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General overview of sheet incremental forming

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ABSTRACT

Purpose: The aim of this research paper is to give a general overview on sheet incremental forming as an emerging field in small and batch production.
Design/methodology/approach: First the historical and literature background of sheet incremental forming will be given, and then some theoretical and practical issues of the incremental forming processes will be described including the research work done by the author at the University of Miskolc. This research is part of an international EUREKA project with the main focus on formability and accuracy in incremental sheet forming.
Findings: In this research paper some important findings on the critical wall angle which is a characteristic formability feature in incremental sheet forming will be discussed. New specimen geometry was elaborated to reduce the great amount of experimental work to determine the formability limits. The main conclusions are that in incremental forming the formability is significantly higher compared to conventional sheet forming. The process is very flexible and economic due to the low tool costs.
Research limitations/implications: One of the main target areas of further research work is the determination of technological window for sheet incremental forming of various materials and to introduce this novel process into industrial practice.
Practical implications: In practical applications besides the economy of the process due to its very low tool expenses, the flexibility should be mentioned which is very important in small batch production and particularly in rapid prototyping.
Originality/value: The results achieved within this research work are equally important both from the point of view of theoretical and practical aspects of sheet incremental forming.
Keywords: Incremental sheet forming; Limit draw angle; Formability; Forming limit diagram; FLD

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1. Introduction

The paper deals with sheet incremental forming. The research work described in this paper was done within a Joint European Project (EUREKA) in cooperation of the University of Miskolc and the University of Ljubljana. The main objective of this project was to elaborate new, effective incremental sheet forming processes and to determine the technological process window.

The term incremental forming is used for a variety of processes, all characterized by the fact that at any time only a small part of the product is actually being formed, and that the area of local deformation is moving over the entire product. This definition covers many processes: from those, spin-forming is often regarded as one of the originating processes of sheet incremental forming. Spinning and incremental sheet forming are closely related, however, there are significant differences as well.

Spinning is usually done while the materials clamped on a rotating mandrel and the required shape formed by a rigid spinning tool (also often having rotating rolls). In sheet incremental forming, the blank edge is usually strictly clamped and the sheet is deformed most usually by a hemispherical tool following the required shape in space by a CNC controlled incremental tool movement as shown in Fig. 1.

Incremental sheet forming can be done on any universal milling machine having at least 3-axis CNC control system. Thus, the basic elements of incremental forming processes are the material to be formed, a blankholder clamping the blank, the very simple, universal forming tool and the forming machine with the CNC control [1].

Incremental forming has many advantages which are particularly important in prototyping and small batch production when the significant tooling costs cannot be justified. Incremental forming is the very process which is particularly useful to reduce the tooling costs.

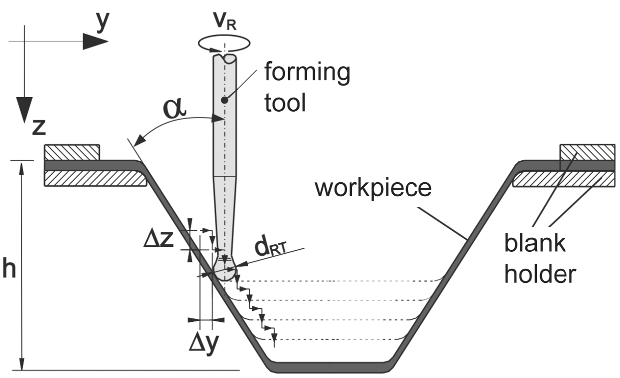

Fig. 1. Basic principle of incremental forming

Besides the much lower tooling costs a further advantage that incremental forming can be performed in conventional CNC controlled milling machines. It is also worth mentioning that due to the special nature of the process, parts can be directly produced from their CAD data files. This possibility also leads to the benefits of flexible and fast design changes. Due to the incremental nature of deformation mechanisms - i.e. the extremely small plastic deformation zone - significantly higher strains can be achieved compared to conventional forming and this is the reason as well that there are significantly lower forming forces, too.

2. Short historical overview of sheet incremental forming

The original idea to produce symmetric parts by a so-called dieless forming method applying a single point tool was patented by Leszak in the United States in 1967 [2]. After that there was a significant interest in processes where sheet metal deformed plastically in a small zone enabling really flexible production of complex parts [3]. The real breakthrough was due to the widespread application of CNC technique in industry and the ever increasing need for more flexible manufacturing processes [5]. Hagan and Jeswiet [4] gave an excellent state-of-the-art overview of this kind of emerging new processes; they suggested spinning as the originating process of incremental sheet forming and emphasized the potential of this technology in rapid prototyping applications.

