Study of Khan-Huang-Liang (KHL) Anisotropic Deformation Model for Deep Drawing Behaviour of Inconel 718 Alloy

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Abstract. Study of anisotropic deformation behavior of a material plays a crucial role in optimizing hot working process parameters and trustworthy Finite Element (FE) analysis in sheet metal forming processes. In this work, Khan–Huang–Liang (KHL) phenomenological based constitutive model and anisotropic yield criteria has been formulated for Inconel 718 alloy. Firstly, uniaxial tensile tests have been conducted at different temperatures (room temperature - 700ºC) and slow strain rates (0.0001 - 0.1 s⁻¹) conditions. KHL constitutive model has been formulated and validated with experimental flow stress data. The prediction capability of the model is evaluated based on correlation coefficient (R), average absolute error, AAE (Δ) and its standard deviation (σ). Subsequently, anisotropic yielding behavior of Inconel 718 alloy is predicted based on KHL yield criterion. Anisotropic coefficient (Lankford parameters) and tension compression asymmetry parameters have been calculated experimentally. The prediction capability of KHL yield criterion is analyzed based on yield locus, yield stress variation and anisotropic coefficient variation. The quality index of performance, namely global accuracy index (β) is evaluated. Further, Finite Element (FE) analysis has been carried out for deep drawing of Inconel 718 alloy using commercially available ABAQUS software. The developed KHL constitutive model and anisotropic yield criterion has been incorporated in FE simulation using UMAT/VUMAT code. The FE results are validated with experimental deep drawn cups at different process conditions.

Key word: Inconel 718 alloy, Deformation Behavior, Constitutive Model, Anisotropy, Deep Drawing.

1. Introduction

The sheet metal forming process is mostly used in manufacturing industries, mainly to switch conventional welding process. Critical components (with definite dimension, mechanics, and appearance requirements), are certainly manufactured with the help of various advanced forming procedures. These processes are mostly limited by the instability occurrence or flow localization. It is strongly depends on intrinsic mechanical properties of material and extrinsic factors such as operation/process conditions, selection of different process parameters and tooling material, etc. The higher performance necessities, safety and environmental concerns have been forcing industry to choose correct parameters to satisfy ever-increasing market needs [1]. But forming of high strength and limited
ductility material is sometimes an unfeasible task. In literature, warm/elevated temperature forming is proposed as one of the proven technique to produce complex shapes of these materials. The elevated temperature forming facilitate easy material flow in the die cavity and substantially decrease the amount of elastic recovery (springback) during the plastic deformation. But, the major issues in industrial utilities are high tooling and material cost, complex die setup, additional temperature and cooling control arrangement [2–4].

In order to explain complicated deformation behavior of different metals/alloys by the process variables such as strain, strain rate & temperature, extensive investigations have been conducted to improve constitutive relations. Lin and Chen presented a study of different constituent models, further split down into 3 groups, namely phenomenological, physical and Artificial Neural Network (ANN) based models [1]. Phenomenological based model gives a classical approach for modeling material behavior by viscoplastic theory. This theory aims at simulating the processing parameters with other variables by considering the hardening and softening [1]. Popular models were Johnson–Cook, Khan Huang Liang (KHL) and Arrhenius [1]. Physical-based models are focused on the physical aspects wherever dislocation movement activated thermally, thermodynamics theory, and kinetics of slips were involved. Presently, artificial intelligence technology, primarily neural networks based on genetic algorithms and back propagation algorithms, provides promising results in the fields of materials science, material processing and shape [2]. These have been well-defined algorithms which reduce complex calculations and require many experiments to find material constants. Limited studies on Inconel 718 alloy have been reported to define relation between deformation parameters and uniaxial flow stress at high temperature. A new constitutive model is developed by Lin et al. [3] to define deformation behavior at slow strain rates of aged Inconel 718. This model is combination of two models namely viscoplastic model (to define work hardening stage and DRX) & phenomenological model (to define dynamic softening stage). But, this new model unable to envisage flow behavior for high temperatures and different strain rates.

Quality of formed product is significantly influenced by anisotropy behaviour. Many researchers have made several efforts on development of the anisotropic yield criterion. Hill and Barlat criteria were popularly in sheet metal productions due to effortlessness to define material constants and easy to apply in FE analysis [4,5]. However, these yield criteria unable consider the biaxial deformation (prominent in the forming processes), deviation in uniaxial tensile strength and anisotropy coefficients is not captured [6]. A new yield criterion proposed by Khan and Yu based on the KHL constitutive model. This model not only describe anisotropic yield behaviour but also compression-tension asymmetricity of alloy. This proposed KHL model is used to predicted yielding behaviour at diverse strains, temperatures and strain rate with excellent relationship with experimental data. Model is generalized to introduce shape independent term for predicting yielding behaviour of different metals [7]. It is noticed that, recently few attempts were made to develop a constitutive models and yield criterion for Inconel alloys [8]. However, anisotropic yield criterion depends mainly on strain rates and temperatures variation dependent of Inconel 718 is not reported yet. Thus, present work mainly focuses on the thorough investigation of anisotropic yield criterion based on KHL constitutive model at different strain levels, temperatures & strain rates.

