Deep drawing behavior of IN625 alloy under the influence of different process parameters

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Abstract The Ni-Cr based IN625 alloy has been extensively used in critical applications of aerospace and nuclear industries. Various components have been manufactured using sheet metal forming processes. In the present work, the deep drawability of material has been examined under the influence of different process parameters such as temperature, punch speed, lubrication, and blank holding pressure using the processing window. The deep drawability has been analyzed in three different zones, namely, safe, wrinkling, and fracture. The limit drawing ratio increased by 7.12% on increasing the temperature from 300K to 673K. The thickness distribution across the deep-drawn component plays a crucial role in examining the quality and life of it. Therefore, in this context, a detailed analysis of different process parameters over the drawn cup's thickness distribution has been done. The minimum thickness was obtained near the punch corner or the cup junction region of the deep drawn cup. The uniformity in the thickness distribution and drawing height also increased with the forming temperature and decrease in punch speed. Additionally, two different yield criteria, namely, Hill 1948 and Barlat 1989, have been analyzed and further used for the numerical analysis using the user material subroutines in Abaqus software. The results predicted using Barlat 1989 yield criterion more closely followed the experimental results as the average absolute error obtained is well within the 5% of the acceptable limit.

1. Introduction

Inconel 625 (IN625) is a Ni-Cr-Fe based superalloy having a right blend of various mechanical properties, namely, high strength, ductility, and resistance towards corrosion, oxidation, creep and fatigue [1,2]. This Ni-based superalloy shows high-performance ability in extreme conditions and hence used in various critical applications of aerospace and nuclear industries [3]. Sheet metal forming (SMF) process is majorly used in different industries to deform material into the required shape. This process helps in forming the material into the required complex shape. This process is cost-effective and reduces the material wastage compared to the traditional machining and welding processes [6].

IN625 alloy is a very high strength metal and has limited workability, which makes it very difficult to form into the desired shape at the room temperature condition. Thus, researchers proposed that in the past, metal forming for such high strength metals at elevated temperature conditions [7–9]. Further, several popular metal forming processes are deep drawing, stretch forming, stamping, etc. Several process parameters play a very important role in determining the quality of a finally formed component. Researchers have adopted the optimization route of process parameters in order to get the best quality components. Determination of processing window is one such method for determining the safe drawing zone of the deep-drawn cups under the combined influence of different process parameters. In the last few decades, several studies have been devoted to designing the processing windows (PW) diagrams for various metal forming processes. Chu et al. [10] determined the theoretical PW of Al extrusion tubes
using the hydroforming process. The PW has been designed on the basis of variation between the axial force (compressive) and internal pressure for predicting the bursting, wrinkling, and buckling phenomenon. Vollertsen et al. [11] determined PW's effect for a micro deep drawing process to investigate the effect of punch velocity. Finally, they concluded that the allowable blank holding pressure (BHP) increases with the punch velocity during the process. Prasad et al. [12] determined the deep drawing PW for the solution treated IN718 alloy to determine the safe drawing region for the material. Gao et al. investigated PW for the compression of the tube using the viscous pressure forming process by considering the variation of tube blank diameter and compression length. They found that the safe and wrinkling zone decreased with the increase in the tube compression length. Further, the wrinkle elimination zone increased, and the safe zone decreased with the tube blank diameter increase. Hashemi et al. [13] found PW for conical cup formation using the hydrodynamic deep drawing process using the Cu, steel, and Al sheets. It has been concluded that the sheets with less thickness and high strength displayed more uniformity in thickness hence better formability on the finally obtained product.

The hardening law and the yielding function play an important role in the accurate prediction of metal's deep drawing behavior. Hill 1948 yield criterion has first been proposed as a modification of von mises criterion in order to include the anisotropic behavior of the material. This criterion has four material constants [14]. The determination of yielding function involves simple calibrations; hence, it has been extensively used in the industries. Although, it has a drawback of not predicting the anisotropy value with high accuracy. Barlat and Lian later found a non-quadratic yielding function for the anisotropic effect in sheet metals and found the r-value accurately [15]. This proposed relation also has four material constants, which can be found using a large number of iterative computations [16].

In the present work, the PW has been determined under the influence of forming temperature and lubricating conditions. Further, the effect of different process parameters on the cup's thickness distribution has been analyzed individually. Additionally, the Hill 1948 and Barlat 1989 yielding function have been calibrated for analyzing the deep drawing behavior using the finite element analysis. The simulated results of thickness distribution and drawn heights have further been validated with the experimental results.