The basic definition for incremental sheet forming was formulated by Jeswiet. According to his interpretation, incremental sheet forming is a manufacturing process done usually with a solid, small sized tool being in continuous contact with a small deforming zone of the sheet without any dedicated die determining the shape of the component [6].

Due to its many advantages, in the recent years, there was a significant research activity in incremental sheet forming. In single point incremental forming (SPIF processes) Jeswiet [7]., Kitazawa [8], Leach [9], Filice és Fratini [10] made important contribution. In two points incremental forming first Powell and Andrew's work [11] should mentioned. Starting out of their work, the two point incremental forming was significantly further developed by Matsubara [12].

It should be mentioned as well, that the first machine clearly dedicated for incremental forming [13] was developed from the principles he created [14].

2.1. Classification of incremental forming

Incremental sheet forming may be classified according to various points of view, e.g. it may be classified according to the forming method, the part geometry, the forming path and tool path strategy, the applied tools, etc. The most usual classification is done according to the forming method. According to it, we can distinguish single-point, two-point and hybrid processes. Single-point incremental forming (SPIF) which is one of the most fundamental processes is often termed as negative incremental forming. Two-point incremental forming (TPIF) is also termed as positive incremental forming.

Further classification according to the forming method may also be done whether the process can be done in a single stage (this is the most frequent type) or as a multi-stage process [15].

Considering the geometry of formed sheet we can also distinguish symmetric and asymmetric incremental forming. In Fig. 2, some basic types of asymmetric incremental forming can be seen. This figure involves another classification based on the tooling apparatus.

In certain respects this classification is closely related to the forming method as well. For example, single point incremental forming can be done without any die (often termed as dieless forming) just using a single tool (see Fig. 2 part a.) or applying a so-called counter tool (Fig. 2 part b.). Two-point incremental forming also can be done without full die using a partial die (Fig. 2 part c.) or applying a full die (Fig. 2 part d.). All these process variants are summarized in Fig. 2.

However, if we strictly insist on the original term of incremental forming, the variant (d) in Fig. 2 cannot be really considered as an incremental forming process since in this case the part geometry is essentially defined by the full die though the forming process itself has its incremental nature.

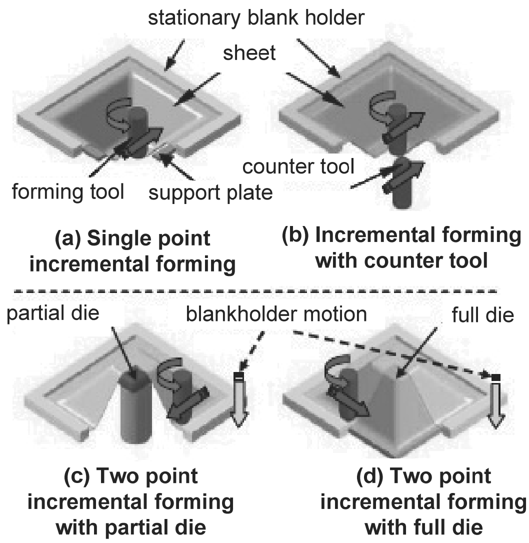

Fig. 2. Classification of sheet incremental forming

The forming path and the tool path strategy as the movement of the forming tool is one of the most important technological process parameters. The tool path is determined by the CNC control of the forming (milling) machine. Practically it means that the profile is mapped by an *xy* section of the component at different *z*-levels and the full geometry is generated by the tool path with small Δz -increments.

The usual tool path may be unidirectional or bi-directional. In some paper it is mentioned that unidirectional tool path in some cases may lead to twisting in the produced part [16]. In each case - i.e. in unidirectional or bi-directional tool path - the appropriate selection of Δz increments has great importance from the point of view of smooth and accurate profile of the component.

2.2. Formability issues

As it was mentioned in the Introduction section, one of the main objectives in this joint research project is the analysis of formability in sheet incremental forming. Therefore, it is also important to review the literature concerning the formability issues in sheet incremental forming.

