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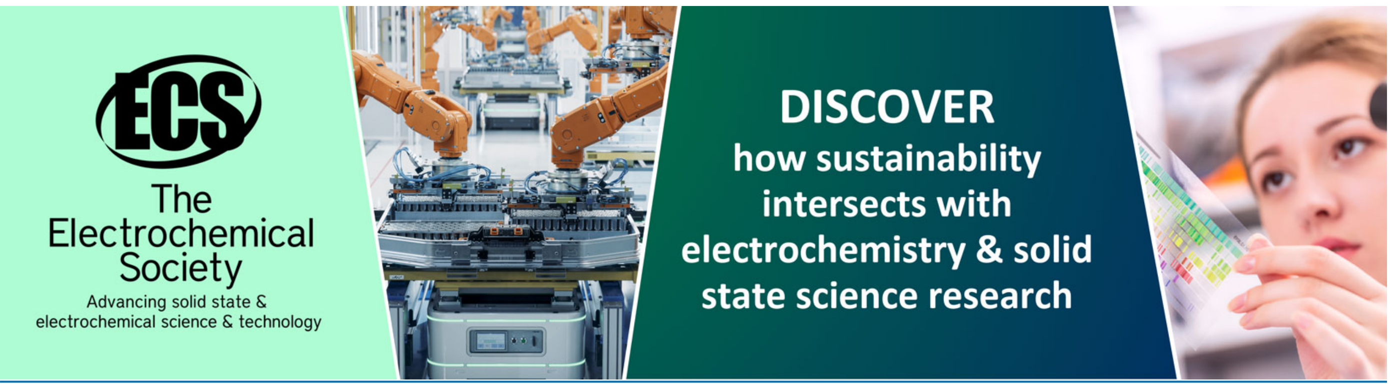

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Experimental research and numerical optimisation of multi-point sheet metal forming implementation using a solid elastic cushion system

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Abstract. There is a growing demand for flexible manufacturing techniques that meet the rapid changes in customer needs. A finite element analysis numerical optimisation technique was used to optimise the multi-point sheet forming process. Multi-point forming (MPF) is a flexible sheet metal forming technique where the same tool can be readily changed to produce different parts. The process suffers from some geometrical defects such as wrinkling and dimpling, which have been found to be the cause of the major surface quality problems. This study investigated the influence of parameters such as the elastic cushion hardness, blank holder force, coefficient of friction, cushion thickness and radius of curvature, on the quality of parts formed in a flexible multi-point stamping die. For those reasons, in this investigation, a multi-point forming stamping process using a blank holder was carried out in order to study the effects of the wrinkling, dimpling, thickness variation and forming force. The aim was to determine the optimum values of these parameters. Finite element modelling (FEM) was employed to simulate the multi-point forming of hemispherical shapes. Using the response surface method, the effects of process parameters on wrinkling, maximum deviation from the target shape and thickness variation were investigated. The results show that elastic cushion with proper thickness and polyurethane with the hardness of Shore A90. It has also been found that the application of lubrication cans improve the shape accuracy of the formed workpiece. These final results were compared with the numerical simulation results of the multi-point forming for hemispherical shapes using a blank-holder and it was found that using cushion hardness realistic to reduce wrinkling and maximum deviation.

1. Introduction

The multi-point forming (MPF) process is a state-of-the-art manufacturing technology which is different from other traditional forming processes. Die elements can be easily adjusted during the MPF process. This research uses finite element modelling (FEM) in the MPF process which is quite a challenging task. This method is established on dynamic result processing, containing the wrinkling, damping various sheet materials and where the designs of the elastic cushion are analysed, forming forces (kN) and the mass. In the numerical calculation of the motion, by using the significant gap method, the analysis related to local deformation in certain layers on the sheet metal problem reduces memory and control times and improves computation productivity. It takes into account non-linear geometry and boundary conditions, such as a discretely adjustable punch (discontinuous contact

