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MANUFACTURE OF THIN MINIATURE PARTS USING ELECTRO HYDRAULIC FORMING AND VISCOUSE PRESSURE FORMING METHODS

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In this paper two methods for manufacturing of miniature parts are presented. Micro- Electro Hydraulic Forming (EHF) is the first method, which is investigated both theoretically and experimentally. An electro hydraulic forming apparatus is designed and made by which miniature parts can be produced. This process is also analysed by the FE method. It is shown that the proposed apparatus is well capable of forming miniature parts with a very good accuracy. An advantage of the proposed method is using a low voltage as compared with voltages usually used in conventional electro hydraulic forming processes.

In the second method, Viscous Pressure Forming (VPF) is used for production of thin sheet metal parts. In this work gold, silver, aluminium and copper sheets are successfully and accurately formed into complex parts. Affecting parameters such as sheet thickness and distance between sheets and forming die on parts quality are investigated. Stress distributions in the main components of the apparatus are obtained by FE method. Accuracy in the product is measured by non contact image processing method. Although the applied mechanism is very simple however measurements of parts and forming die reveal that the accuracies in products are about 8 -10 microns.

Keywords: Micro electro hydraulic forming, viscous pressure forming, thin sheet metal forming

W artykule przedstawiono dwie metody wytwarzania miniaturowych części. Pierwszą jest metoda elektro-hydraulicznego formowania, która jesr analizowana w pracy zarówno teoretycznie jak i doświadczalnie. Zaprojektowane i wykonane zostało urządzenie do elektro-hydraulicznego kształtowania, na którym miniaturowe części zostały wykonane. Teoretyczna analiza procesu obejmuje symulację metodą elementów skończonych. Wykazano, że zaproponowane urządzenie umożliwia uzyskanie miniaturowych części o dobrej dokładności wykonania. Zastosowanie niskiego napięcia, w porównaniu z konwencjonalnymi metodami elektro-hydraulicznego kształtowania, jest podstawową zaletą zaproponowanej metody. Drugą metodą zastosowaną do produkcji cienkich miniaturowych części jest kształtowanie ciśnieniem lepkiej cieczy. Stosując tą metodę wykonano z dobrą dokładnością części o skomplikowanym kształcie zrobione ze złota, srebra, aluminium i miedzi. W pracy badano wpływ takich parametrów jak grubość taśmy oraz odległość między taśmą i kształtującym narzędziem na jakość i dokładność wykonania części. Symulacje metodą elementów skończonych dostarczyły informacji odnośnie rozkładów naprężeń w głównych elementach urządzenia. Dokładność wykonania produktu mierzono bezstykową metodą obróbki obrazu. Chociaż zastosowana metoda jest prosta, to pomiary części wykazały, że dokładność wykonania jest rzędu 8 - 10 mikronów.

1. Introduction

With the development of modern industry, complex demands on sheet metal parts are increasing. The forming applications of high strength, low formability and difficult-to-form materials and complex-shaped parts and miniature parts become wider and wider, which make conventional sheet forming technology face new challenges. Industrial demands on miniature products with high accuracy and complex shapes are increasing.

The demand of miniaturization comes not only from consumers, who are wishing more handy electronic devices and more integrated functions, but also from technical applications like medical equipment, sensor technology and optoelectronics [1, 2]. All these products contain mechanical parts such as leverages, connector pins, resistor caps, screws, contact springs and chip lead frames [2]. Several non-traditional techniques have been proposed for low volume production of complex miniature parts with high accuracies.

Industrial demands on miniature products with high accuracy and complex shapes are increasing. For this

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reason various methods have been invented to produce these parts [3, 4, 5, 6 and 7]. The estimated rise in turnover from 15 to 35 billion US$ in the last 7 years shows a growing demand on micro technical products, which is mainly driven by a rising trend of miniaturization of products [4].

Significant numbers of micro-sheet components, which are popularly used in the electronics industry, are still produced largely by using various stamping configurations. As demands on the variations of the component-forms and the types of the materials increase, process- and toolengineers face new challenges [6].

In this work, viscous pressure forming (VPF) and electro hydraulic forming (EHF) are successfully used to manufacture miniature parts with high accuracies. It will be shown that viscous pressure forming is one of the simplest methods for production of small features in low volumes.

Viscous pressure forming (VPF) is a relatively new sheet forming process. VPF is very similar to conventional flexible sheet forming technology, such as hydro-forming and forming with a rubber or polyurethane pad. Compared with the conventional sheet metal forming processes, the viscous medium can fill a complex-shaped surface very well. The parts formed by VPF have good surface quality and high dimensional accuracy [8]. The thickness distribution of parts with VPF is more uniform than conventional stamping [9]. The stress state of sheet metal with VPF can avoid the inner wrinkling that is brought about with steel punch forming [10].

VPF offers a potentially simple and versatile approach to “soft” tooling forming. In its simplest version, it can be thought of as hydro forming where a viscous yet flowable semi-solid medium is used instead of water. Potential applications of VPF include prototyping and low-to-medium volume production of stretched or drawn sheet metal components, forming of hard-to-form strain sensitive materials, and scratch-free forming of painted or coated sheets [1, 2]. In the present work a viscous pressure forming apparatus is designed and made. Tests are carried out in various conditions and affecting parameters on parts quality are investigated.

Another forming method under high strain rates is Electro Hydraulic forming (EHF), which allows significant improvement of formability, because the technique is associated with a high deformation rate of blank materials [11]. EHF has been extensively studied by [12-19]. EHF is a method suitable for small series production of sheet metal with complex geometries. High velocity sheet metal forming methods, such as electromagnetic forming and EHF, are based on high voltage electrical energy, and aroused considerable interest in the 1950’s and 1960’s in the USA, Japan and Russia (the former Soviet Union) [20].

