The second most influential parameter having impact on the manufacturing time of the product is the increment of the vertical step of the forming tool. Four various vertical step sizes Δz of 0.1, 0.5, 1 and 3 mm were used for determining the impact of the vertical movement on the main logarithmic strains. The other process parameters remain according to the reference values as presented in Table 2.

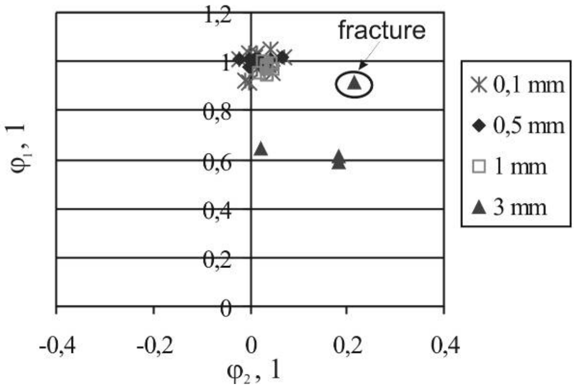

Fig. 8. Influence of vertical step size on the maximal principle strains

It is evident from the diagram that with the step size of 0.1, 0.5 and 1 mm the same value of maximum logarithmic strain could be observed. In case of vertical step size of 3 mm the exceeding of critical triaxial deformation state is observed in the sheet metal (Figure 8). In this moment the fracture on the specimen appeared at the forming depth of 12 mm. It occurs during material stretching due to the vertical movement of the forming tool.

Influence of the tool diameter

Two tool diameters of 10 mm and 16 mm were used to perform the experiment. Other fixed process parameters are presented in Table 2. Figure 9 shows the diagram of maximal main logarithmic strain versus tool diameter.

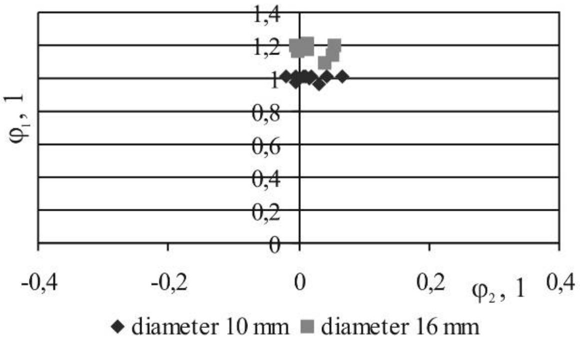

Fig. 9. Influence of tool diameter on the maximal main logarithmic strains, (φ_1) in (φ_2)

It is evident that at equal forming depth, larger value of maximal logarithmic strain (φ_1) is achieved if larger tool diameter is used. That means the specimen surface is more locally deformed in case of larger tool diameter. Consequently, a small tool diameter shall be used to achieve large forming depth.

Influence of the lubrication

The influence of specimen lubrication on the size of maximal strains was analyzed. The experiments were made under three different conditions: with lubrication and the tool rotation speed of 40 rpm, without lubrication and the tool rotation speed of 40 rpm and without lubrication and the free tool rotation speed. The other process parameters are presented in Table 2. The results are shown in Figure 10.

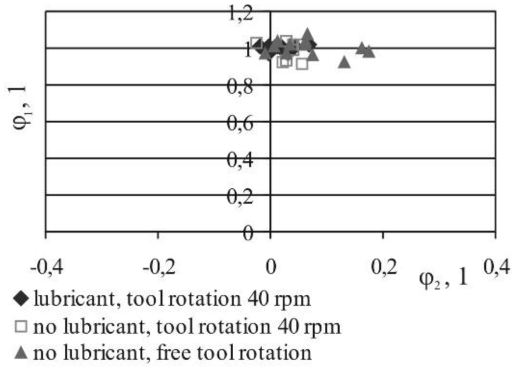

Fig. 10. Variation of the lubrication of the specimen

In the case of forming without lubrication and the tool rotation speed of 40 rpm the crack occurs on the specimen already at the forming depth of 39 mm. Because of the forcible tool rotation very large value of friction appears in contact between the tool and specimen. This leads to increased tool temperature and also to the kneading of the base material (Figure 11).

Fig. 11. The cone formed with tool rotation of 40 rpm and dry friction

In this case the maximum strain does not appear in the fracture area. The crack occurred already at the depth of 39 mm, while the maximum strains appeared at the depth of 15 mm. This is the critical area in which the crack occurred because of the excessive plastic strain.