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surface) [1]. A numerical study in which pins are assembled next to each other in the X, Y axis and pins' heights are set in the Z plane forming a (3D) curved surface. A numerical optimisation technique is used for coupling with FEA of the stamping/sheet, with the cushion processing used in manufacturing techniques to form parts in many industry sectors. Here we have theorised an elastic cushion optimisation method for multi-point sheet metal forming. Sheet metal parts are usually made by metal forming using cold forming, creating curvature described by applying spline functions. The curvature was optimised using the software in order to minimise production cost, whilst finding the accuracy and deformation of the end sheet metal. In the present work, contact elements are generated between the sheet and the upper and lower cushions for the forming process [2]. The contact pressure, stress and load requirements are captured for different radius of curvatures of multi-point forming. In order to reduce deformation in flexible MPF techniques, various elastic cushions with different harnesses (A85 and A90), different sheet thicknesses and two tips of pin radius (10mm,20mm) were simulated with FE modelling, producing an optimal polyurethane with the hardness of Shore A90 ,thickness and pin size. Kim Y stated that the pin size of the die provides a continuous pressure distribution on the workpiece, thus preventing possible wrinkles.[3] The method of choice is the introduction of an interpolating polymer layer "interpolator" between the die and the workpiece, Alsayyed B and Harib K [4] proposed the use of a protective cushion layer with a circular shape for MPF. Desari Z B and Davoodi B 2017 presented the first alternative set-up of an MPF prototype. They recommended the use of a mechanically, reconfigurable shape consisting of thin wires related together with a retainer. Investigated tests were conducted for two different geometries employing AA 2024-O aluminium alloy as their sheet material. They used the obtained minor and major strains from FE simulations and employed FLD criterion, then the location and depth of the rupture were predicted. It was proved that the elastic cushion, as had been expected, had an impact on wrinkle, deformation and dimpling, separation and dimensional accuracy of formed parts by MPDD process. It is recommended by Nishioka F et al that reconfigurable pins could be controlled by a numerical 3-axis small (CNC) machine [5]. Olsen proposed an optional discrete die surface (ODS) system controlled by automatic design and a shape controller by mathematic algorithms for the discrete die tooling [6]; which is well known as a type of reconfigurable tooling for flexible forming technologies [7]. The paper details work on the investigation of 3D ABAQUS/Explicit code FE software used to conduct numerical simulations for an multi-point sheet forming process. Basic research was carried out on fundamental mechanisms of flexible MPF techniques (e.g. with an investigated the effect of cushion thickness and hardness) on the quality of deformed parts. FEM and simulation of deformation defects (sheet dimpling and wrinkling), to produce the desired the desired shape of the metal part with minimum cost by measure sheet profile and thickness. The optimum factor of elastic cushion thickness and hardness was determined based on the numerical simulation results and was validated by experiment.

2. Mechanical model set-up

2.1 MPF details

The commercial MPF process sheet having a uniform the thickness of 1mm was used in the present work. Two types of polyurethane with the hardness of Shore 90 A, 85 A were tested as elastic cushion materials. The MPF process model is performed with two groups, the lower and upper groups, of punches being simultaneously moved toward both surfaces of a sheet. The FEM simulations are done for two applications placing an elastic cushion on both sides of blank and using an elastic cushion have various thicknesses between the matrixes and blank-holder[8].The decrease of thickness by increasing the hardness of the elastic cushion. At this position, all pins were in contact with the thickness 3 mm elastic cushion and plastic deformation started to take place. After that, the force rapidly increased with plastic deformation due to strain hardening of the material. Due to symmetry, only a quarter of the MPF die was FEM simulated to reduce computation time is shown in figure 1. The pins have a hemispherical tip and square cross section. The pin tip, elastic cushion, blank holder, radius curvature was considered. The mesh density was allocated in a way to provide appropriate results in analysis [9].Since only a quarter of the FE model was considered, symmetric boundary conditions were applied to the sheet metal steel (DC05) and polyurethane with the hardness of Shore A90. The sheet and elastic cushion were modelled as deformable bodies and the ABAQUS/Explicit software C3D8R quadratic element type was used.