Formability is always a very complicated issue and it is particularly valid for incremental forming. At the beginning of the recent research activity, it was shown that the formability in sheet incremental forming is in close correlation with the wall angle (ϕ) of the part to be produced. It is well known from the theory of spinning that the thickness of the component is changing according to the sine-law (for notations see Fig. 1)

$$t = t_o \sin\alpha = t_o \sin(90^o - \phi) = t_o \cos\phi \quad (1)$$

Following from Eq. (1), it is clear that increasing the wall angle the wall thickness will decrease and thus at a certain degree the thickness reaches a minimum value, and fracture will occur. Thus to a certain extent the wall angle can characterize the formability limit.

Obviously, this is just a very rough approximation of the formability in incremental sheet forming, since the formability - particularly in incremental sheet forming - is much more complex than a single parameter could define it. Therefore, a special benchmark specimen was proposed by Micari [17] to get comparable formability results by simple tests (Fig. 3). This benchmark specimen was a truncated cone with a base diameter of 72 mm and the height equal to 40 mm. Tests are carried out with various cone angles and that value is accepted as the limit wall angle *(ϕ_{max})* when fracture occurs.

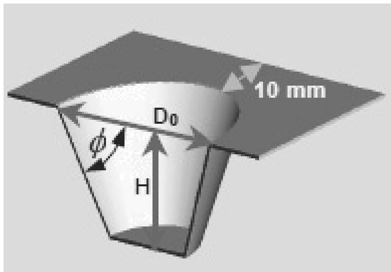

Fig. 3. Benchmark specimen to determine the limit draw angle

The limit wall angle is an important parameter, but it is hardly enough to characterize the complex strain state and formability behavior in incremental sheet forming. For this purpose - as it is widely used in sheet metal forming - the forming limit diagram is the more appropriate solution. As it is well known in conventional sheet metal forming, the forming limit diagrams (originated from the Keeler-Goodwin diagram [18]) have V-shaped form as shown by dashed lines in Fig. 4. For the determination of conventional forming limit diagrams nowadays the Nakajima [19] and the Marciniak [20] methods are used worldwide.

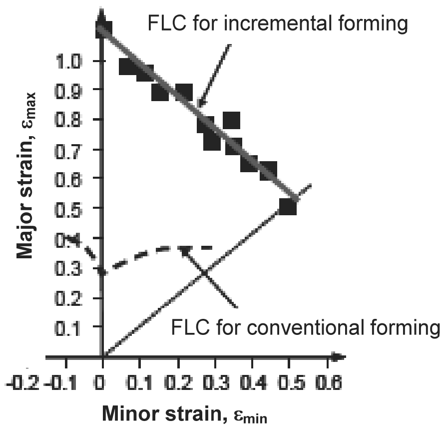

Fig. 4. Forming Limit Diagrams for conventional and incremental sheet metal forming

Extensive research works in this field have shown that the forming limit diagram is very different for incremental sheet forming. Filice and his co-workers [20] determined the Forming Limit Curve (FLC) for incremental forming just for the $\varepsilon_2 > 0$ zone, and they found that the forming limit curve in this range has a negative slope and it goes much above of the conventional FLC as shown in Fig. 4 with the continuous red curve.

Further studies on the forming limit diagrams in incremental sheet forming led to some contradiction. In some papers [21] you may find that the formability on the left hand side is further increasing linearly as shown in Figure 5, while others state that achieving its maximum at $\varepsilon_2 = 0$ (i.e. along the ε_1 major true strain axis) it will decrease, thus the FLD has a reverse V-shape compared to the FLD in conventional forming [22].

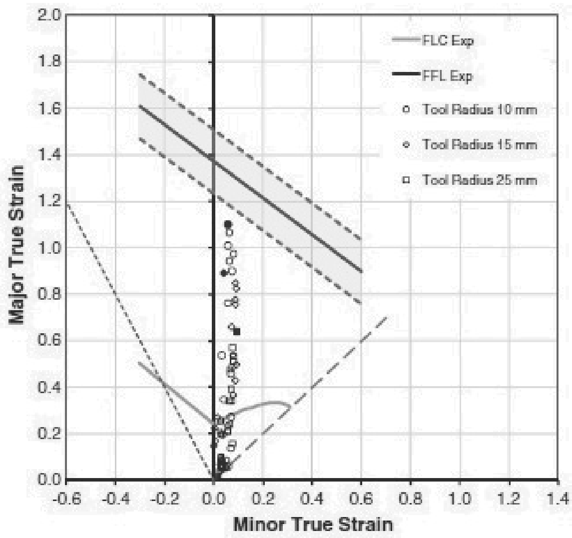

Fig. 5. Straight extension of FLD into the negative region reported by Silva [21]

Due to this contradiction in the literature of incremental sheet forming the analysis of the forming limit diagrams in sheet incremental forming was one of the main objectives in our joint European project.