2. Materials and Experimental Methods

Inconel 718 sheet (commercially available) of 1 mm thick was used in the current study. Major alloying elements of Inconel by % mass are 51.5%Ni, 20%Fe, 18.4%Cr, 5%Nb 3%Mo along with balancing elements (≤ 0.17%). Uniaxial tensile tests were conducted at different test temperatures (room temperature(28°C) -700°C) and slow strain rates (0.0001-0.1s⁻¹) conditions. Authors in their previous work discussed detail experimental procedure [8–10]. Tensile strength were evaluated by sequence of experiments as listed in Table 1. Lankford Coefficients (r values) (r0, r45, r90), which defines resistance to thinning and further promotes the material flow into the die cavity, were also evaluated at different tension axis/sheet orientations of RD(0°), DD(45°) & TD(90°) to RD. Due to unavailability of biaxial
test facility, GN738 superalloy (similar chemical composition and mechanical properties), biaxial ($r_b$ and $\sigma_b$) properties have been used in present work [11].

Table 1: Representative mechanical properties of Inconel 718 alloy

| Temp. | $\sigma_0$(GPa) | ($r_0$) | $\sigma_{45}$(GPa) | ($r_{45}$) | $\sigma_{90}$(GPa) | ($r_{90}$) | $\sigma_b$(GPa) | [% elong] |
|-------|----------------|---------|-------------------|---------|-------------------|---------|----------------|----------|
| RT(28 °C) | 0.545 | 0.781 | 0.5006 | 0.941 | 0.504 | 1.043 | 0.502 | 42 |
| 300 °C | 0.424 | 0.997 | 0.4109 | 1.095 | 0.396 | 0.969 | 0.404 | 48 |
| 500 °C | 0.371 | 1.142 | 0.3478 | 0.969 | 0.328 | 0.917 | 0.338 | 52 |
| 700 °C | 0.324 | 1.123 | 0.3100 | 1.336 | 0.295 | 1.132 | 0.281 | 55 |

To perform warm deep drawing, laboratory-scale tool setup (consisting flat bottom punch, blank holder and die) is designed and fabricated as per schematic shown in Fig 1a. The warm deep drawing setup is designed with independent heating of die with induction heating elements with K-type thermocouples at three different locations. The warm deep drawing experiments are conducted using a 40-Ton double acting hydraulic press. All experiments are performed with applying graphene-based moly-spray as lubricant. Mainly deep drawing experiments performed under different die-punch temperature combination at 28-28°C, 300-28°C and 500-28 °C with fixed blank holding pressure (BHP = 2.5 MPa). Inconel 718 blanks of different diameter namely 58, 60 and 62 mm are used for drawing (Fig.1b). Specimens are wire cut out from parent sheet and centering to Inconel 718 blanks is done so as to reduce deep drawing defect. For each setting, 3 test were performed and avg. value was stated for consistent results. Fig 1c shows the drawn Inconel cup for 60 mm blank diameter at room temperature.

Fig. 1: Schematic of (a) warm deep drawing set up (b) Inconel blank dimensions (c) Inconel 718 drawn cup (D = 60 mm)

3. Material Modeling

3.1. Khan–Huang–Liang (KHL) Phenomenological Constitutive Model

The constitutive model expresses the flow behaviour as a function of processing variables, like strain, strain rate, and test temperature. Predicted flow stress by KHL model [9] is stated as,

$$\sigma = \left[A + B \left(1 - \frac{\ln \dot{\varepsilon}_p}{D_p} \right)^n \varepsilon_p^n \dot{\varepsilon}_p \dot{\varepsilon}_p^C \left(\frac{T_m - T}{T_m - T_{ref}}\right)^m\right]$$

where, $\varepsilon_p$ & $\sigma$ are true plastic strain & true stress. $T$, $T_{ref}$ & $T_m$ are the current, reference (28°C) and melting (1337°C) temperatures of the Inconel 718 alloy respectively. $D_p = 10^6$ s$^{-1}$, called as the deformation rate (subjectively selected strain rate upper bound) and $\dot{\varepsilon}_p^*(reference strain rate) = 0.01$ s$^{-1}$.
at $T_{\text{ref}}$, where $A$, $B$ and $n_0$ constants were evaluated). Additional constants are $n_0, n_1, C$ and $m$. Material constant are evaluated by detailed procedure followed by Khan et al.[12] and listed in the Table 2.