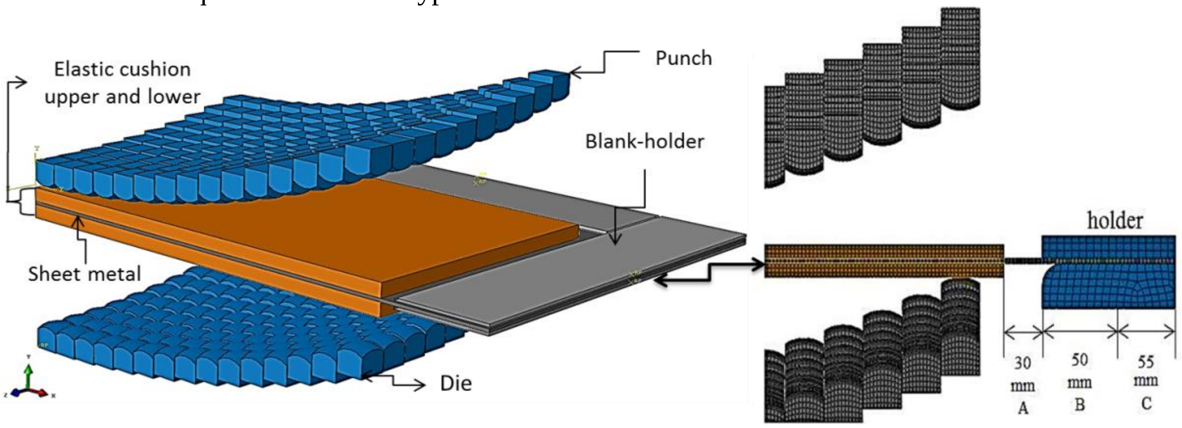


Figure 1. MPF with blank holder (BH), geometry element mesh size and boundary conditions.

2.2. Material analysis
The material of the blank sheet used in the numerical simulation is medium strength DC05 steel with 1mm thickness. To determine the mechanical properties of the material, tensile tests were carried out using a Zwick/Role test machine on specimens prepared at 0^0 ,45^0,90^0 with respect to the rolling direction. Table 1 shows the material properties.

Table 1. The mechanical properties of the sheet metal steel (DC05) included in the experimental test.

Property/Units	Value
Density/(kg/m^3)	7850
Young's modulus /(GPa)	220.3
Yield stress/(MPa)	201.9
Strain-hardening exponent (n)	0.17

The experimental behaviour of the elastic cushion was also compared against three material models, namely, Mooney–Rivlin, Neo-Hooke and Yeoh. As shown in figure 2, the hyperplastic model Mooney–Rivlin model describes well the hyperplastic behaviour of polyurethane (A90).

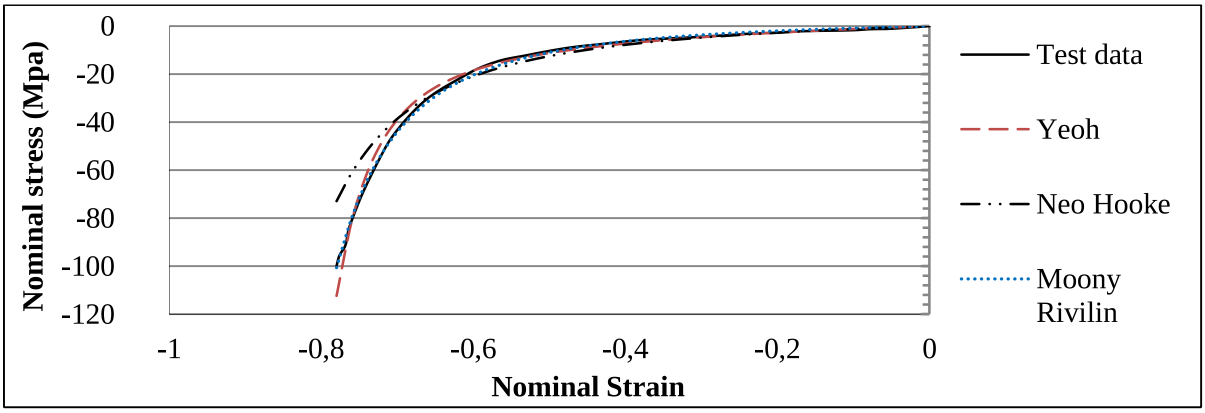


Figure 2. Nominal compression stress and strain relationship for elastic cushion material.

Power law equation was selected to represent the flow stress of the material as shown in equation 1. [10]. In the analyses, the square sheet of 30×20mm is discretized into element groups. Their materials: steel DC05, were involved in numerical investigations.

$$\sigma = k.\varepsilon^{n} \tag{1}$$

Where is true stress, k is strength coefficient, ε is a true strain, and n is strain hardening.