In the case of dry lubrication and a free rotating tool, which rotates with the speed of 65 rpm, the crack of the specimen does not occur when the complete forming depth is reached. The sizes of maximum strains are approximately the same as in forming with lubrication and tool speed of 40 rpm. In contrast to forced rotation (40 rpm), the tool rotates freely in this case. The friction, which appears between the specimen and forming tool, is much smaller and does not cause kneading and increasing of tool temperature. The surface quality is better in this case, but compared to lubricated specimens, insufficient.

2.4. The force measurement

Beside deformations analysis, special emphasis was also given to the investigations of the forming forces, which are very important especially in the case of choosing the appropriate equipment and optimal process parameters in order to assure perfection and precision of SPIF. Figure 12 shows the measuring system for forces measurement.

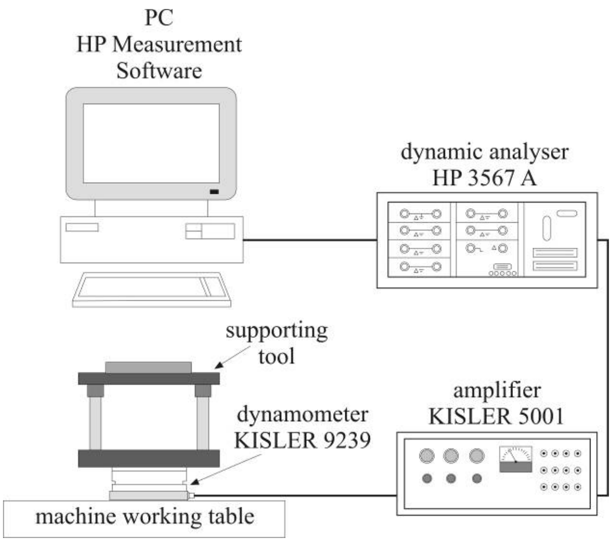

Fig. 12. Measuring equipment for forces measurement

The dynamometer operating on the piezo effect principle changes the mechanical signal into the electrical one enlarged with the charge amplifier. It has twelve amplifying levels so that the convenient amplification and consecutively the largest separability of output signal could be chosen. The analyser was used for recording and analysing the measuring value, which has advantage in working speed and has no limitation at low resolution in comparison with analyser with parallel filters. It is constructed on the basis of modular concept and connected with the personal computer. This presents the system software for setting up the measurement parameters and environment for the present measured results. The main characteristic of the analyzer and amplifier are shown in Table 3 and Table 4, respectively.

Table 3.
The characteristics of the amplifier KISLER 5001

Output voltage	+ / - 12.5 V
Input impedance	10 Ω
Output impedance	100 Ω
Frequency range	10 Hz – 180 kHz
Linearity	+ / - 0.05 %
Environment temperature	0 – 50 °C

The force analyses were achieved for the forming force in z–direction (F_z) which is, at incremental forming, the most critical when the load is observed. The influence of some process parameters on the size of forming force was analysed with the same process parameters as by deformation analysis. The measurements were performed on equal specimens. From a large number of force data, which were stored by the analyser, the filtered force, according to the floating average, was calculated for the majority of influential parameters. Only with such data condition the comparison of various influential parameters on the force magnitude could be analyzed. The problem is in leaping increase and decrease of force at the entrance into the next horizontal forming plane. If 120 such passes for a particular specimen are used (final depth of 60 mm and the vertical step size of 0.5 mm) on three different samples, the diagram force versus time is unreadable. Where the force peaks due to vertical tool movements were observed, the real signal peaks were considered.

Influence of the wall angle

Figure 13 shows the influence of the wall angle on the size and distribution of the filtered forming force (F_{za}) versus time. The experiments were carried out with the wall angles of 40°, 50°, 55°, 60°, 65°, 70°, 71°, 75° and 90°, respectively. Other process parameters were fixed according to the reference values presented in Table 2. All cone specimens were formed to the maximum forming depth, which could be reached with our support tool.

When increasing different wall angles, the forming force is also progressively enlarged. A specimen with the wall angle of 40° does not have a prominent force peak in the critical field. That is the significant difference when compared to other specimens where prominent force peaks appear right after the beginning of forming. The phenomenon is clearly presented in Figure 13. This force peak is prominent at a larger wall angle until the fracture on the specimen occurs. The fracture appears in the critical area - this is the region after the maximum force peak where the magnitude of force reaches the minimum value. This area could also be the indication of the maximum wall angle, which can be used as a limit factor in the single point incremental forming.