3. Analysis of the formability in sheet incremental forming

In our research project, we studied both the determination of the limit draw angle and the Forming Limit Diagrams for sheet incremental forming. In this section, these two sets of theoretical and experimental research work will be introduced.

3.1. Determination of the limit draw angle

As we could see in Section 2.2., the benchmark specimen proposed by Micari [17] provides a common basis for the determination of the limit draw angle, however it still requires a large amount of experimental work.

Tests should be carried out with various cone angles and that value is accepted as the limit wall angle *(ϕ_{max})* when fracture occurs. Thus, the determination of the limit draw angle requires several subsequent tests starting from a wall angle much lower than the expected limit value and continued with a step-by-step increased wall angle until the fracture occurs.

To reduce the tremendous work for the determination of limit wall angle, there are several proposals: among them the application of axisymmetric test specimen with changing slope is one of the most promising ones [23]. There are different possibilities to apply changing slope along the part to be manufactured. They differ first of all how the generatrix of the profile is generated. The most usual generatrix profiles are: circular, elliptical, parabolic or exponential curve. These generatrix curves can be easily derived by analytic functions and also the tool path on CNC machines can be programmed easily.

In Fig. 6, an illustration of a changing slope profile generation using a circular arc can be seen, while in Figure 7, the principle scheme for the calculation of limit draw angle and the limit thinning is shown.