Where U is the strain energy per unit volume; (I1) and (I2) are the first and second invariants of the deviatory strain tensor; and (C_{10}) and (C_{01}) are temperature dependent sheet metal material properties obtained from a uniaxial compression test conducted using a Shore hardness of A90. The values of (C_{10}) and (C_{01}) are 0.861 and 0.354 individually. The solid elastic cushion was obtained using a Zwick tensile test machine. In this investigation, the material of the elastic cushion was chosen to be (Mooney–Rivlin) polyurethane hardness A 90 as it is commonly used in this process are shown in table 2. The material was assumed to be isotropic and the elastic-plastic model was used. Ludwig's equation was selected to represent the flow stress of the material as shown in equation (2) [10].

$$\mathrm{U} = \mathrm{C}_{10}(\mathrm{I}_1 - 3) + \mathrm{C}_{01}(\mathrm{I}_2 - 3). \tag{2}$$

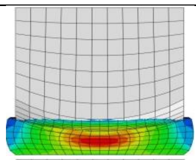
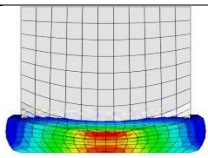
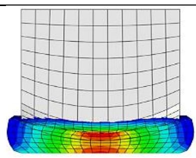
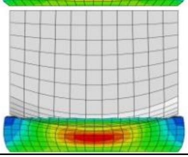
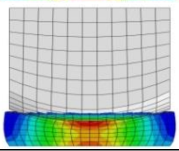
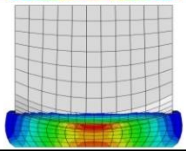
Table 2. Shows experimental compressive test material parameter of the elastic cushion.

Method	Material/Hardness	Material thickness	Model of elasticity (E)	Poisson's ratio (υ)
Zwick tensile test machine	Mooney–Rivlin / A90	3 mm	2.87 MPa	0.499

3. MPF processes

The use of material (Mooney-Rivlin) FEM simulation considers the metal sheet as polyurethane A90, which is the more realistic way to FE model mesh and boundary condition in the single pin as shown in Table 3, the three different compression (30%,40%,50%) decrease with the thickness of elastic cushion is 3 mm. However, almost all of the reduction is obtained with an elastic cushion thickness 3 mm where the maximum interior stress is reduced from 10.120 N/mm^3 for a hard seat to 10.870 N/mm^3. In fact, the shear stress increases slightly for thickness elastic cushions. The maximum interior stress is indeed greater than the maximum interface pressure, but they are not in constant proportion. FEM for a hard seat 1.1mm, the interface pressure is 30% of the maximum interior pressure; whereas for a 1.2mm seat it is 40% of the maximum interior pressure, whereas for a 1.5 mm seat it is 50%.

Table 3. The maximum interior stress on maximum seat interface pressure, and maximum shear stress

Note	Factor/ Polyurethane	Compression of single pin ratio=30% from thickness 3mm	Compression of single pin ratio=40% from thickness 3mm	Compression of single pin ratio=50% from thickness 3mm	Values
1.	A85				1.3178 (MPa)
2.	A90				0.7883 (MPa)

Regarding the compression of single pin ratio=40% from elastic cushion thickness 3mm simulation results, the polyurethane A 90 suitable to use with MPF die in this study.

3.1. Validation of MPF

FE models were investigated for a MPF die, which consists of a pair of pin matrices, a blank-holder, sheet and upper and lower elastic cushions. To reduce deformation defects (dimpling, wrinkling and thickness of the metal sheet), FE simulation for one-pin configurations (tip of pin radius 10 mm) has been carried out using a solid elastic cushions of hardness polyurethane Shore A90 thicknesses 3 mm. The MPF and FE simulation load gradually increased to 53.84 kN which corresponds to 40 mm of the upper die displacement.

3.2. MPF and FEM simulation

The CAD designed lower die and upper punch was simulated using 3D ABAQUS/Explicit with 1mm sheet metal thickness on the MPF set-up for the method for processing sheet metal with a blank holder (BH) device. At this position, all pins were in contact with the elastic cushion 40% compressed and plastic deformation started to take place. The model was developed to form doubly curved parts the MPF set-up for the case with 400 radiuses of curvature is 10 × 15 pins with 10 mm tip radius were used.