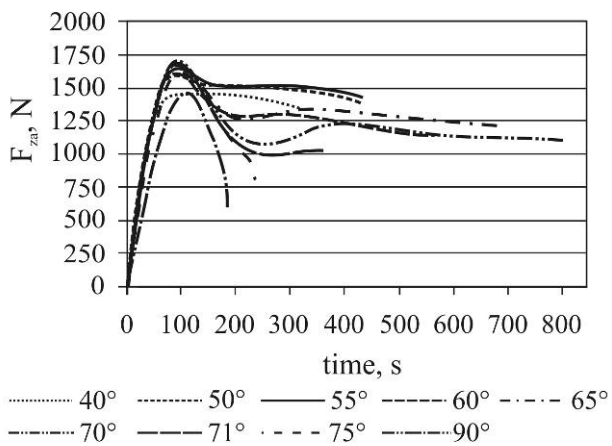

Fig. 13. Floating average force (F_{za}) curves for various wall angles

Figure 14 shows the comparison between the values of maximum force F_{zm} (max. real peak), filtered maximum force F_{zma} (floating average) and filtered force after the critical area F_{zp} (liner part of diagram force – time) for the single wall angle.

Table 4.
The main characteristic of the analyser HP 3567 A

Number of input modules	Frequency resolution [lines]	Frequency range [kHz]	Dynamically range [dB]	Noise [$nV_{rms}/\sqrt{Hz}$]	Speed of sampling [samples / sec]
6	Max. 3200	Max. 102.4	80	< 40	262144

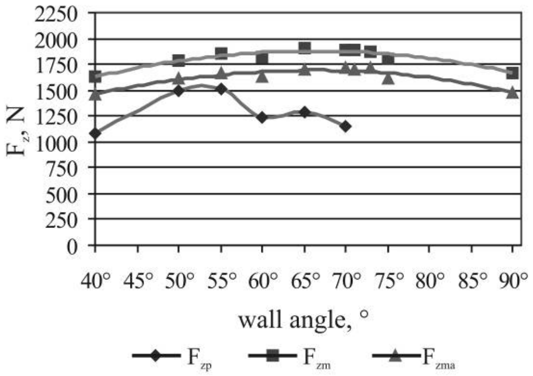

Fig. 14. Comparison of force by various wall angles

The maximum force at different wall angles increases to the limit forming angle (71°) and, then, slowly decreases. The average force behind the critical area in contrast to the maximum force slowly increases to the wall angle of 55° and then suddenly decreases until the limit wall angle is achieved. At larger wall angles the floating average force above the critical point can not be measured because the fracture occurs prior to it.

Influence of the tool rotation

The test was made with tool rotation of 40 rpm, fixed and free tool rotation. The other process parameters are presented in Table 2. Figure 15 shows the influence of the forming tool rotation on the size and distribution of floating average forces (F_{za}) versus time.

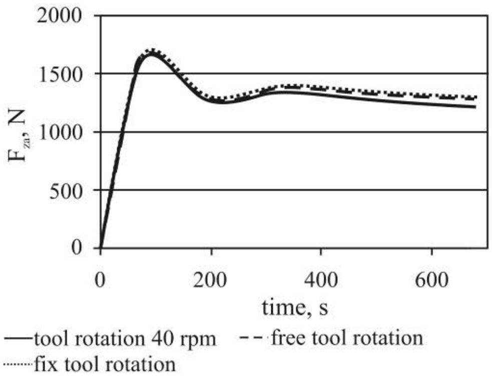

Fig. 15. Filtered force curves (F_{za}) for various tool rotation speeds

The curves show a similarly increasing trend of the filtered force to the maximum value, which is in case of fix tool rotation the largest and then suddenly decreases until the forming force stabilizes. This level is larger in the case of fix and free tool rotation. It is interesting to analyse the distribution of real force (F_{zr}) in fix tool rotation at which, in comparison to other two examples, larger peaks of the force appear when the tool passes over the horizontal forming planes.

The size of the maximum force (F_{zm}), the filtered maximum force (F_{zam}) and the filtered average forces of uncritical area (F_{zp}) are shown on the diagram (Figure 16).

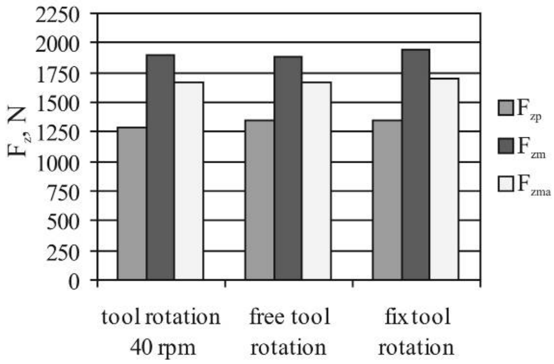

Fig. 16. The comparison of force magnitude with variation of tool rotation speed

Influence of the tool diameter

By the experiments the punch diameter of 10 and 16 mm was used. Other process parameters are fixed according to the reference values presented in Table 2. In the case of changing the tool diameter the forming depth was presented on the x – axis of the diagram. Otherwise, the comparison of the distribution force at different parameters is not possible because the part's production time at various punch diameters is not equal. Figure 17 presents the influence of the forming tool diameter on forming forces (F_{za}) versus the finite forming depth.

