Enhanced application of virtual manufacturing: influences of material parameters on numerical Simulation of forming process

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Abstract. This paper describes the sensitive influence of material parameters on the final numerical simulation result of forming process as one of virtual manufacturing applications. Although existing commercial software system provide predefined material properties, these can nevertheless differ with the actual material which might result in inaccuracies. Hence, material data needs to be enhanced to gain better simulation results. This investigation begins with development of flow curve of steel DC04 (1.0338) based on compressive test with various effective plastic strains under consideration of rolling direction. Further, Forming Limit Diagram (FLD) is to be defined by using Nakajima test to determine the strains up to the fracture for deep drawing process. In this research, the enhanced application on sheet forming process is modelled and simulated as well as verified under laboratory condition using an oil-hydraulic press. It can be demonstrated that the numerical simulation results are very sensitive due to the essential differences in material properties. However, this procedure will lead to time and cost intensive measurements of the material behaviour, which is mandatory for an accurate forecast of real forming process.

1. Introduction

Virtual Manufacturing (VM) is a system in which the abstract prototypes of manufacturing objects, processes, activities and principles evolve in a computer-based environment to enhance one or more attributes of the manufacturing process. The use of VM will provide a computer-based environment to simulate individual manufacturing processes or the total manufacturing enterprise. VM is also focusing on available methods and tools that allow continuous, experimental depictions of production processes and equipment using digital models. Areas that are concerned are (i) product and process design, (ii) process and production planning, and (iii) machine tools, robots and manufacturing system, and virtual reality applications in manufacturing [1]. Many aspects of products may be simulated, but for sheet metal products, mainly physical properties are of interest. A well-known method that is commonly applied in industry is Finite Element Method (FEM). The FEM is the general method to model and simulate the physical behaviour of bodies. In the process domain, the manufacturing processes are modelled and simulated. Examples of processes are laser cutting, punching, welding, and a variety of forming processes [2]. Nowadays, the increasingly growth in computer performance and rapid developments in numerical methods have allowed faster and more accurate predictions of computer modeling. VM can be also seen as an extension of CAD/CAM system in which computer is
used in aiding design and product manufacturing. Through VM, manufacturing system is modeled using audiovisual or other sensory features to simulate or design alternatives for real manufacturing environment, and the proposed product can be manufactured using computers [3].

Deep drawing is an important sheet metal forming process which was developed in the 1700s. A punch presses a sheet metal blank into die cavity and formed into a cylindrical or box-shaped part. Parts such as beverage cans, pots, containers of all shapes and sizes, kitchen sinks and automobile panels are typical products that can be produced by this method [4]. In [5], the effects of blank holder forces were investigated in producing LPG bottles through deep drawing process. It was found out that high blank holder force restricted the material flow from the beginning of the process which led to maximum thinning. Low blank holder force in the initial stage managed to avoid necking failure between punch and die radius. The thickness distribution in drawn part was influenced by the magnitude of blank holder force at initial stage. Chandra Pal Singh et al. [6] performed a research on deep drawing process parameters. The important parameters were such as blank holder force, punch radius, die radius, material properties and coefficient of friction. Blank holder force could control the metal flow, thickness variation and wrinkling behaviour. The thickness of deformed material was dependent on the punch and die radii. Meanwhile, one of the vital parameters which was friction would affect relative thickness distribution and surface quality.

2. FEM Simulation Procedures using Simufact.Forming 13.3.1

Figure 1 shows the models used in the simulation that consist of punch, blank holder, matrix and specimen. In this research, all models are built in solid condition. The specimen model was meshed using sheetmesh that produces 3D geometry built of hexahedral elements of 1.5 mm in length which are suitable for geometry that has a sheet form.

![Figure 1. Complete models involved in simulation](image)

In this simulation, DC04 or mild steel, has been employed to predict the strain of deformed part. The material was selected in accordance with experiment. This type of steel has been widely used in many applications due to good formability. There were many material properties involved in simulation process. However, for sheet metal forming, Forming Limit Diagram (FLD) and flow curve are two dominant material properties which are vital in characterizing the flow behavior of deformed material. In this study, both properties used for simulation purpose were obtained from experiments. The FLD was obtained from Nakajima Test using three specimens of different shapes but same in thickness. The FLD was drawn by plotting minor strain in horizontal axis and corresponding major strain in vertical axis. The subsequent Equation 1 and Equation 2 were applied to characterize the limit of deformation in which the plotted curve split up the safe region from the unsafe region. In these equations, $C_0$ is strain coefficient of y-intercept when the minor strain is zero, while $D_1$ and $C_1$ are strain coefficients of slopes of graph for negative and positive minor strains respectively. The graph of FLD is illustrated in Figure 2.
There are a few methods that can be conducted in order to extract the flow curve. In this case, compressive test has been selected and carried out. The flow curve was constructed by plotting plastic strain in horizontal axis and corresponding flow stress in vertical axis. In constructing the flow curve, only plastic strain region was interested instead of elastic strain region. Figure 3 exhibits the flow curve used for computational analysis. The forming parameters that have been employed during the simulation and experimental verification were tabulated in Table 1.
Table 1. Forming parameters

| Parameters                        | Values |
|----------------------------------|--------|
| Punch velocity, \(v\) (mm/s)     | 10     |
| Coefficient of friction, \(\mu\) | 0.05   |
| Blank holder force, \(F\) (kN)   | 25     |