Improvement of ductility in several materials has been observed under high strain rates [21]. This of course requires the development of methodology for controlling the impulsive pressure waves, i.e. the distribution and time evolution, in EHF [21, 22]. Electro hydraulic forming is based on rapid increase of pressure of water inside a chamber. This water pressure which is in fact a shock wave, acts as a punch. The main advantages of electro hydraulic forming are as follows [23, 24]:

- Minimal spring back of formed sheets because of the extremely fast forming process
- It is an extremely rapid forming process, which increases formability without the need for heat treatment, as is the case with ordinary forming processes.
- Different manufacturing processes can be combined, such as forming, punching, and flanging.
- The method is well suited to small series production, since it is based on economical tool technology, which also leads to fast prototyping.
- For small batches of products with complex 3D forms the EHF method is a cost effective method since only one and inexpensive die is needed and the other side is replaced by hydraulic pulses which acts as punch. Contact friction is also small resulting in minimal surface damage.
- Modular tools can be used.
- It is suited to a wide range of materials.
- EHF can be installed in a conventional hydraulic press that has sufficient free space on the table.

EHF technology shows the greatest potential for forming pieces with a low depth and a complex shape.

The main difference between electro hydraulic forming and socalled traditional forming processes is the tool technology. With EHF, only the die side is required. Hence there is a great potential for tool costs reductions. For small series production, tools can be made from ordinary materials such as wood, plastic or even concrete. Tool steel is widely used, as well as aluminum, for small and medium sized series production [23, 24].

Micro electro hydraulic forming of thin aluminum sheet is investigated in this paper both theoretically and experimentally. Experimental results were compared with numerical results obtained by FE Explicit code.

One of the other advantages of this proposed method is using a low voltage as compared with voltages usually used in conventional electro hydraulic forming processes. The other advantage is using an effective sealing mechanism of fluid between pressure chamber and blank. This method can be employed for small electronic parts. In this paper it will be shown that electro hydraulic forming can be employed for miniature parts. EHF is successfully used to manufacture miniature parts with high accuracy.

Contact measuring methods such as CMM systems are not suitable for thin parts. For this reason a non contact measuring method which is based on image processing is used. In the present work an ATOS system is used to obtain 3D point's cloud of produced parts and also their forming die. In the spite of simplicity, image processed measurements show that the proposed VPF and EHF systems are up to a few microns accurate.

2. Elements of VPF and EHF apparatuses

2.1. VPF apparatus

In viscous pressure forming apparatus, a viscous medium is employed instead of a solid punch for generating pressure on one side of sheet metal. The experimental setup is schematically illustrated in figure 1.

In this apparatus, two pairs of V-Rings are used for effective sealing of pressure cham-ber and preventing leakage of the viscous fluid. To perform the test, the sheet metal is clamped between these two pairs of circular v-rings on the middle plate and lower plate of the die as shown in figure 1. Thus, a fully clamped sheet metal is only allowed to stretch with no drawing. Then the pres-sure chamber is filled with a viscous medium through the ground cylinder. When piston moves down, trapped air on the top of cylinder as well as some of the viscous fluid is drained out through the air vent holes on cylinder body. Then piston moves downwards and pressure is generated in the fluid. This pressure acts on the upper side of sheet surface which stretches the sheet.

One of the most important problems in VPF is fluid leakage. Fluid Leakage causes pres-sure decrease in the chamber.

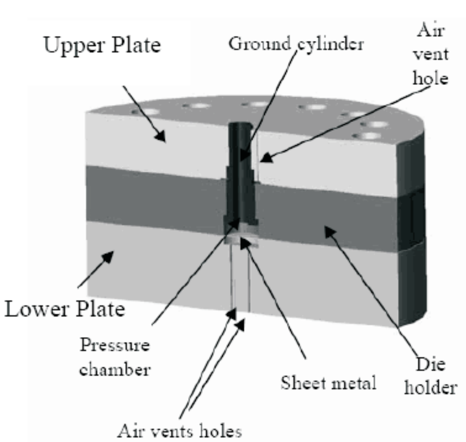


Fig. 1. VPF system components

The leakage process of viscous medium is shown in figure 2. In the present work leakage is prevented by using V-rings as will be mentioned in section 2.

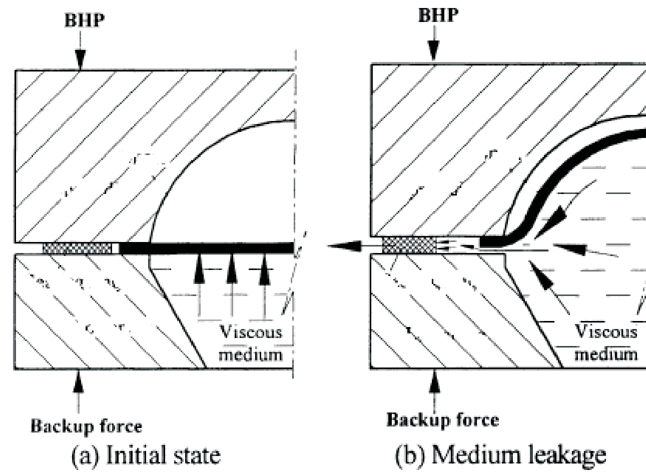


Fig. 2. Leakage of viscous medium [25]

In figure 3, a ground cylinder and a piston which are used in this apparatus are shown. These are made from hardened steel and ground with 2 microns accuracy.

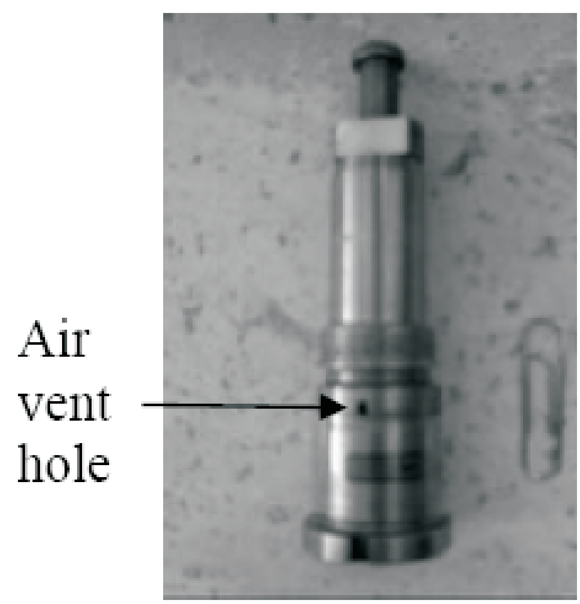


Fig. 3. Ground cylinder with an air vent hole on the middle of cylinder

2.2. EHF apparatus

The EHF experimental setup designed and made in the present work is schematically illustrated in figure 4.