$$\sigma = \left[828.9 \times 10^6 + 580.06 \times 10^6 \left(1 - \frac{\ln \varepsilon}{\ln D_p}\right)^{\sigma_{10}}\varepsilon^{0.62}_{\sigma} \left(\frac{\varepsilon}{k}\right)^{1.3417} \left(\frac{T_m - T}{T_{\text{ref}} - T}\right)^{1.385}\right]$$

(2)

### 3.2. Khan–Huang–Liang (KHL) Anisotropic Yield Criterion

A novel anisotropic yield criterion is suggested by Khan et. al. [7] disassociating not only anisotropic yielding behaviour but also compression-tension asymmetry. Generalized form of yield function is given by

$$\left[\frac{2}{3} \sin \left(\frac{\theta + \pi}{3}\right)\right]^k [e^{-C(\xi + 1)}(F\sigma_1^2 + C\sigma_2 + H(\sigma_2^2 + P\sigma_{22}^2))] = 1$$

(3)

where $\theta$ - Lode angle, $k$-material constant (calculated by fitting the plane strain experimental data, $k = 0.5$ considered in the present study). Lode angle in the deviatoric stress plane, expressed as $\cos \theta = \frac{\sqrt{3} \Sigma_1}{2 \sqrt{J_2}}$ [13], where $S_1$ & $J_2$ - first and second deviatoric stress invariant. First term in yield function $\left[\frac{2}{3} \sin \left(\frac{\theta + \pi}{3}\right)\right]^k$, is called as shape-dependent term. Further, Eq. (3) can modify as function temperature, strain rate or strain to consider subsequent shape revolution in the work hardening. Ratio $e^{-C(\xi + 1)}$ describe tension compression asymmetry, where, $\xi = 1$. Material constants are given as,

$$F = \frac{1}{\tau^2}; H = \frac{1}{\sigma_1^2}; P = \frac{1}{\sigma_2^2};$$

$$G = \frac{1}{\tau^2} - \frac{1}{\sigma_1^2} - \frac{1}{\sigma_2^2}; C = -\frac{1}{2} \ln \left(\frac{\sigma_2}{\sigma_{1T}}\right);$$

(4)

where, $X, Y$ and $Z$ - 0.2% of yield strengths (compressive) along RD(0°), DD (45°) & TD (90°) to loading direction respectively, $\tau$ - initial yield strength (shear), $\sigma_{1T}$ - 0.2% of yield strengths (tensile) along RD. Initial value of $C$ is 0.074 (average of evaluated yield results along RD and TD). Values of $G, H, F$ and $P$ are listed in Table 3.

### Table 3: Anisotropy coefficients for KHL yield model

| Temp.  | $G$     | $H$     | $F$     | $P$     |
|--------|---------|---------|---------|---------|
| RT(28°C) | -0.5171 | 1.185   | 1       | 1.1769  |
| 300°C  | -0.3085 | 1.759   | 1.6506  | 1.8229  |
| 500°C  | -0.2251 | 2.455   | 2.1599  | 2.5947  |
| 700°C  | -0.1204 | 2.754   | 2.3571  | 2.9575  |

### 4. Result and Discussion

Fig.2a shows the plots of predicted flow stress and experimental stresses at different temperatures and strain rates. KHL constitutive model displays comparatively superior agreement for the predicted flow stress. Fig.2b shows plots between yield loci with experimentally measured stresses at different test strain rates & temperatures. It is clear from plots that yield loci of KHL model passes well through uniaxial and biaxial tensile points. This confirms suitability of KHL yield model for Inconel 718 alloy. A statistical parameters namely correlation coefficient (R), is generally used for the suitability. Fig. 3(a) shows evaluated correlation coefficient among predicted and measured (experimental) flow stress of
KHL model at tested strain rates. As, correlation coefficient was biased near higher or lower values. Therefore, it is essential to calculate other statistical parameters namely average absolute error (AAE) (Δ) and its standard deviation (s) [14]. Here, KHL constitutive model show moderate values for lower error (Δ), and its standard deviation. It is also possible to test the capability of any yield parameters by comparing the estimated values of r and σ values with experimental values. Fig. 3(b-c) show deviation of normalized σ and r-value with the loading axis. It has been found that yield function has good agreement for stress and significant inconsistency for r-variation. Therefore, it is helpful to estimate numerically the yield criteria performance before finalizing their suitability for the yielding behaviour prediction for Inconel 718 alloy. To evaluate performance of the yield criteria, global accuracy index (ω) is used to analysis the yield locus shape, and to visualize the planer distribution of uniaxial strength and the anisotropic coefficients [15]. Mathematically, it is given as,