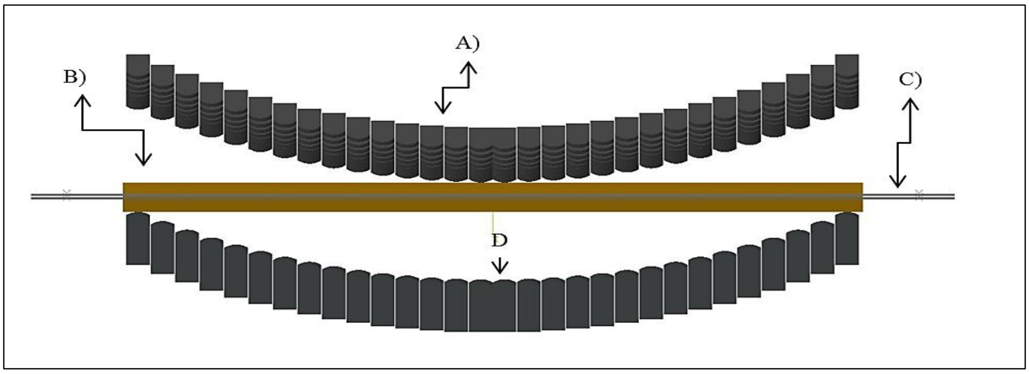


Figure 3. Finite element model

Where: A) punch, B) elastic cushion, C) blank holder with sheet metal, D) lower die.

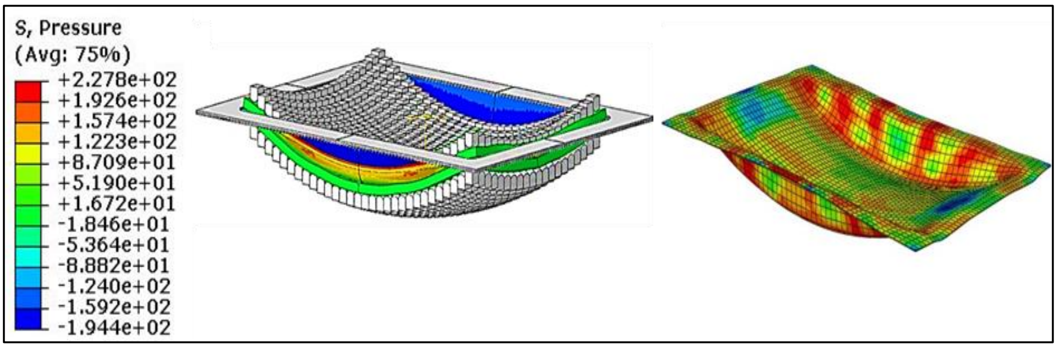


Figure 4. Pressure distribution on the multi-point forming and FEM simulation.

4. Experimental investigation of MPF implementing in an elastic cushion system

4.1. Validation of experimental multi-point sheet metal forming configuration

The experimental MPF parameters used from the above literature were the upper die, lower die, sheet-metal plate, upper and lower rubber material, which was modelled with a (die-punch) tool composed of two working arrays with (300) pins for each array,(30) rows of X-direction and (20) columns on Y-direction. The active blank dimensions 300 mm × 200 mm. The punch and die each contained 30 × 20 pins. The sheet material was steel DC05 of 1 mm thickness. The MPF set-up for the case with 400 mm radiuses of curvature shows the figure 5 was 40% compression distribution on the completed deformed sheet when 10 mm pins are used.

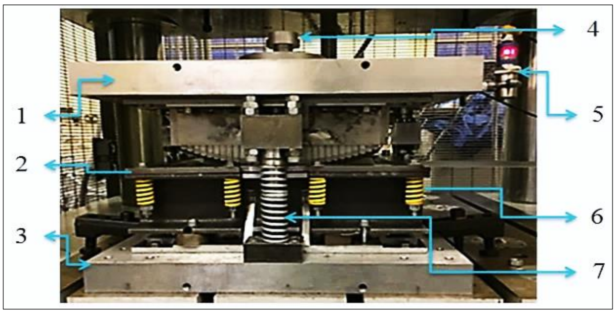


Figure 5. Experimental investigated final test set-up on MPF.