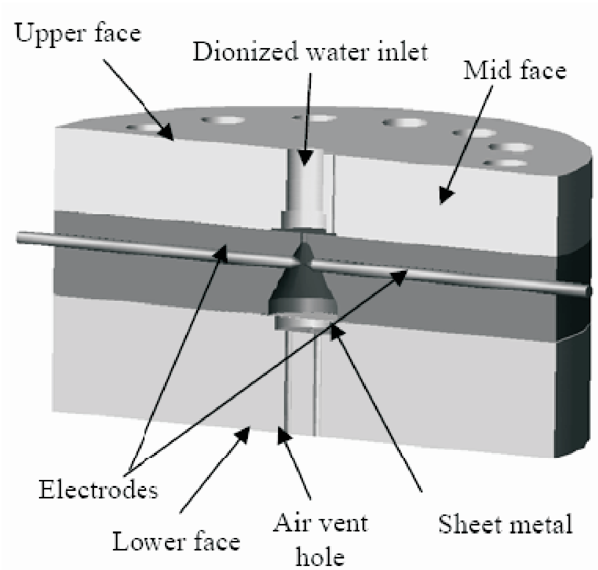


Fig. 4. Electro hydraulic forming apparatus components configuration

In this apparatus, a flat sheet metal is clamped between two pairs of circular v-rings made on the middle face and lower face. Then the pressure chamber is filled with deionized water. There is a pair of electrodes which are inserted into the pressure chamber. Deionized water should be used to prevent unwanted electric discharge between the electrodes. The electrical energy stored in a capacitor bank is converted into hydraulic pressure. The main switch is rapidly closed, leading to a rapid discharge of capacitor bank through the electrodes inside the chamber which is filled with water. This produces an expanding plasma channel and a high intensity shock wave which forces the work piece to move to-wards the die.

The dimension and angle of pressure chamber is very critical.

Very small angle and also very large angle can cause pressure loss. The angle of chamber must be such that to focus the shock wave on the upper side of sheet metal.

3. Design of pressure cham-ber and estimation of the required pressure

In this work, for VPF apparatus a hydraulic press is used and maximum acting force is 30000N. Since the diameter of VPF piston is 10mm then target pressure in the forming chamber is 400MPa.

Considering the maximum pressure and diameter of the chamber, total clamping force can be calculated which is about 500KN. The required screws can then be designed based on this clamping force.

A stress analysis was performed on the components of VPF apparatus by the finite element methods. The result of finite element simulation of pressure chamber holder is shown in figure 5.

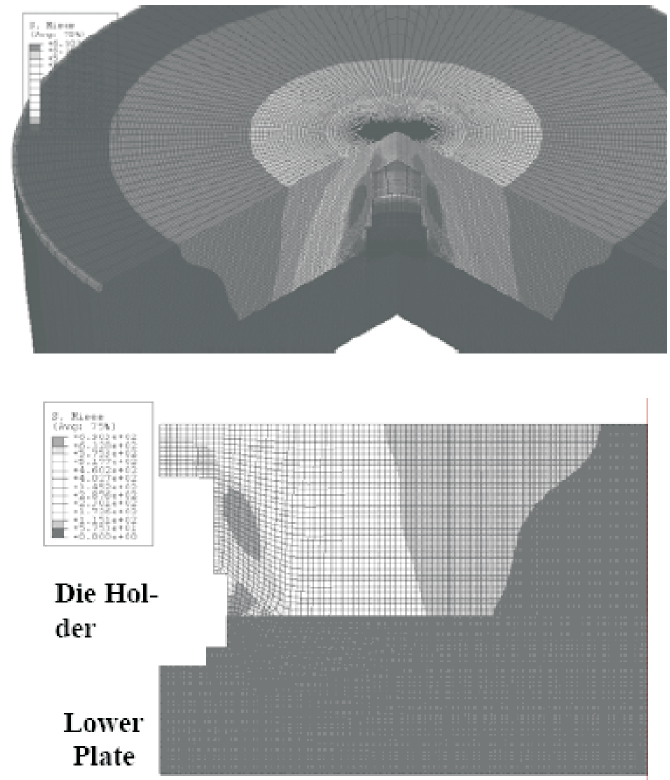


Fig. 5. Finite element results on pressure chamber

In the simulation of the pressure chamber a more critical state was assumed by ignoring the ground cylinder. Hence the estimated pressure is applied to the upper section of the die holder. The upper edge of the die holder and bottom edge of the lower plate are constrained in vertical direction. The maximum estimated pressure in this simulation was 400MPa which is applied to the internal face of the die holder.

Simulation result is verified and compared with thick cylinder theory. Von Mises stresses shown in figure 5, ensures that pressure chamber can withstand the required pressures with a safety factor of 3.

For EHF apparatus based on the stored energy estimated pressure in chamber is lower than 56 MPa. The chamber is made of MO40 steel (corresponding to DIN 42CrMo4). The two V-rings are also ma-chined on this chamber. This type of steel has a very good stiffness. Knowing the yield stress of MO40 and using thick cylinder equations, dimension of pressure cham-ber has been calculated. The chamber was also simulated by the finite element method. The result of FE simulation is shown in figure 6.

