Experimental Investigation of Multi-stage Deep Drawing of IN718 Sheet at Elevated Temperature

Kanhu C Nayak1, Prashant P Date1
1Department of Mechanical Engineering, Indian Institute of Technology Bombay, Mumbai 400076, India

E-mail: nayakkanhu83@gmail.com

Abstract. IN718 is a nickel-based super alloy that retains its mechanical properties at elevated temperatures and hence has numerous applications in the aerospace industry. In this study, deep drawing of IN718 sheet at elevated temperatures (700-1000°C) has been investigated experimentally. Initially, stress-strain response with failure strain at different temperatures was evaluated by uniaxial tensile tests along different orientations. Subsequently, hot deep drawing and re-drawing tools were designed and fabricated. A circle-grid marked circular blank of 3mm thickness was used in the first draw to form a circular cup followed by re-drawing (2nd draw). The major and minor diameter of the circular grid on the blank after the deep drawing was used to examine the strain distribution in the drawn cup and further used to calculate the thickness strain. These deep drawing operations were carried out at different temperatures with a constant blank holding force. Further, the deep drawing force at different temperatures was examined. The effect of the test temperatures during hot deep drawing and the process parameters on the variation of the thickness strain over the surface of the drawn cup has been studied. Finally, the major and minor strains are plotted in Keeler and Arcelor V9 forming limit curve to examine the formability of IN718 sheets at elevated temperature.

Keywords: Forming limit diagram; hot deep drawing; Inconel 718; thickness strain

1. Introduction

Inconel 718 is widely used in high-temperature applications such as in aerospace industry, oil, and chemical industries, and also nuclear power plants due to its high strength, creep resistance, oxidation, corrosion properties and structural stability [1-3]. Different manufacturing processes are involved to produce Inconel alloy based mechanical components. Sheet metal forming such as, deep drawing and stamping are among the important manufacturing processes for aerospace and nuclear industry. However, it is difficult to deep draw the components from Inconel super alloy sheets at room temperature in comparison to other aerospace alloys [4-6]. Therefore, hot forming of these sheets at elevated temperature is a promising processing technique. Many researchers have investigated to improve the formability with reduced forming load for different alloys [4,7]. Hot deep drawing process has advantages to produce drawn parts without springback from high strength materials like steel, Inconel and lightweight materials like Ti alloy, Al alloy etc. In addition, the deep drawing at elevated temperature reduces the load and hence high strength materials can be easily drawn [8].

Recently the formability of solution treated IN718 material has been investigated [9-11] at room temperature. Further, the formability of In718 has been studied at elevated temperatures by conducting
the tensile test, compression test and numerical modelling [12,13]. There is limited literature related to the hot drawability of IN718 thick sheet.

In the present work, a hot deep drawing die has been designed and fabricated to investigate the drawability of the IN718 sheet at elevated temperature. In addition, the hot tensile test has been performed in 0 and 90° to the rolling direction. The variation of deep drawing load with punch travel at different drawing temperatures has been studied. The thickness strains are calculated from the measured diameters of deformed grid marks on the deep drawn and re-drawn cups. The earing on these cups has been examined. Finally, the major and minor strains are plotted in a forming limit curve based on Keeler and Arcelor V9 and the drawability was discussed.

2. Materials and methods

In the present work, commercially available IN718 sheets of 3mm thickness were used for the experiment. Tensile as well as samples for plastic strain ratio, were cut from these sheets. The tensile properties in two orientations (90° and 0° to the rolling direction of sheet) were measured at three different temperatures of 700, 850 and 1000°C. Similarly, the plastic strain ratio was calculated at 0, 45 and 90° to the rolling direction of the sheet. Thereafter, circular blanks of 114mm diameter were cut from 3mm thick of IN718 sheet. Circular grid pattern (2(+0.02 to 0.04)mm diameter and center to center distance is 2.5(+0.02 to 0.04)) was laser marked with a depth of impression 70 microns on one side of the blanks (Figure 1). In-plane, major and minor diameters of deformed grid circles were measured using Camscope followed by analysis using the ImageJ software. Further, these measured diameters were used for the calculation of major and minor strains. Then, thickness strains were estimated by the principle of volume constancy.