Where: 1) upper die; 2) blank holder with an elastic cushion; 3) lower die ; 4) load cell; 5) distance sensor fixing; 6) blank springs; 7) punch spring.

Table 4. The best process parameters were used in the experimental validation of MPF specification.

Factor	Forming curvature	Blank holder force	Elastic Cushion A90/Thickness	Punch movement	Steel DC05/sheet thickness
Level	R= 400 mm	F= 11.40 kN	EC= 3.0 mm	40 mm	1mm

The optimal working experimental process parameter as shown in Table 4 MPF loads gradually increased to 55.98 kN, which corresponds to 40mm of the upper die displacement. At this position, all pins were in contact with the elastic cushion 40% compressed and plastic deformation started to take place. The experimental sheet metal forming was measured using a Faro Arm 3D laser scanner for best-fit comparison results and dimensional analysis as shown in figure 6.

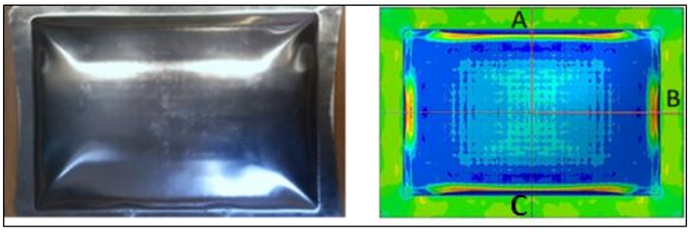


Figure 6. Comparison of experimental shape with numerical shape parts of steel formed by the 400mm radius of curvature with blank holder.

4.2. Prediction effect of forming thickness and wrinkle

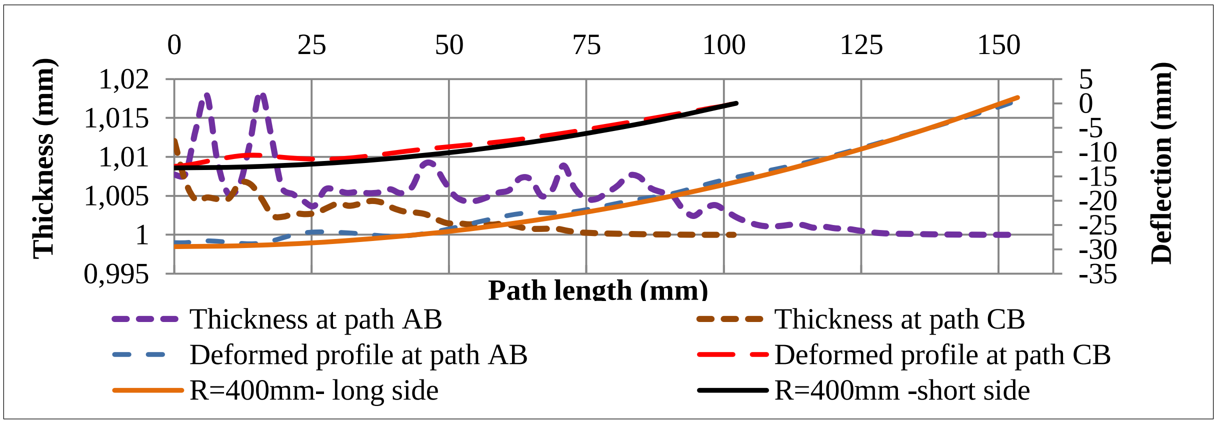


Figure 7. Model validation: Effect of elastic cushion thickness on wrinkling and thickness variation in (radius of curvature=R400mm).