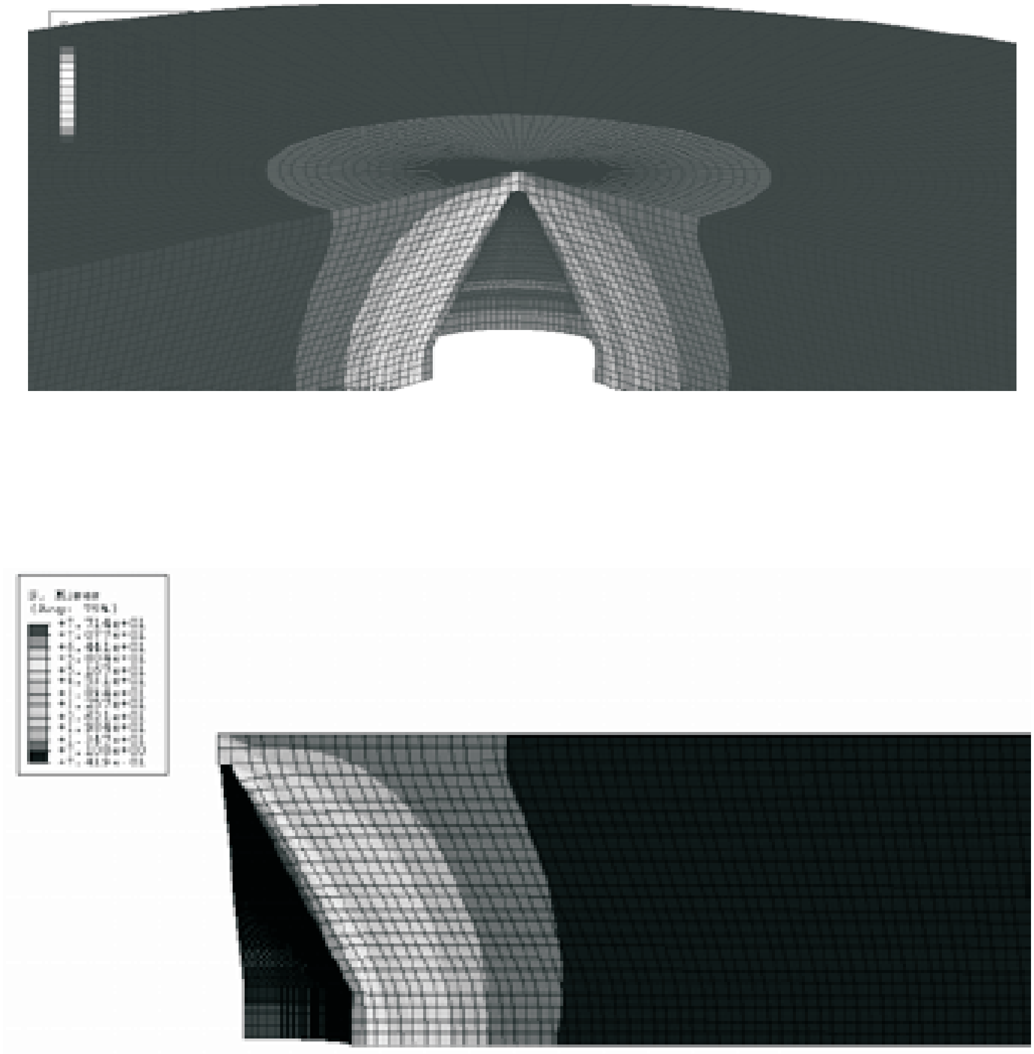


Fig. 6. Von Mises equivalent stress result

Simulation results are verified by thick cylinder analysis. As shown in figure 6 Von Mises equivalent stresses of the pressure chamber are well below its yield stress and hence it can withstand imposed pressures with a safety factor of 5.

4. Simulation of forming process by the fem

A FEM model is used to simulate micro forming of sheet metal with known material properties into a product with a desired geometry. The simulation results are shown in figure 7, where the Von Mises stresses of an aluminium sheet are plotted.