3. Influences of Material Parameters on Forming Simulation

The most important material-specific properties, which influence the quality of the simulation results in the present case, are the flow curve and the forming limit diagram to describe the deformation behaviour of the sheet material.

For the calculation of the flow curve, a series of plane strain compressive tests were applied (Figure 4a). The sample dimensions were 20 mm, 50 mm and 2 mm in width, length and thickness respectively, which was mechanically removed from the batch of the component sheet. These samples were deformed in universal testing machine Galdabini Quasar 50 kN and the force-displacement-curves were recorded. The plain strain compressive test is very well suited for the characterization of sheet material as the stress condition is analogous to the real test by taking into account the real process parameters (temperature, strain rate). The punch width is an important factor in the plain strain compressive test, because this should be smaller than the sample width (punch:sheet > 1:5) so that the spreading can be ignored.

By means of the force-displacement-curves, the flow curve could be calculated by using the equivalent stress hypothesis of von Mises under consideration of an additional friction and heat development during the deformation. The corrections are necessary since increasing friction requires higher forces for the deformation of the material. The temperature correction results from the generation of dissipation heat, which means that this material test does not operate under isothermal conditions. As a reason for the fact, that the plain strain compressive test causes a plain stress state, the equivalent stress hypothesis of von Mises is necessary as the flow curve is defined for uniaxial stress states [7]. The following flow curve (see Figure 4b) was obtained for the sheet material DC04.

![Figure 4. Experimental setup of the plain strain compressive test (a) and flow curve of DC04 for room temperature and strain rate of 0.1 s\(^{-1}\) (b)](image)

Because of a deep-drawing process should be designed, the determination of forming limit diagram according to DIN EN ISO 12004-2 has a great importance. Nakajima-Test was carried out using a universal sheet testing machine BUP 600 (see Figure 5) at the Institute of Metal Forming in Freiberg, Germany. The shape changes were analysed by means of the AutoGrid system.
Technical data:
- drive: hydraulic
- maximum test load: 600 kN
- maximum clamping force: 600 kN
- maximum punching force: 600 kN
- test temperature: RT … 350°C
- heating: RT … 350°C
- test atmosphere: air
- maximum testing speed: 20 mm/s
- maximum ram stroke: 120 mm
- maximum sheet thickness: 10 mm

Figure 5. Sheet Forming Machine BUP 600

The test was also carried out on samples from the batch of 2 mm sheet thickness. By evaluating the occurrence of cracks, it was possible to determine the maximum forming behaviour of this material (see Figure 6).

Figure 6. Forming limit diagram with three measurements for steel DC04

With the help of these sensitive material data and their implementation in the FEA software Simufact.Forming 13.3.1, the deep drawing process could be specifically modelled, analysed and validated with the real tests for the investigated material. Further material data were used from the material database of the FEA program.
4. Results and Discussion

Figure 4 to Figure 7 present the actual results obtained from experiment. In order to measure the deformation, the results of plastic strains were calculated using geometric detecting system as shown in Figure 8 (left). However, the degrees of deformation were measured in logarithmic plastic strains ($\varphi$). After the simulation was finished, the post-processing analysis could be implemented in which the plastic strains ($\varepsilon$) of the deformed part occurred due to the deep drawing process could be observed. In order to compare the simulated results with the experimental measurements, the relation between both units was stated by Equation 3 as below:

$$\varphi = \ln (1 + \varepsilon)$$  \hspace{1cm} (3)

When comparing the results as displayed in Figure 8, the plastic strains obtained from simulation analysis were in good agreement with the experimental values. The computational analysis was successfully executed to deform the part until full stroke without thinning effect and even the cross shape has been successfully formed which similar to that of part produced by means of experiment.

![Figure 7. Deep drawn part produced through experiment](image)

![Figure 8. Results from experiment (left) and simulation (right)](image)

5. Conclusions

From the analysis of the results, it was found that a good agreement has been achieved between finite element prediction and experimental verification. This outcome revealed that the capability and reliability of virtual manufacturing has been obviously proven in forecasting the degree of deformation sensibly. In order to obtain a good prediction, the flow behavior of material must be well characterized to reflect the real deep drawing process. In addition, the specimen model should be properly meshed since it would affect the computational time as well as the accuracy of prediction. Therefore,
significant impact from this study shows that the material parameters will have great influence towards the precision of numerical simulation.

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