2. Material and Method

1 mm thick IN625 alloy sheet has been used in the present study for all analyses. The dimensions and design of the tensile test specimen have been considered according to the ASTM E08/E8M-11 standard. These specimens were cut using wire cut Electric discharge machining in five different directions, namely, 0°, 22.5°, 45°, 67.5°, and 90° with respect to the sheet's rolling direction for determining the anisotropic material properties. All the experiments have been carried out three times and the average material properties are reported below in Table 1.

| Temperature (K) | Yield Stress (MPa) | Ultimate Stress (MPa) | Elongation (%) | Anisotropic Coefficient r₀ | r₉₀ |
|----------------|--------------------|-----------------------|---------------|-----------------------------|-----|
| 300            | 812.07±8           | 978.55±9              | 39.65±0.3     | 0.851                       | 0.749 |
| 673            | 609.51±6           | 805.18±4              | 46.57±0.5     | 1.086                       | 0.741 |

The deep drawing experiments have been carried out on a 40-ton hydraulic press equipped with the induction coil heating setup to perform forming operations at elevated temperature conditions. The Molybdenum disulfide based Molykot lubricant has been used during the whole experimentation as it remains stable 1000K temperature. The punch speed, blank holding pressure, and temperature have been varied according to the experiments' requirement. The blank diameter of the circular blanks considered in the present study varied from 52mm to 62mm. The K-type contact thermocouple has been used in the present study to measure the temperature during all the high-temperature experimentations. The thickness and height measurement digital gauge has been used to measure the thickness and draw height accurately.
after the experiments. The experiments have been carried out at two different temperatures i.e., 300K and 673K. The BHP and punch speed were to 35bar, and 50mm/min, respectively, as these are the safe operating limits of the used hydraulic press in the present study.

3. Result and Discussion

3.1. Processing Window

The process windows obtained by performing deep drawing experiments at 300K and 673K under the influence of lubricating condition are shown in Figure 1(a & b) respectively. All the cups were drawn at different BHP within the range of 1bar to 35bar pressure and were characterized under different zones, namely, wrinkling, safe, and fracture. All the deep drawing operations were performed until 35bar pressure. The drawing ratio in the process window corresponds to the ratio of diameter for blank to that of punch. The different zones i.e., safe forming zone, fracture zone, and wrinkling zone, are marked in the process window at different conditions. It was observed that the processing temperature and BHP play a vital role in sheet metal forming industries. While performing the deep drawing operation, at lower BHP (up to 2bar) under all the processing conditions, the cups were difficult to form because of the formation of wrinkles, which in turn restricted the easy flow of material under all the considered processing conditions. Finally, this resulted in the cup fracture from the region of the punch corner. The increase in the formation of wrinkles has been observed with the increase in blank diameter, but it can also be compensated and suppressed by increasing the BHP. The cups were also fractured at higher BHP because of the hindrance in the flow of material and increase in the tensile stresses along the cup's walls above the critical limit [12].

The maximum diameter of 56mm blank size was observed to be successfully drawn at a BHP of 20bar at 300K. As a result, the LDR of 1.867 has been observed in Figure 1(a). At 673K, under the lubricated condition, the LDR has been increased to 2 and the successful cup has been drawn at 10bar BHP, as shown in Figure 8(b). Thus the LDR improved by approximately 7.12% as the forming temperature increased from 300K to 673K. This effective change in the LDR is due to the thermal softening, which made the material soft and helped in the easy forming of the material. The lubrication also helped and provided an added advantage for the easy drawing of material into the desired shape. Thus, the study of process window help in optimizing the process parameters for obtaining safe drawing limit of material.

Figure 1. Processing window at (a) 300K and (b) 673K
3.2 Effect of Different Process Parameters over the Thickness Variation

The thickness distribution across the deep drawn cup is highly influenced by different process parameters. Maximum thinning rate (MTR) and thickness deviation (TD) are two different statistical parameters used for the quantitative evaluation of the thickness under the influence of different process parameters. In the formulation of TD and MTR, the terms $t_i$, $t_m$, $t_{\text{min}}$ and $N$ correspond to the initial thickness, average thickness, minimum thickness, and the total number of observations. The thickness has been measured at a fixed distance of 2mm in three different directions and the average values are reported in Figure 2.

$\text{TD} = \frac{\sum(t_i - t_m)^2}{N} \times 100\%$ (1)

$\text{MTR} = \frac{(t_i - t_{\text{min}})}{t_i} \times 100\%$ (2)

The thickness distribution obtained from the successfully drawn cups with the highest drawing ratio at 300K and 673K are shown in Figure 2(a). All the cups drawn under different conditions displayed a similar trend for the thickness distribution. The thinning near to the base of the cup is less due to the increase in friction between the sheet metal and punch at this point of contact as stated by Prasad et al. [17]. Thus, the material near the base region of the punch will always be constrained, resulting in very less deformation than other regions of the deep-drawn cup. Additionally, the thickness near the cup junction is minimum because of large stretching and subsequently losing the contact with the punch corner. This is known as the critical region, and mostly deep-drawn cups fail from this region. More uniformity or less deviation in the thickness has been observed at higher forming temperatures. Further, the use of lubricant provides an added advantage in the deep drawing process as it helps in easy forming by reducing the forming load. In the present case, the cup formed at 673K under the lubricating condition was found to have the least variation in thickness, highest LDR, and drawn height.