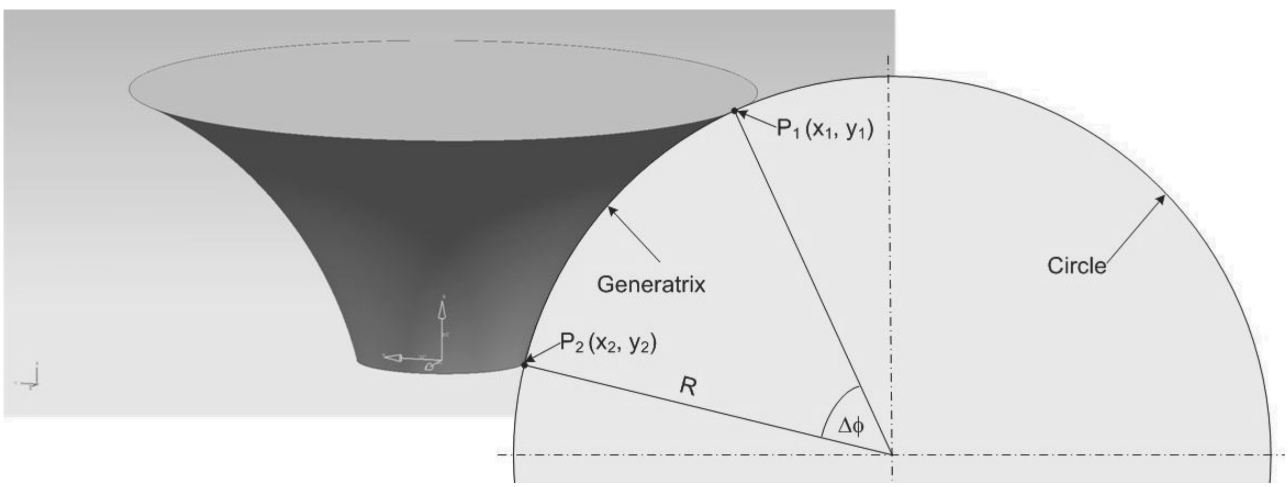

Fig. 6. Illustration of a circular generatrix derivatio

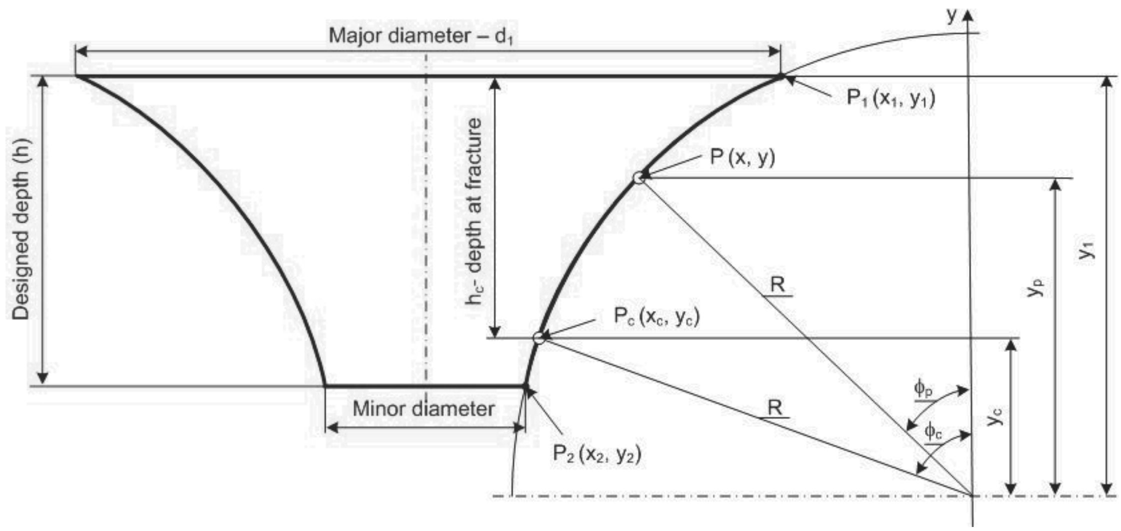

Fig. 7. Principle scheme for the calculation of limit draw angle and the limit thinning

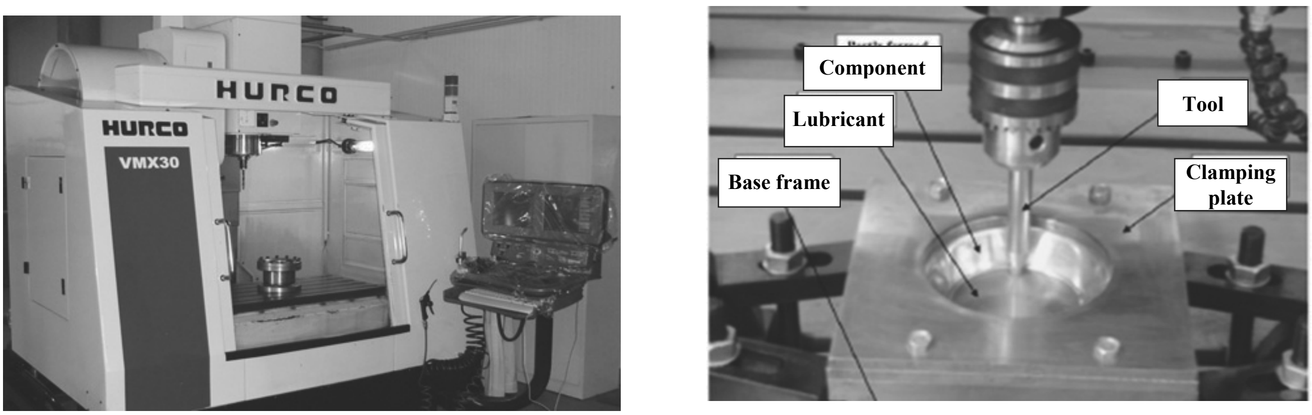

Fig. 8. The CNC milling machine with the tool setup applied during the experiments

The basic principle is similar for the different generatrix profiles; however, the selection of curves may affect the test results. In the following, the mathematical description of the limit draw angle determination will be shown for a part having changing slope defined by the generatrix profile as a circular curve. An arc of a circle between the starting wall angle and that of somewhat higher than the expected limit wall angle can serve for this purpose – see Fig. 6. Denote R the radius of the circular arc and $\Delta\phi$ the included angle which should be selected as large as possible to assure that the fracture during the incremental forming could be observed.