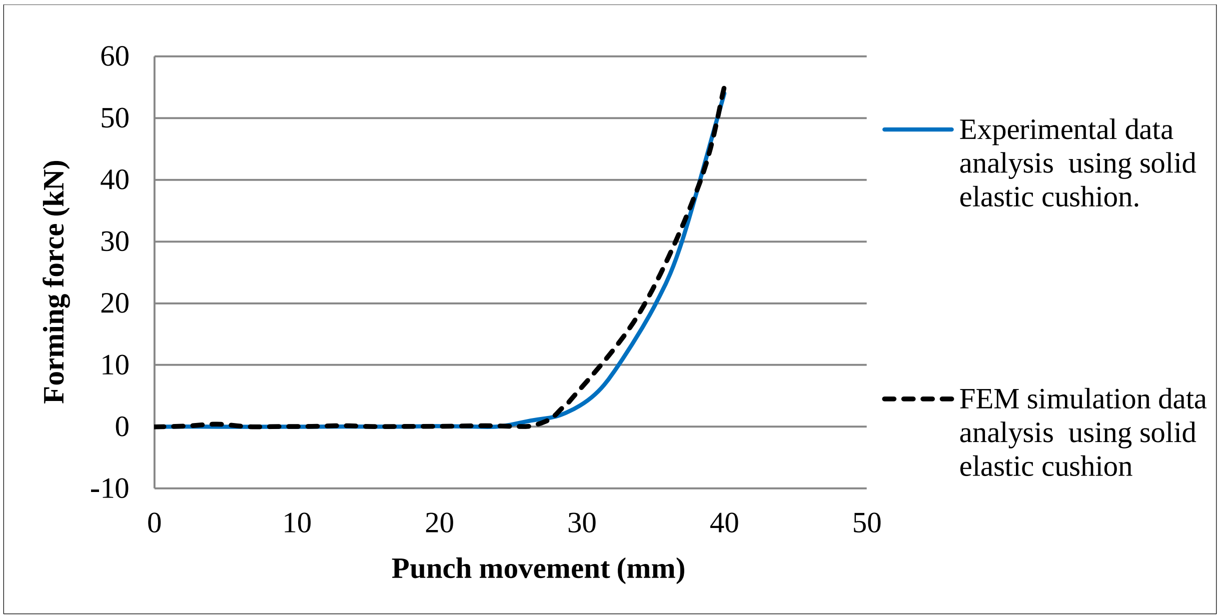


Figure 8. MPF model validation: Forming force

4.3. Results and discussion

Figure 7 the predicted profile of the formed sheet using the FEM and the experimentally measured profile a Faro Arm (Geomagic Control-X) Edge 3D surface scanner. There was good agreement between the experimental and simulation results wich is the deffected by at most 1.5741 mm near the centre of the sheet A to B.

MPF load gradually increased to 53.84kN, which corresponds to 40mm of the upper die displacement. At this position, all pins were in contact with the elastic cushion and plastic deformation started to take place. After that, the force rapidly increased with plastic deformation due to strain hardening of the material [11]. The maximum predicted force is about 55.98kN when the upper and lower dies are closed.

The criterion for thickness variation calculations was formulated as follows:

$$\text{Thickness variation} = (\tfrac{1}{N}\textstyle\sum_{i=1}^{n}(x_i - \bar{x}))^{1\,^{1/2}} = 0.19850 \tag{3}$$

Table 5. Predicted and observed response parameters effect of experimental MPF.

Level	Wrinkling [mm]	Max. deviation [mm]	Thickness variation [mm]	Forming force/kN
Predicted	(2. 8900E-007)≈0	1.0967	0.10000	53.84
Measured	1.5741	0.0558	0.15850	55.98

5. Conclusions

An experimental investigation of polyurethane hardness of Shore A90 and steel DC05/sheet thickness 1 mm was carried out by using MPF with 400 mm curved then the validation between FE analysis numerical simulation and experimental results have done. The results show that the solid elastic cushion with thickness 3 mm, polyurethane with the hardness of Shore A90 of the most important working parameter and significantly affects thickness variation and maximum division of a spherical shape. The response surface and analysis of variance methods were using to identify the parameters significantly affecting wrinkling and thickness variation. The predicted forming force was compared

to the measured force, as shown in figure 8, and the best agreement was found with a maximum error of about 1.04%. All results validated experimentally and showed good agreement between experimental and simulation results.
The following conclusions can be drawn from this study:

1. As the elastic cushion increase, wrinkling increases and thickness variation decrease this is opposite to the effect of the blank-holder force.
2. The optimum compression to achieve minimum wrinkling and thickness variation was found to be 400 mm for radios of curvature, 11.40 kN for blank-holder force and 3mm for elastic cushion thickness.
3. Having a large plastic deformation through sheet stretching and thinning while avoiding sheet thickening is the key factor in minimizing dimpling and wrinkling. This can be achieved by using small radii of curvature and high blank-holder forces.

Acknowledgments
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