Figure 2(b) shows a representative comparison of thickness for the case, 673K and 5mm/min punch speed, at three different BHP, namely, 3bar, 12bar, and 20bar for the blank size of 58mm. In the deep drawing process, at low BHP (below 3bar in the present case), the thickness of the sheet became closer to the outer periphery of circular blanks due to the formation of wrinkles. This ultimately led to the restricted flow of material followed by the fracture from the cup junction region. At high pressure, the blank experiences a rapid increase in the tensile stress along the cup's vertical walls. This results in the increase of stress concentration near the contact region of blank and punch, ultimately leading to the fracture of the cup. Thus, the cup's failure occurs when the generated tensile stress exceeds the material's load-bearing capacity at the cup junction. The blank holding pressure also seems to have an effective contribution in deciding the thickness distribution across the formed cup. With the increase in BHP, more uniformity in the thickness distribution has been observed. Further, the minimum thickness of the drawn cups also improved by 7.48% on increasing the BHP from 3bar to 20bar. Thus, the determination of optimum BHP is important in order to remove any failures in terms of wrinkling and fracture. The thickness distribution w.r.t the punch speed is shown in Figure 8(c). The punch speed seem to have significantly influence the drawn height of the cup. The TD seem to have reduced by 36.2% when deep drawing has been performed at 5mm/min. Hence, from the above discussion, it can be concluded that better quality deep drawn cups can be obtain at higher temperature, lower punch speed and nominal BHP.
3.3. Numerical Analysis

The numerical analysis of any forming process is highly influenced by the used yielding function. Hence, in the present study two different yielding functions, namely, Hill 1948 and Barlat 1989 have been used for accurate prediction of deep drawing behavior of material. The material constants for both the yield criteria have been evaluated using the procedure mentioned by Pandre et al. [18]. Figure 3 shows the yield locus calibrated using these yield criteria. Barlat 1989 yield criterion seem to have closely following the experimentally normalized yield stresses at both the temperatures.

Table 2. Hill 1948 yield criterion material constants

| Temperature | H       | G       | F       | N       |
|-------------|---------|---------|---------|---------|
| 300 K       | 0.614015| 0.540103| 0.459897| 1.694937|
| 673 K       | 0.739487| 0.479180| 0.520820| 1.415115|

Table 3. Barlat 1989 yield criterion material constants

| Temperature | a       | c       | b       | p       |
|-------------|---------|---------|---------|---------|
| 300 K       | 0.887581| 1.112419| 1.036294| 0.89    |
| 673 K       | 1.025793| 0.974207| 0.881727| 0.94    |
The setup for performing deep-drawing operation consists of circular die, flat circular punch, blank holder plate, and circular blanks. The blanks are assigned with the properties of the deformable object. S4R planar elements have been used for the fast computation of results. Further, the die, punch, and blank holder plate are assigned with the rigid R3D4 elements as no results are desired over them. The user-defined material subroutine has been used for including the effect of yield criteria while doing the numerical simulation of the deep drawing process in ABAQUS software. The thickness distribution and drawn height have been obtained using both the above-calibrated yielding function and compared with the experimental results. The cup with height drawing ratio has been considered for the comparison with the numerically obtained results of thickness and drawn height, shown in Figures 4 (a and b) at 300K and 673K, respectively. Both the yield criteria helped in predicting the results with high accuracy. Though, Barlat 1989 criterion best predicted both the thickness distribution and drawn height among the two considered yielding functions. The average absolute error obtained is well within the 5% of the acceptable limit.

4. Conclusions
The analysis of warm deep drawing process has been done in the present study. Some of the important results from the above study are stated below.
• The processing window has been obtained at 300K and 673K temperature. The safe drawing limit of the material improved with the forming temperature. LDR has been found to be increased by approximately 7.12%. The thickness distribution across the successfully drawn cup has been found to be greatly influenced by different process parameters. The minimum thickness in all the cases has been found to be near to punch corner region. The uniformity in thickness has been found to be increased with the increase in temperature and decrease in punch speed. The nominal BHP needs to be maintained during the whole process. The cup's wrinkling and fracture have been observed in the case of very low and high BHP, respectively.

• The Hill 1948 and Barlat 1989 anisotropic yielding function has been considered for the accurate prediction of the deep drawing behavior using numerical simulations. Barlat 1989 criterion helped in predicting the numerical results of thickness distribution and drawn height more accurately compared to Hill 1948 criterion.

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