If $P(x, y)$ is an arbitrary point (see Fig. 7 for notations) on the generatrix profile of the part, the ϕ_P wall angle at this point can be calculated by the following expression:

$$\phi_P = \arccos\left(\frac{y_P}{R}\right) \quad (2)$$

and the thickness of the component at this point P can be calculated according to the Eq. (1) as

$$t_P = t_o \cos\phi_P = t_o \frac{y_P}{R} \quad (3)$$

Thus, from known values of R and the coordinates of an arbitrary point $P(x, y)$, the corresponding angle ϕ_P and the thickness t_P at this point can be calculated by using the Eq. (3) and (2).

The aim of this calculation is to determine the limit draw angle: if $P_c(x_c, y_c)$ denotes the point on the curve where fracture occurs and h_c is the depth of the part at the occurrence of crack, the limit wall angle (ϕ_c) can be calculated with the following equation:

$$\phi_c = \arccos\left(\frac{y_1 - h_c}{R}\right) \quad (4)$$

and correspondingly the thickness at the occurrence of fracture *(t_c)* by the expression

$$t_c = t_o \frac{y_1 - h_c}{R} \quad (5)$$

To verify experimentally the above considerations and the suitability of the component with changing slope for the determination of limit draw angle, a series of experiments were performed using both the traditional way (i.e. applying several components each with constant but different wall angle) and applying the above described component with changing slope. The material was Al 1050-A with different material thicknesses from t = 0.6, 1.0 and 1.5 mm.

The experiments were done on a 3-axis HURCO VMX30 CNC controlled milling machine which is shown in Fig. 8. with the experimental tool setup. The applied tool was a hemispherical one with a diameter d = 10 mm made of HSS tool steel. The horizontal feed rate f = 600 mm/min and the vertical pitch of the tool e = 0.2 mm. For lubricant mineral oil was used. The CNC control program was made by the PowerMill program package.

In each case - i.e. during the large series of tests of conventional specimens with different but in a given test constant wall angle and in this unconventional way with changing slope - several experimental tests were performed and the average values (which showed very low scattering) were compared. The results for three different thicknesses are summarized in Table 1.

Table 1.
Limit draw angle for different material thickness

Material grade	Material thickness, t_o (mm)	limit draw angle	
		with constant slope	with changing slope
Al 1050A	0.6	64.8	65.2
Al 1050A	1.0	67.9	68.1
Al 1050A	1.5	71.0	71.0

The comparison of the results obtained by specimens with constant wall angle and that of with changing slope show very good agreement confirming the suitability of this testing procedure for the determination of limit draw angle.

As it was already mentioned before, the limit wall angle is an important parameter, but it is hardly enough to characterize the complex strain state and formability behavior in incremental sheet forming. For this purpose - as generally in sheet metal forming - the forming limit diagram is the more appropriate solution. Therefore in following subsection it will be described in detail.

3.2. Determination of the Forming Limit Diagrams for incremental sheet forming

For the determination of the FLD in incremental sheet forming special specimens elaborated within the Joint European Project - Eureka - were used [27]. These specimens are a modified version of the conventional Marciniak test adapted to the special conditions of incremental sheet forming. As it is well-known, for the Marciniak test different work piece geometries are required. Five different workpiece geometries were applied: the first work-piece is a plate with a dimension of 150×150 mm; the other four work-pieces were cut from the base plate to various strips. The widths of the strips are 20, 30, 40 and 50 mm. All work-pieces are formed using only pyramid-shaped tool path, which correspond to the truncated pyramid shapes. The base of the pyramid is 84 mm by 84 mm with the corner diameter of 10 mm. To prevent striking against the strip a guiding plate between the forming tool and the work-piece is used. The shape of the guiding plate is similar to the base plate whereas it is made from material having better formability in order to prevent crack of the guiding plate before the crack of the work-piece occurs. These modified specimens make possible the determination of both sides of the FLD diagram realizing linear strain path both on the left and on the right side.

Before the experiments 2×2 mm square grid was printed on the surface of the blank sheets. The tests were performed on a universal formability testing machine shown in Fig. 9 which is equipped with the Vialux optical strain measurement.