The hot deep-drawing set up is schematically illustrated in Figure 2(a), whereas the experimental set up is shown in Figure 2(b). Diameter of first stage deep drawing die and re-drawing die is 69mm and 50mm respectively. The hot deep drawing was carried out in a hydraulic press of 200 tonnes capacity. The die and blank holder were heated to 250°C using cartridge heater. A thermocouple was connected to the die for measuring the temperature (Figure 2(b)). The grid circle marked circular blank was heated separately in a muffle furnace, which was kept near to the hydraulic press. This blank was maintained at a temperature of 900°C in one set of drawing experiments and 1000°C for another, using a muffle furnace. Re-drawing operations were carried out at 1000°C. There is a transportation (bringing blanks from furnace to deep drawing station) temperature loss of approximately 15-20°C over approximately 2-3 seconds. Nickel-based anti-seize compound (NTC, solid lubricant up to 1400°C) was used as a lubricant on the die surface. First, the furnace is heated up to the required temperature, and then the blank was put in the furnace for 5 minutes of soaking time for uniform heating. After that, the heated blank was placed centrally on the die and immediately, the spring-loaded blank holding force (4.75kN) was applied to the blank and then the drawing process started. The punch speed was kept 14mm/sec during the deep-drawing process. The entire drawing process took 3-4 seconds.

Figure 1. Circular blank with laser marked circular grid patterns
Figure 2. Hot deep-drawing, (a) Schematic view (1-Ram, 2-Punch, 3-Hole for heater, 4-Die, 5-Die holder, 6-Blank, 7-Spring loaded blank holding and 7-Blank holding force) and (b) experimental set up

3. Results and discussion

3.1. Tensile properties

The engineering stress-strain curves of IN718 Inconel at different temperatures are shown in Figure 3(a) and (b). It is observed that the ultimate and yield strength of samples along the rolling direction is approximately 50MPa smaller than the samples that are perpendicular to rolling direction up to the test temperature of 850°C. The stress-strain curve at a temperature of 700°C shows a hardening behaviour irrespective of the rolling direction. This behaviour has been studied using the Hollomon equation [14]. The strength coefficient and strain hardening exponent of IN718 sheet along the rolling direction is 1305.9MPa and 0.340 respectively, whereas along transverse direction, these values are 1443.7MPa and 0.345 respectively. The percentage of elongation of IN718 sheet at 1000°C is higher than at a temperature of 850°C as per the fracture strain. At 1000°C, the yield strength of this sheet is low, and elongation is more. Therefore, in this study for low deep drawing load and more drawability, the deep drawing temperature was maintained at 900 and 1000°C, whereas re-drawing temperature was kept at 1000°C. The material was found to be close to isotropic with an R value of 1.071 at the drawing temperature. The ΔR value is -0.414. The nature of fracture and length of tested tensile samples are shown in Figure 3(c). The trends of the overall length of the tested samples shown in Figure 3(c) are in good agreement with the engineering strain, as observed in Figure 3(a) and (b). There was no distortion of the sample at higher temperatures in the pin region where it was fixed with the tensile fixture.
Figure 3. Engineering stress-strain of IN718, (a) rolling direction, (b) perpendicular to the rolling direction and (c) samples after tensile test

3.2. High temperature deep drawing

3.2.1 Hot deep drawn cups and forming load

The cylindrical cups were drawn from a circular blank of 114mm diameter and 3mm thick IN718 Inconel sheets. The deep drawn (first drawn) and re-drawn cups are presented in Figure 4(a). The variations in dimensions of the circular grid patterns on deep drawn cups were compared with the re-drawn cup in Figure 4(a). The deformed grid patterns on the curvilinear surface and wall of a re-drawn cup are illustrated in Figure 4(b). The grid circles are deformed to shape of an ellipse. This deformed grid circles further gives the strain distribution on the surface of the deep drawn and re-drawn cups that have been discussed in the successive section.

The deep drawing load at a drawing temperature of 900°C is compared with the re-drawing load in Figure 5(a), whereas Figure 5(b) shows the comparison of deep drawing load between first deep drawn cups at 1000°C with re-drawn cup at 1000°C. There is an effect of temperature on the load required for the deep drawing process. Deep drawing load decreased with increasing operating temperature and vice versa for an isothermal condition. At a constant operating temperature re-drawn cup required larger load compared to first deep drawn cups as seen in Figure 5(b). It is because of the accumulated strain hardening in the first drawn cup results the increase in drawing load during re-drawing. Further, the load vs. punch travel curve can be divided into three zones such as initial punch travel, actual deep drawing operation and end of deep drawing. During deep drawing process, load gradually increased and attained a peak load.