$$\omega = \varphi + \delta + \gamma \ [%]$$

where,

$$\varphi = \frac{\sum_{i=0}^{j} d^2(P_i, Q_i)}{j} \times 100 \%$$

$$\delta = \frac{\sum_{i=0}^{j} (\sigma_{\theta_i} - \sigma_{\theta_i}^{pre})}{j} \times 100 \%$$

$$\gamma = \frac{\sum_{i=0}^{j} (r_{\theta_i} - r_{\theta_i}^{pre})}{j} \times 100 \%$$

Where, \(d^2(P_i, Q_i)\) - Square of distance from the \(P_i\) (experimental to \(Q_i\) (its projection) in the predicted yield loci, \(j\) is total number of considered experimental points. \(\theta_i\) is angle measured from loading axis. \(\sigma_{\theta_i}^{exp}, r_{\theta_i}^{exp}, \sigma_{\theta_i}^{pre}, r_{\theta_i}^{pre}\) are experimental and predicted yield strength and anisotropy coefficients along \(\theta_i\) respectively. Fig. 3d shows error function compared at different temperature and strain state. It specifies suitability of the yield criterion for Inconel 718 at different temperatures with error function 15 < ω < 29%

Fig. 2: Comparison of predicted and measured (experimentally) (a) flow stresses and (b) Yield loci at different strain rates
A quarter input FE model was developed in Abaqus-Explicit-SIMULIA™ version 6.14 due to symmetric geometry and to reduce total computational time. Fig.4a gives FE simulation model of deep drawing set up with blank, die, blank holder and flat bottom punch where except Inconel blank, and all tools are assigned as rigid bodies. In FE model, punch is allow to move downward (y-direction) with a velocity profile (trapezoidal) with fixed die. In order to restrict material flow in flange portion, blank holding force of 2.5MPa was considered in y-direction. Inconel blank is considered as deformable body with planar and normal anisotropy properties and material properties from Table 1 are considered as input. The developed KHL constitutive model and anisotropic yield criterion has been incorporated in user defined material subroutine (UMAT) for FE simulation. The FE results are validated with experimental deep drawn cups at different process conditions in terms of limit dome height (LDH) and average thickness (Fig 4b). LDH is measured as drawn height of formed cup just before occurring of fracture. Comparison of experimental and numerical results for punch displacement in terms of limit dome height at different test temperature is shown in Fig 5a. It is noticed that the FE predicted results are well comparable with experimental values. Average thickness distribution for specimen with diameter 60 mm with distance from the centre of cup is shown in Fig 5b. It is observed that thickness of drawn specimen remains constant initially and then it underway declining. Minimum thickness is perceived at a bending location wherever friction between punch and blank was maximum (as shown in insert in Fig.4b). FE predicted results are well comparable. Uniform thickness distribution is main concern in deep drawing, thus relative error, between experimental and FE predicted results, was evaluated. The avg. error (in %) for limit dome height and average thickness distribution were 2.93% and 4.64 % respectively. As error is within acceptable range, hence KHL constitutive model coupled with KHL yield criteria are best suited for execution of deep drawing of Inconel 718 alloy by FE analysis.
Fig 4: (a) FE model of deep drawing setup (b) Deep drawn cup at 28ºC (D= 60 mm)

Fig 5: Experimental and FE predicted (a) Limit dome height (b) Average thickness at different test temperature.

5. Conclusion

Khan–Huang–Liang (KHL) constitutive and yield model has been formulated for Inconel 718 alloy. Some of the important conclusions:

1. Uniaxial tensile flow stress of Inconel 718 have been considerably affected by test temperatures and strain rates. KHL constitutive model display good agreement with higher correlation coefficient (R > 0.9182), lower Average absolute error (AAE) and its standard deviation with experimental flow stress.

2. Anisotropic yield behaviour for Inconel 718 have been calculated by KHL yield criteria. The criteria were assessed based on the experimental yield strength values, yield stress and anisotropic coefficient variation. It was noticed that yield function a good agreement for σ-variation and significant inconsistency has been perceived for r-variation.

3. The developed KHL constitutive model and anisotropic yield criterion has been incorporated in FE simulation using user defined material subroutine UMAT code. The avg. error (in %) for limit dome height and average thickness distribution were 2.93% and 4.64 % respectively.

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