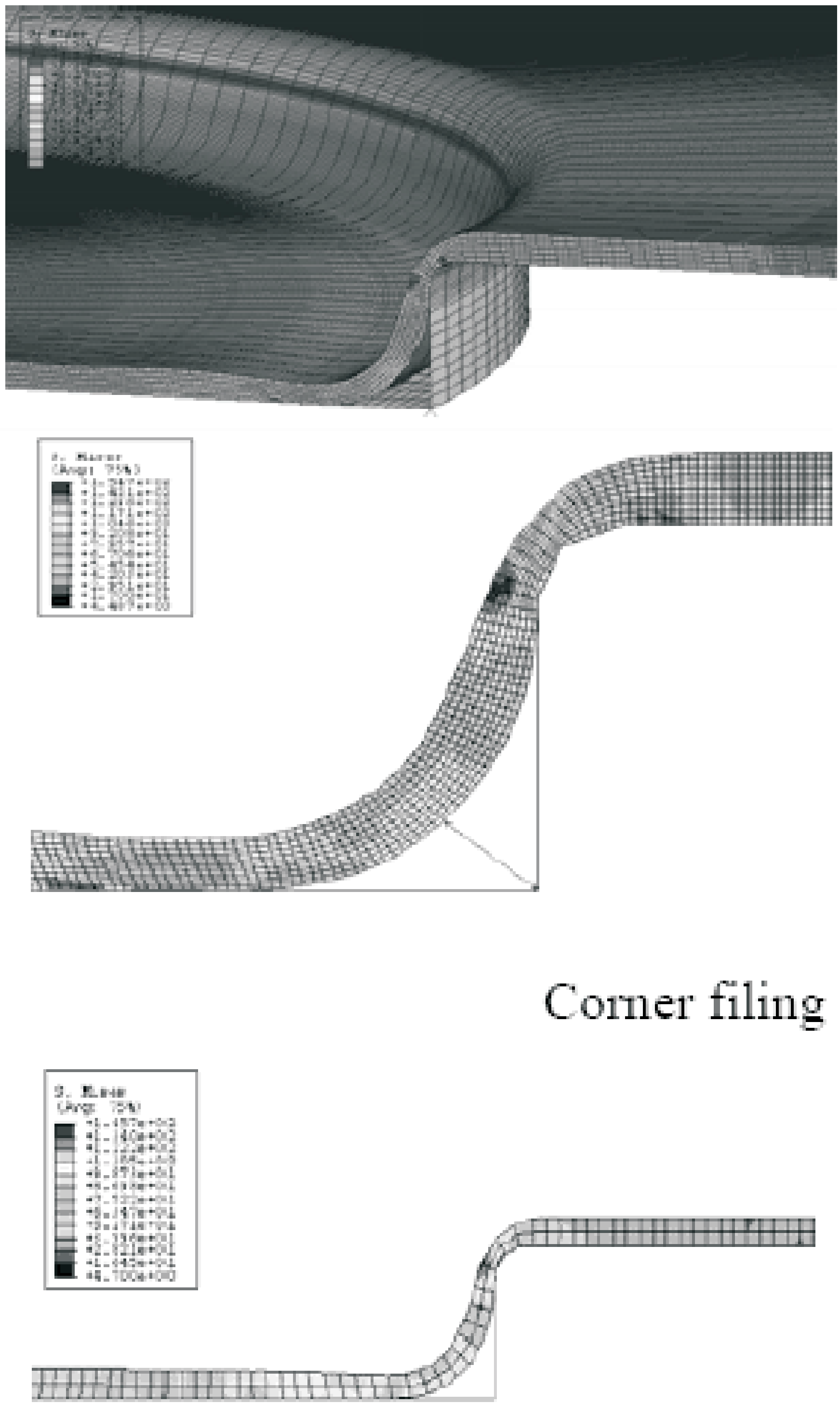


Fig. 7. FEM simulation results of micro forming process for an aluminium sheet

The edge of the sheet is completely constrained. A rigid die with a coefficient of friction of 0.1 is assumed. The distance between die and sheet was altered. The concave radius on the part for an acting pressure of 15 MPa was compared with its analytical value obtained by equation 1.

$$R = \frac{\sigma \times t}{p} \tag{1}$$

p: acting pressure
r: concave radius of formed part
t: sheet thickness
σ: yield stress

The difference between FEM results and equation 1 was less than 15% which shows a good agreement and hence verifies the FEM results.

There is another parameter called corner filling which is studied in these simulations. Corner filling is shown in figure 3 and is defined as the minimum distance between the part and die corner. Step time and mesh sizes were also altered to check the FEM accuracy. This proves that the results are mesh and time independent.

TABLE 1
Effects of step time and mesh size on corner filling predicted by FEM

Corner Filling (mm)	step time (s)	Mesh size (mm)
0.1497	0.05	0.5
0.1485	0.05	0.05
0.1493	0.05	0.033
0.1494	0.02	0.5
0.1495	0.02	0.033

The simulation result of micro forming for a miniature part is shown in figure 8.

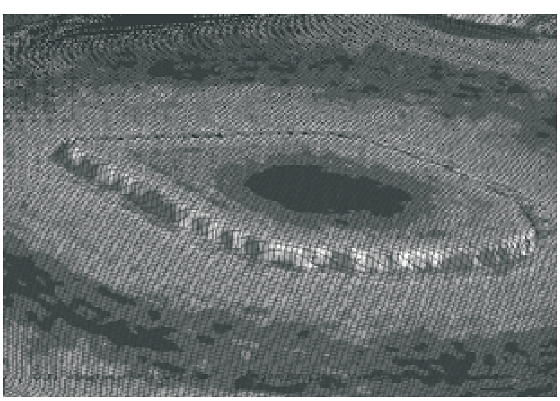


Fig. 8. FEM result of forming simulation for a miniature part

An aluminium sheet of 0.05 mm thickness was formed by 40MPa pressure. The edge of the sheet was completely constrained and a rigid die with a friction coefficient of 0.1 was assumed.

Figure 9 shows the internal energy and kinetic energy diagrams of FEM simulation of micro forming process. As shown in the figure, the kinetic energy almost lies on the x-axis and is very much lower than the internal energy which validates the assumed step time.

5. Design of power supply circuit for the EHF

In the present research an innovative low voltage circuit as compared with those usually used in conventional electro hydraulic forming processes, has been used. Besides reducing the costs, this increased the safety of the apparatus.

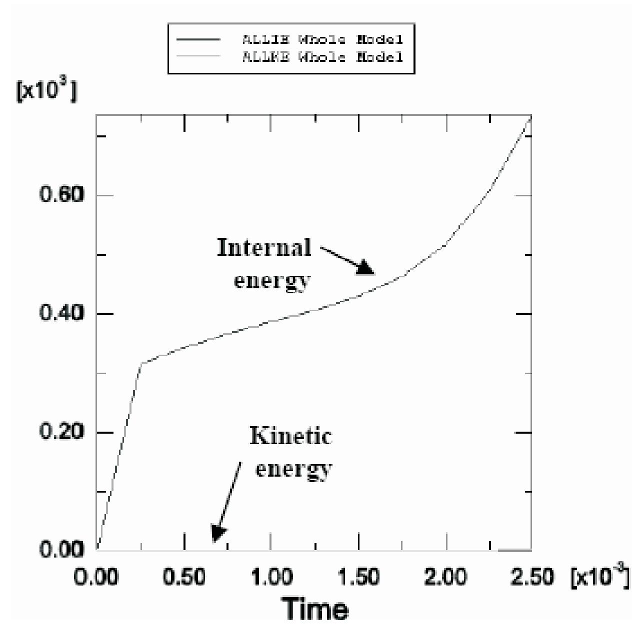


Fig. 9. The internal energy and kinetic energy diagrams of FEM simulation

In this work, a rectifier is used to convert alternative current into direct current as shown in figure 10.