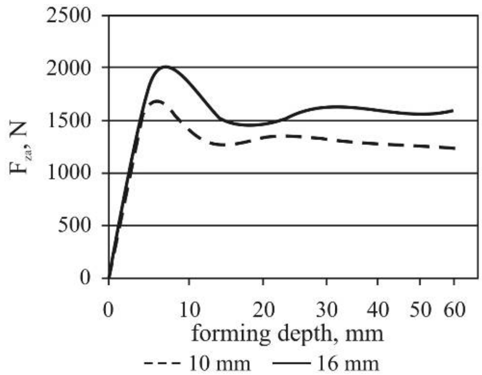

Fig. 17. Floating average force *(F_{za})* curves for various tool diameters

The increase in the forming force appears with the increase in the tool diameter. This is due to a larger contact surface between the tool and the specimen, which is connected with the increase in the needed forming force. Thus, a larger forming force appears in the critical area as well as in the uncritical one – see Figure 18. The maximum force needed for the forming with the tool diameter of 16 mm is approximately 15% larger than the one needed for the forming with the tool diameter of 10 mm.

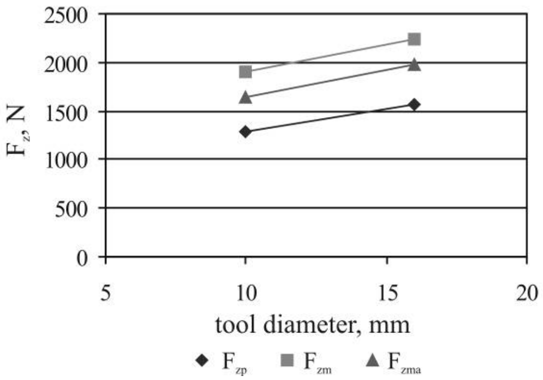

Fig. 18. Comparison of force value on variation of tool diameter

Influence of the vertical step size

To determine the influence of the vertical step size on the real magnitude of forming force (F_{zr}), four different movement sizes of 0.1, 1.5, 1 and 3 were analysed. Other fixed process parameters are presented in Table 2. In this case the real forming forces instead of the filtered forces were analysed. This allows an accurate comparison of force peaks, which appear at the crossing of the tool into the next forming surface, by increasing the vertical step size. The results of the force measuring are shown in Figure 19.

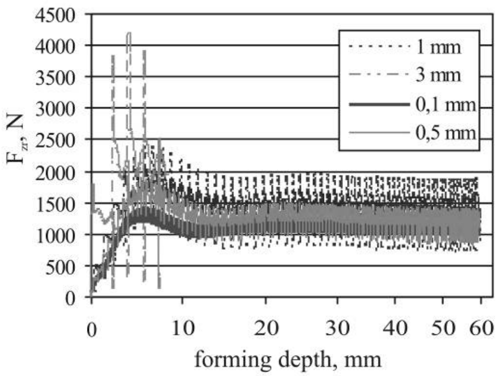

Fig. 19. Real force curves for various vertical step sizes

It is evident that the distribution of the forming force is larger if the vertical step size increases. In the case of vertical step size of 3 mm the forming force is quite large (4200N). In this instance the fracture appears at the depth of 12 mm and at the time when the tool moves into a vertical direction. The crack of the sheet metal occurred because the biaxial strain state is exceeded. Diagram in Figure 20 presents the magnitude of maximum force and filtered forces in an uncritical area.

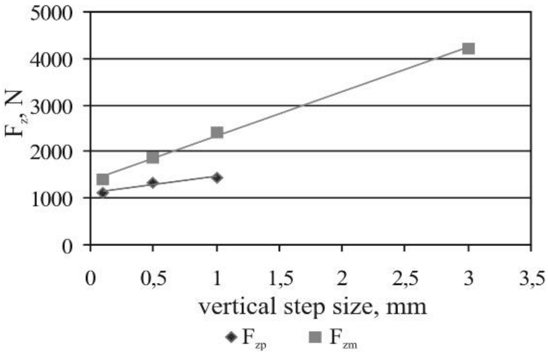

Fig. 20. The comparison of force magnitude on the variation of step size

The diagram (force versus vertical step) presents two straight lines illustrating, in the first place, the maximum force value (F_{zm}) and, secondly, filtered force value after the critical area (F_{zp}) reached at forming with different vertical step sizes. If the vertical step sizes increased, then the force magnitude also increased. The magnitude of force is directly proportional with the size of the vertical step between the single horizontal tool contours, and matches well to the linear trend as is shown in Figure 20.