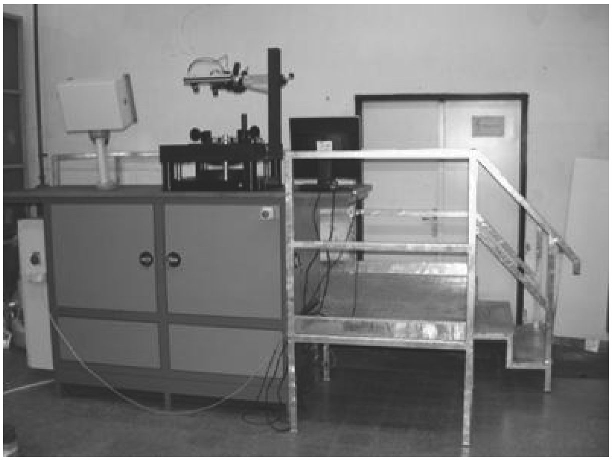

Fig. 9. The universal formability testing machine with the Vialux optical strain measurement device

Detailed description of this measurement procedure together with the basic principles of strain calculations are given in a PhD Thesis prepared at the Department of Mechanical Technology at the University of Miskolc [28].

During the experiments for the determination of the Forming Limit Diagrams for incremental sheet metal forming the same material grade (Al 1050-A) was applied with the same thicknesses as shown in Table 1.

The experimentally determined Forming Limit Diagrams for both conventional forming and for incremental forming are shown in Fig. 10.

From this diagram the following important conclusions may be drawn:

- Using the special specimen geometry and test conditions applied in these experiments, both sides of the FLD can be determined.
- The formability in incremental forming is much higher than in conventional sheet forming. The highest difference can be observed in plane strain conditions. Starting from this peak

values, the formability is decreasing both on the left and on the right side.

- The formability in incremental forming is also increased with the increasing thickness.

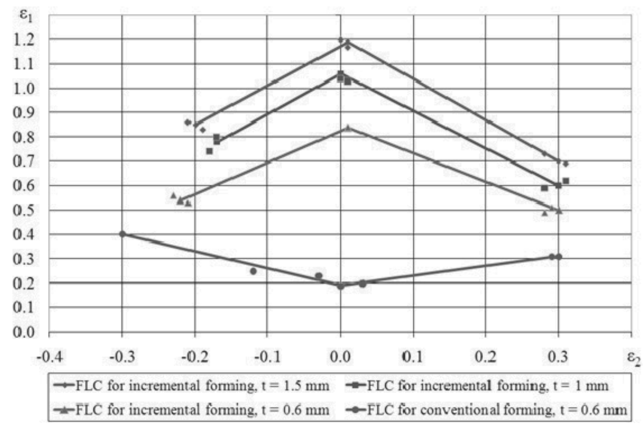

Fig. 10. Comparison of FLDs for incremental and conventional sheet forming (Material grade: Al 1050-A)

4. Summary

Development of new technologies and processes for small batch and prototype production of sheet metal components has very important role in the recent years. The reason is the need for quick and efficient response to the market demands. Incremental sheet metal forming (ISMF) may be regarded as one of the promising developments for these purposes.

There are many advantages of incremental sheet forming: among them the following main benefits are particularly useful making this process very popular for research activities:

- usually it does not need dedicated tools, forming can be performed with simple universal tools;
- the process can be done at any conventional CNC milling machine without investing on new equipment and tools;
- due to the above mentioned benefits, the cost of the incremental sheet forming is significantly lower compared to conventional sheet forming using dedicated machines and tools;
- the process is very flexible: parts can be directly produced from their CAD data files making design changes fast and very effective;
- due to the special incremental nature of deformation process, significantly higher deformation can be achieved compared to conventional sheet metal forming processes;
- it also follows from its unique deformation characteristics that materials with lower formability in conventional forming may be manufactured in an economic way;
- the process is very suitable for producing complex parts making the incremental sheet metal forming particularly useful in small batch and prototype production.

During the recent years, an intensive research work is going on in this field at the Department of Mechanical Technology at the University of Miskolc with close cooperation with other European research institutes.

In this paper some theoretical and practical issues of incremental sheet forming were analyzed mainly from the point of view of formability. Two generally used characteristics of formability - i.e. the limit wall angle and the Forming Limit Diagrams - were introduced. It was proved experimentally that specimens with changing slope can be used to determine the limit wall angle with significantly less experimental work.

Using special specimen geometry, Forming Limit Diagrams for Al 1050-material with various thicknesses were also determined. It was shown that the formability in incremental forming is significantly increased compared to conventional sheet forming. The highest increase in formability can be observed in plane strain conditions. The applied method is suitable to determine both sides of the FLD with simple experimental techniques.

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