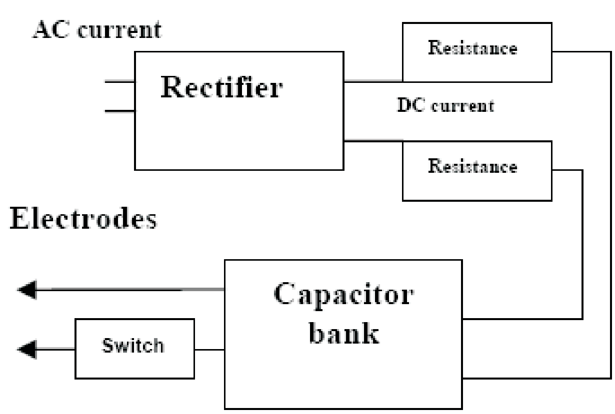


Fig. 10. Power supply circuit

High power ceramic resistances have been used to prevent a sudden spark and to delay the charging time. These ceramic resistances have been serially connected to external rectifier poles. The electric current passes the resistances and enters to the capacitor bank.

While the capacitor bank is being charged to the desired energy level, the switch is set to an open position.

When the capacitor is fully charged, the switch can be closed as required. On the other hand, in some applications, the switch can be left closed while the capacitors are being charged.

In this apparatus the stored energy in the capacitor bank is about 230 Joules. The theoretical discharge time of 80% of total energy is 0.14 s and the total discharge time is 12.49 s. After being charged, the capacitor bank can also be automatically and gradually discharged after a long time. It is one of the other advantages of this power circuit. Automatic discharge of the capacitor bank increases the safety of the apparatus.

As mentioned earlier, in the present work due to miniature size of target parts, a low voltage circuit is used as compared with conventional electro hydraulic forming processes. For example, the electro hydraulic forming machine at VTT (Technical Research centre of Finland) has the following technical characteristics: maximum capacitance 60 μF (10 x 6 μF), maximum charging voltage 40 kV, maximum impulse energy 48 kJ and impulse frequency 0.2 Hz [22]. In their machine a set of capacitors is charged using a fully controlled three-phase six-pulse rectifier. A maximum current up to 200 kA can be achieved, and the maximum input power required is 25 kW [22].

Two 4mm diameter copper electrodes were used in the present research. The heads of electrodes have been ground conically to concentrate the discharged of energy. The electrodes must be isolated and for this reason plastic covers were used. The isolated electrodes used in this work are shown in figure 11.

Sealing of electrodes is very important to prevent the leakage of dionized water from pressure chamber during the process. Because when the fluid leaks from the chamber, pressure is lost. This problem was solved by using a soft rubber.

In this process sheet metal is stretched dur-ing the process and for this reason it is fixed at the edges other wise it will be drawn and it may wrinkle.

Fig. 11. Isolated electrodes used in the present work

In this work, two V-Rings are used to prevent the fluid leakage and also to clamp the sheet. Two V-Rings have been machined on the middle face and lower face of the pressure chamber as shown in figure 12. The V-Rings should be designed and made such that not to tear the sheet.

Figure 12 shows the position of electrodes in pressure chamber as well as the machined V-Rings.

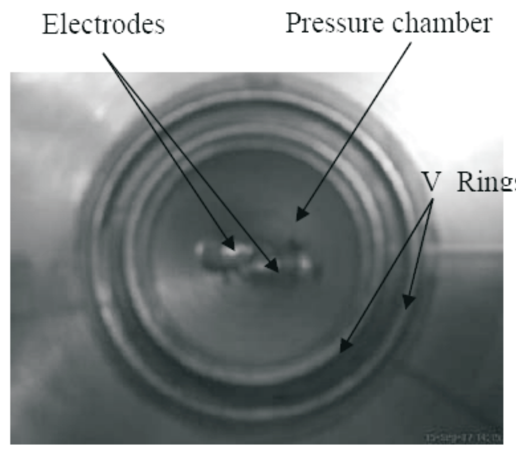


Fig. 12. Copper electrodes and machined V-Rings on the pressure chamber

Considering the maximum pressure and diameter of the chamber, total clamping force can be calculated. The required screws can then be designed based on the clamping force.

6. Experimental results of VPF method

VPF process is used to manufacture miniature parts. In this study the commercial aluminium foil with a thickness of 0.05mm, copper 0.1mm and 0.2mm thick, also gold and silver sheets of about 0.2mm thickness have been used.

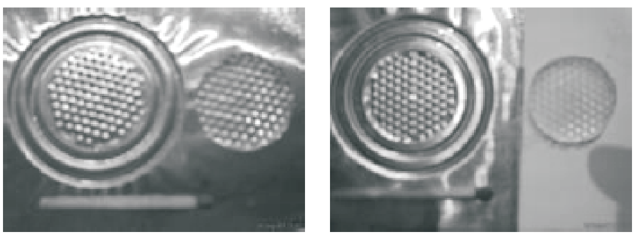
In figure 13 deformed aluminium specimen and its obtained precise features are shown.

Fig. 13. Deformed specimen and its precise features

The effect of various parameters on the viscous pressure forming is investigated by experiments. The qualities of parts were improved by optimizing influencing parameters.

6.1. Influence of stand -off on part quality

In experimental tests on copper sheets of 0.1mm and 0.2 mm thickness with a reticular forming die, it is seen that stand-off (distance of between lower side of sheet and upper side of die) is one of the most effective parameters on part quality. Optimum stand-off distance depends on sheet metal material and thickness. Manufactured parts by reticular die are shown in figure 14.



a b

Fig. 14. The effect of sheet metal thickness on stand-off distance. a: Smaller stand-off (copper sheet 0.2 mm thick), b: Larger stand-off (copper sheet 0.1 mm thick)

6.2. Manufactured sculptural parts

In cases that sculptural feature die is used, it is better to allow some drawing by loosening the clamping screws. Then the piston is moved down slowly for example by hand to make a preform on part. In the next step the sheet is fully clamped and piston is moved down faster by press to stretch the sheet. By this approach better sculptural features can be made. Some of the results are shown in figure 15.