Influence of the lubrication

The influence of lubrication of the sheet metal on the filtered forming force (F_{za}) was examined according to its time dependency. The experiments focused on three different tests:

- lubrication of the specimen and tool rotation speed of 40 rpm,
- dry lubrication of the specimen and free tool rotation speed.
- dry lubrication of the specimen and tool rotation speed of 40 rpm and

Other process parameters are presented in Table 2. The results are presented in Figure 21.

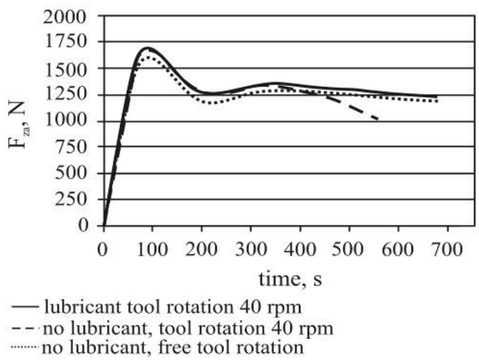

Fig. 21. Filtered force curves for various parameters of lubrication

In the case of lubrication combined with tool rotation speed of 40 rpm the leaping decrease of the forming force, at the time of 500 s (forming depth 39 mm) occurs due to the fracture of the specimen. Reasons for fracture are described in detail in chapter 2.3.6. Figure 22 shows the magnitude of maximum forces, filtered maximum force and filtered force after the critical area at various parameters of lubrication.

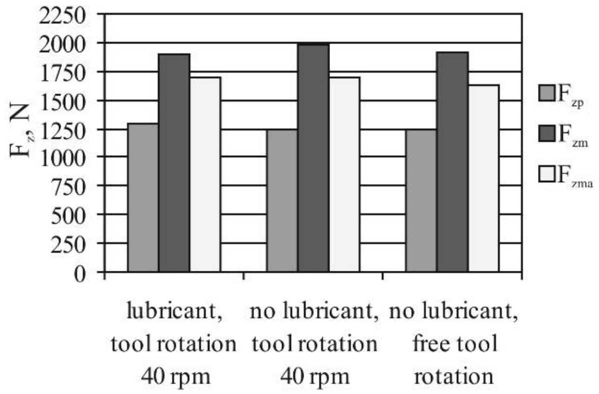

Fig. 22. The comparison of force magnitude on various parameters of lubrication

3. Conclusions

Single point incremental forming is a method used for manufacturing of the sheet metal products and brings new opportunities in the field of sheet metal forming as shown in the paper. These methods are useful for making shapes which are very costly or impossible to produce with other methods and for small quantity production.

Forming force is very small in comparison to the deep drawing process and it does not depend on the product size. That is why the production of very large products is absolutely appropriate for forming. Besides this the ISMF is a process with high reproducibility. Therefore, only minor changes of process parameters are necessary to improve the part geometry.

In the paper the analyses of some influential process parameters on the deformation size and forming force (F_z) were presented. The biggest deviation could be found by the variation of wall angle of forming, tool diameter and vertical step sizes of tool. By increasing any of those parameters we influence the increase of forming force. It is clear that this increase is a consequence of a large load appearing on the sheet metal, which requires bigger tool energy. In this case it is difficult to determine the parameter with the least influence on the forming forces and deformations. If the parameter could be defined it would be possible to increase it whereby it would have no influence on the force and strain results.

The analysis results of influential parameters on the force size and product deformation could be summarized as follows:

- The force right after the peak and the deformation peak in a field with larger wall angles (up to 55°) could be noticed in the area where the fracture appears at the maximum wall angle. This is the most critical forming region on which the fracture in the case of critical angle will occur.
- With the increase of a wall angle the forces and deformations increase as well.
- Rotation tool does not have any influence on the force and deformation size but has a strong influence on the quality of the surface.
- The increase of the tool diameter causes larger forces and deformations.
- With larger vertical step, forming forces and deformations are increased.
- Lubrication does not influence the forces and deformation magnitude but it has a large influence on the quality of the surface.

In the future the research work will be concentrated on the investigations of critical areas of the specimen and SPIF formability determination in the digital environment and also on the process mapping using design of experiments.

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