Figure 4. (a) Deep drawn cups showing deformed grid marks and (b) the evolution of deformation of circular grids during re-drawing at 1000°C
In sheet metal forming, thickening and thinning are the two major issues. The final thickness distribution of deep drawn cup and re-drawn cups can be measured directly or by indirect calculation from the thickness strains ($\varepsilon_t$). The thickness strains are obtained using the principle of volume consistency. The variation of thickness strain with curvilinear distance (Distance from one end of the cup to the other end in a longitudinal sectional plane) of the cup along 0, 45 and 90° to the rolling direction are presented in Figure 6(a)-(c). It has been seen that thinning occurs at the corner of the cup and thickening occurs at the edge of the cup. The grid circles at the center of the bottom of the cup do not show any variation in diameter for the first deep drawn cups. Zero thickness strain results in a flat land, as is evident from Figure 6(a) and (b) for the first drawn cups. However, in the case of re-drawing this land becomes narrow even if it has a flat bottom of 10mm diameter. It is because of increase in grid circle diameter due to deformation at a higher temperature (here 1000°C). Therefore, one cannot expect a flat land in Figure 6(c) as in the case of deep drawing at room temperature on the bottom of the cup. Hence there is an effect of temperature on dimensions of grid circles resulting in additional strain. Moreover, Maximum thickness strain occurs at corner radius of cup in both deep drawing operation and it is higher for re-drawn cups. However, the thickness strain distribution is independent of the rolling direction of the sheet as well as deep drawing temperature. The small variation in thickness strain at the corner of the cylindrical cup as shown in Figure 6(a)-(c) is due to distortion of grid circle dimension at higher temperature. Similar observation found at the edge of the re-drawn cylindrical cup.

3.2.2 Thickness strain and earing

In sheet metal forming, thickening and thinning are the two major issues. The final thickness distribution of deep drawn cup and re-drawn cups can be measured directly or by indirect calculation from the thickness strains ($\varepsilon_t$). The thickness strains are obtained using the principle of volume consistency. The variation of thickness strain with curvilinear distance (Distance from one end of the cup to the other end in a longitudinal sectional plane) of the cup along 0, 45 and 90° to the rolling direction are presented in Figure 6(a)-(c). It has been seen that thinning occurs at the corner of the cup and thickening occurs at the edge of the cup. The grid circles at the center of the bottom of the cup do not show any variation in diameter for the first deep drawn cups. Zero thickness strain results in a flat land, as is evident from Figure 6(a) and (b) for the first drawn cups. However, in the case of re-drawing this land becomes narrow even if it has a flat bottom of 10mm diameter. It is because of increase in grid circle diameter due to deformation at a higher temperature (here 1000°C). Therefore, one cannot expect a flat land in Figure 6(c) as in the case of deep drawing at room temperature on the bottom of the cup. Hence there is an effect of temperature on dimensions of grid circles resulting in additional strain. Moreover, Maximum thickness strain occurs at corner radius of cup in both deep drawing operation and it is higher for re-drawn cups. However, the thickness strain distribution is independent of the rolling direction of the sheet as well as deep drawing temperature. The small variation in thickness strain at the corner of the cylindrical cup as shown in Figure 6(a)-(c) is due to distortion of grid circle dimension at higher temperature. Similar observation found at the edge of the re-drawn cylindrical cup.
Figure 6. Distribution of thickness strain; (a) deep drawn at 900°C, (b) Deep drawn at 1000°C, (c) re-drawn at 1000°C and (d) earing of different drawn cups

Figure 6 (d) illustrates the earing that occurs during the deep drawing process. It is one of the major defects observed during the deep drawing process due to the anisotropic nature of the sheet. There is no significant earing in the first draw. However, higher earing occurs for re-drawn cups compared to first drawn cup.