Fig. 15. Manufactured sculptural parts made by copper sheet with 0.1 thicknesses

6.3. Sample parts made with plastic dies

One of the best advantages of this apparatus is the ability to manufacture miniature parts with almost any die material.

Figure 16 shows the manufactured parts by plastic dies. As shown in the figure, various futures can be made by using plastic dies. However the accuracy depends on the stand off distance and allowing some drawing as the pre-form stage as mentioned in section 6-2.

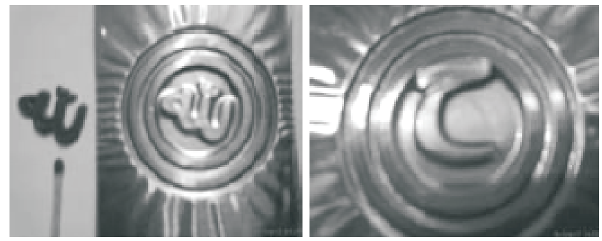


Fig. 16. Manufactured parts over plastic dies

It should be mentioned that two bottom air vents are also used as shown in figure 4. With an entrapped air the formed parts might either rupture or bulge as shown in figure 17.

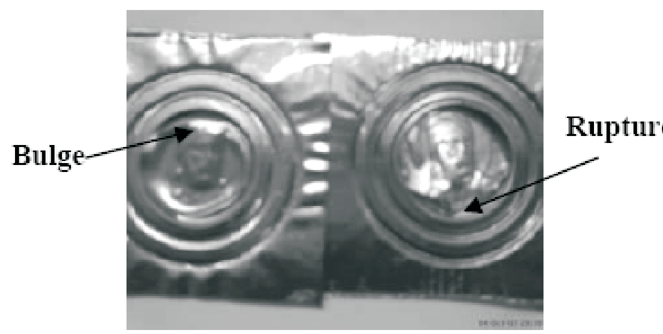


Fig. 17. Effect of entrapped air, on products quality

6.4. Viscous pressure forming of gold sheets

Figure 18 and 19 show a formed complex part from gold metal.

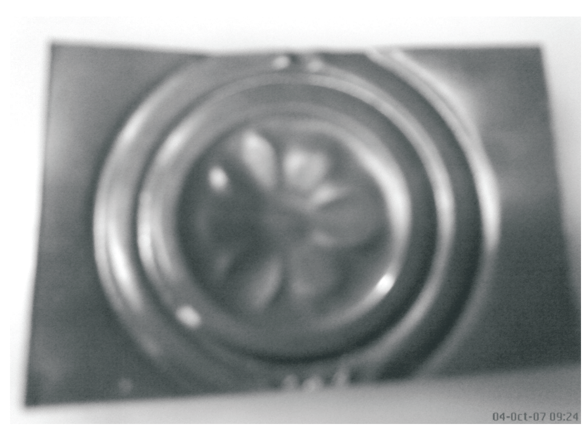


Fig. 18. A golden part before polishing made by VPF method

Figure 18 and figure 19 show the part before and after polishing respectively. Before VP forming the gold sheet was rolled down to 0.2 mm.

Fig. 19. A golden part after polishing made by VPF

6.5. Viscous pressure forming of silver sheets

In order to use silver sheet, it was rolled down to 0.2 mm thick, similar to gold sheet. The formability of silver sheet was better as compared with gold sheet. Some of the parts made with silver sheet are shown in figure 20. The silver purity of the sheet in these tests was 92%.

Fig. 20. Silvery formed parts

6.6. Comparison of the quality of formed parts of different sheet materials

Figure 21 shows successfully formed parts using gold, silver and copper sheets. Comparisons reveal that cooper sheet has a better formability and each sheet material has a particular optimum stand-off.

Fig. 21. Formed parts made from silver, copper and gold (left to right)

6.7. Effect of viscosity on parts quality

As compared with the hydro forming processes in which the viscosity of used fluid is low, viscous pressure forming yields better results. This is due to the fact that in VPF process leakage of fluid is decreased directly with the fluid viscosity. Two fluids with different viscosities have been used to check this parameter. Experiments revealed that more viscous fluid yields better results.

7. Experimental results of EHF method

Deformed parts and obtained precise sam-ples of aluminium sheet by EHF method are shown in figure 22.

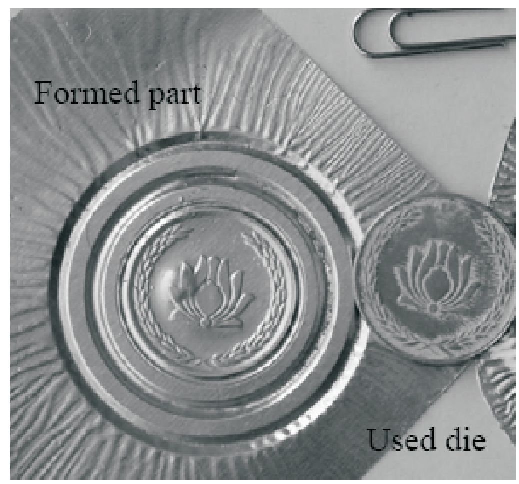


Fig. 22. Deformed precise aluminium parts made by EHF process

The effect of entrapped air, on the product is shown in figure 23. As it can be seen, sheet inflation can occur in the product when the air vents are closed.

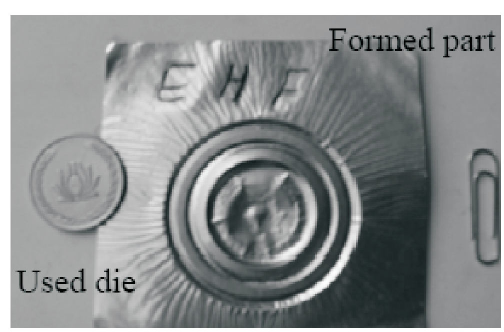


Fig. 23. Effect of entrapped air, on the product quality

8. Non contact measuring method to investigate product accuracy

Contact measuring methods such as CMM systems are not suitable for thin parts. For this reason a non contact measuring method which is based on image processing is used. In the present work an ATOS system is used to obtain 3D point's cloud of produced parts and also their forming die.