3.2.3 Formability analysis

The major and minor strain distribution in three different directions (0, 45 and 90 degree) to rolling for cylindrical cups, drawn from as received IN718 Inconel sheet is shown in Figure 7. Both the first drawn cups and the re-drawn cup give five modes of deformation namely uniaxial mode, biaxial mode, pure shear mode, equi-biaxial mode and plain strain mode as seen in Figure 7. It is observed that major strain and minor strain distribution is also independent of rolling direction of sheet. To check the formability of IN718 sheet at higher temperature, two forming limit curves have been used. One is Keeler's criterion [15] and the other is Arcelor's V9 criterion [16]. These two forming limit curves are obtained only using the various parameters from uniaxial tensile test in the mathematical model according to Keeler and Arcelor. The Keeler's forming limit curve (FLC) is used because of its simplicity where tensile test data (strain hardening exponent=0.345, strength coefficient=1305MPa and strength=640MPa) at 90° to rolling direction and thickness data are required to generate the FLC. For the Arcelor V9 FLC model, ultimate tensile strength, percentage of deformation, yield strength,
strain hardening exponent, strength coefficient, normal anisotropy and thickness of the sheet data is required to generate the FLC. In this study, the mechanical properties obtained from the hot tensile test are used to produce both the FLC. The options are available in the AutoForm to generate the Keeler and Arcelor V9 FLC which is explained elsewhere [16]. FLD and fracture FLD for commercially available IN718 of 1mm thick at different temperatures (max 700°C) have been developed by Mahalle et al. [17], using limit dome height test. It is observed, the forming limit curve in tension-compression region is similar to Keeler’s FLC. By increasing the forming temperature, the major safe strain increases. The major and minor strains are in safe zone with respect to these two FLCs. However, thinning at the corner of cylindrical cup occurs without fracture. Also thicker sheet have more volume and hence can be stretched to a greater extent, increasing the thinning without causing fracture.

![Image](image-url)

Figure 7. Presentation of major and minor strain in the forming limit diagram (yellow colored dash line indicates the initial grid circle)

4. Conclusions

In this research work, IN718 sheets were used for hot deep drawing process. Mechanical properties of this sheet were investigated at high temperature. Cylindrical cups were drawn from circular blanks cut from sheets and strain distribution was observed along different directions inclined to rolling directions. The conclusions drawn from the results can be summarized as follows:

- Deep drawing load decreased with increase in the drawing temperature.
- First deep drawing cups of 40mm height and re-drawing cups of 67mm height cylindrical cups are successfully drawn without necking from circular blanks.
- Both the first drawn and re-drawn cups undergo five modes of deformation namely uniaxial mode, biaxial mode, pure shear mode, equi-biaxial mode and plain strain mode.
- Thickness strain, major strain and minor strain distribution is independent of rolling direction of sheet.
- Thinning occurs at the corner of deep drawn and re-drawn cylindrical cups without causing fracture and it is temperature dependent.
References

[1] Yuan H and Liu W C 2005 Mater. Sci. Eng. A 408 281–289
[2] Prasad K S, Panda S K, Kar S K, Sen M, Murty S N and Sharma S C 2017 J. Mater. Eng. Perform. 26(4) 1513-30
[3] El-Bagoury N, Hessien M M, Mohammed A, Mahmoud M H H, Alanazi A K, Alshanbari N A 2019 Metall. Microstructure, and Analysis 8 642–655
[4] Toros S, Ozturk F and Kacar I 2008 Journal of Materials Processing Technology 207 1–12
[5] Date P P and Padmanabhan K A 2001 Journal of Materials Processing Technology 112 68-77
[6] Kesharwani R K, Panda S K and Pal S K 2015 Journal of Materials Engineering and Performance 24 1038–1049
[7] Lee Min-sik, Baeck Seung-cheol and Kang Chung-gil 2012 Journal of Engineering Manufacture 226(5) 898–908
[8] Mori K, Bariani P F, Behrens B A, Brosius A, Bruschi S, Maeno T, Merklein M and Yanagimoto J 2017 CIRP Annals - Manufacturing Technology 66 755–777
[9] Prasad K S, Panda S K, Kar S K, Sen M, Murty S N and Sharma S C 2017 Journal of Materials Engineering and Performance 26 1513-1530
[10] Prasad K S, Panda S K, Kar S K, Murty S N and Sharma S C 2018 Materials Science & Engineering A 733 393–407
[11] Jinhui D, Xudong L, Qun D and Luo Y 2011 Adv. Mater. Res. 197–198 1125–1128
[12] Yuan H and Liu W C 2005 Mater. Sci. Eng. A 408 281–289
[13] Prasad K S, Panda S K, Kar S K, Singh S K, Murty S N and Sharma S C 2018 IOP Conf. Series: Materials Science and Engineering 418 012055
[14] Kleemola H J and Nineminen M A 1974 Metall. Trans. 5 1863–1866.
[15] Keeler S P 1978 Forming Limit Criteria-Sheets (In: Burke J.J., Weiss V. (eds) Advances in Deformation Processing, Springer, Boston, MA)
[16] Jadhav S, Schoiswohl M and Buchmayr B 2018 BHM 163 (3) 109–118
[17] Mahalle G, Morchhale A, Kotkunde N, Gupta, A K, Singh S K and Lin Y C 2020 Journal of Manufacturing Processes 56 482-499