In figure 24, a non- contact image processing equipment is shown which is used in the present work.

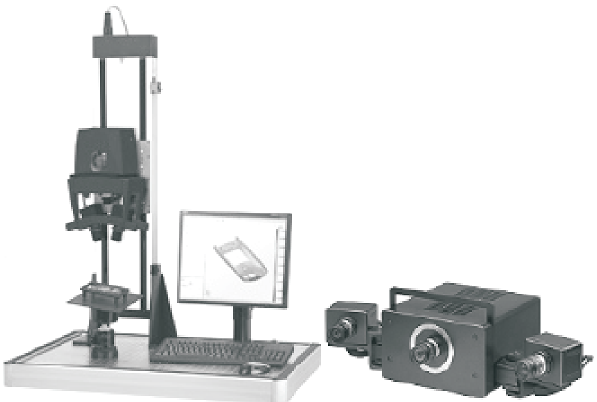


Fig. 24. Apparatus for non-contact image processing, used in the present work

Figures 25, 26 show the measured part by non-contact measuring method and also 3D point's cloud of the formed parts.

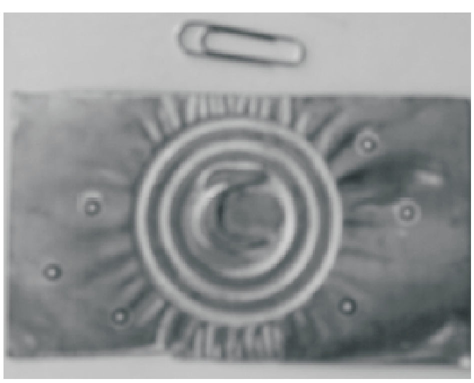


Fig. 25. Measured part by non-contact measuring method

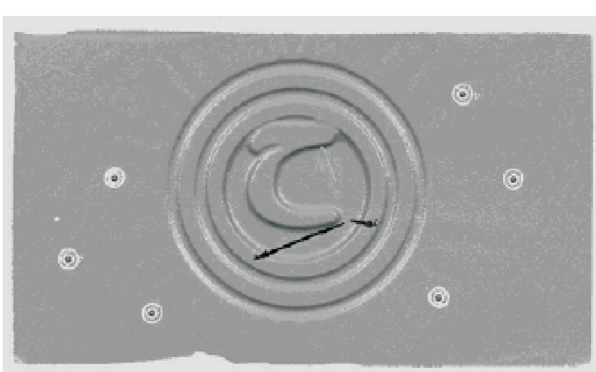


Fig. 26. 3D point's cloud of produced parts

The forming die which is used in this test is seen in figure 27.

Fig. 27. Used forming die

Measured data obtained by non-contact image processing are about 1 micron accurate. The point's cloud of the forming die and manufactured part are compared as shown in figure 28 which reveals that VPF process is up to 7 microns accurate. Contours show the dimensional deviation of die and part. Maximum dimension deviation is seen on the boundaries of part and minimum dimensional deviation occurs in the middle.

Hence although the proposed VPF system is simple but image processed measurements show that it is up to a few microns accurate. The EHF results are even better than VPF.

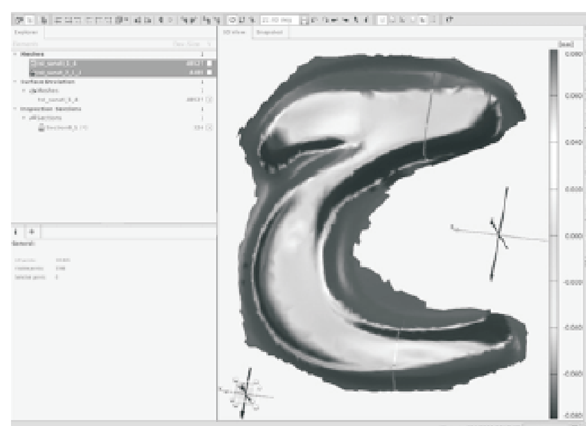


Fig. 28. Dimensions deviation of die and produced part by non-contact measuring method

9. Conclusions

In this work, an innovative electro hydraulic forming (EHF) method for forming thin sheet metals and miniature parts was developed. The produced parts had a good accuracy. An experimental apparatus was made to show the feasibility of the idea. Besides experiments the micro electro hydraulic forming of the aluminum thin sheet was studied by the FEM.

A low voltage electric circuit was also designed and made in this apparatus. It was shown that highly accurate products can be made and also due to low voltages used in the apparatus safety of the process was increased. Another advantage of the low voltage is reduced electrode erosion. By this method, miniature parts can be made to be used in adornment arts.

On the other hand viscous pressure forming process has found many applications in industry because of its simplicity, rapid set up, product quality and economical aspects. In this article, viscous pressure forming process was also successfully used to make miniature and adornment parts. The process principles, features and its development were introduced in detail and important parameters affecting product quality were discussed. It was shown that VPF process can be used in micro sheet metal forming indus-try.

It was realised that parameters such as type of material, metal sheet thickness, fluid viscosity and stand-off distance are very important aspect of viscous pressure forming and can have a direct impact on the quality of the formed part.

VPF can be used in jewellery workshops and production of adornment parts. The obtained products by VPF and EHF methods had high surface qualities and no scratches on the part surfaces and high dimensional accuracies.

One of the obvious advantages of theses processes was that only one side of the embossing die is necessary and it may be made out of any material. Among the advantages of the designed apparatuses were rapid tool manufacture and easy equipment set-up. The forming die could be rapidly changed to make a new geometry with a complex shape and miniature feature with an accuracy of about 8 to 10 microns. The proposed apparatuses were simple and used effective sealing and clamping mechanisms.

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