Analysis of Flow Stress Behaviour of Inconel Alloys at Elevated Temperatures Using Constitutive Model

Gauri Mahalle\textsuperscript{a}, Nitin Kotkunde\textsuperscript{a*}, Rushabha Shah\textsuperscript{a}, Amit Kumar Gupta\textsuperscript{a}, Swadesh Kumar Singh\textsuperscript{b}

\textsuperscript{a}Department of Mechanical Engineering, BITS-Pilani, Hyderabad Campus, Telangana, India – 500078
\textsuperscript{b}Department of Mechanical Engineering, GRIET, Hyderabad, Telangana – India – 500072

* nitink@hyderabad.bits-pilani.ac.in

Abstract. A reliable and accurate prediction of flow behaviour of metals considering the coupled effects of strain, strain rate and temperature is vital in analyzing the workability of the metal. In this study, Khan-Huang-Liang (KHL) phenomenological based constitutive models has been developed for flow stress prediction of Inconel 625 and 718 alloys. Firstly, uniaxial tensile tests have been performed from room temperature to 400\degree C at an interval of 100\degree C and slow strain rate ranges of 0.0001–0.01\text{s}^{-1}. KHL constitutive model has been developed using uniaxial tensile test data. The predicted flow behaviour has been compared with experimental stress-strain data. The prediction capability of these models has been verified using various statistical measures such as correlation coefficient ($R$), average absolute error ($\Delta$) and its standard deviation ($S$). Based on the analysis of statistical measures revealed that KHL model has good in agreement with experimental flow stress behaviour.

1. Introduction:
Nickel and its alloys have proven themselves to be superior and cost-effective materials for a wide range of applications in various industries such as aerospace, automotive, marine, nuclear reactors and cryogenics. These alloys are mainly suitable for service in high temperature environment, withstand severe mechanical stresses and strains, and remain resistant to thermal shock, corrosion and creep [1]. Most of the popular alloys in this family are Inconel 625 and Inconel 718 alloys used in modern aircraft engines and mission-critical defence operations where operations increasingly depend on the peak performance of the engines required [2]. Despite the above advantages, Inconel alloy are considered more difficult to deform and often have less predictable forming characteristics than other commonly used metallic alloys such as steel and aluminium [3].

Nowadays, Finite Element (FE) analysis has been extensively used as an effective tool to find out the optimum process parameters. Optimization of process parameters in metal forming is a vital task to reduce manufacturing cost and understand their influence on the deformation behavior of the sheet metal [4]. Constitutive models describe the relationship of the dynamic material properties with process parameters [5]. An accurate determination of constitutive equations is crucial for precise measurement and description of local and instantaneous response of the material. This lead to trustworthy and accurate numerical simulations [6].
Huang & Strangwood studied the hot deformation behavior of Inconel 718 alloy by using hot compression tests at temperatures ranging from 950 to 1100 °C with strain rates of 10^{-3} to 1 s^{-1}. They studied hyperbolic-sine type constitutive equation to model flow stress prediction [7]. Recently, Lin et al. [8] compared multi-gene genetic programming (MGGP), artificial neural network (ANN) and Arrhenius type phenomenological models for flow stress prediction on nickel based super alloy at elevated temperatures. They concluded that MGGP model is more accurate and reliable in describing the hot deformation behaviors of the nickel-based superalloy. However, very sparse efforts have been made for the constitutive model development for Inconel alloys. Thus, the objective of this study is to implement Khan–Huang–Liang (KHL) constitutive model to predict the flow stress behavior of the Inconel alloys at various temperature and low strain rates.

2. Experimental Details
In this study Inconel alloys sheet of 0.9 mm thickness were used for tensile testing. The samples are machined out of the raw material sheet by wire-cutting electro-discharge machining process for high accuracy and finish. The dimensions of the specimen are as per sub-size ASTM E8/E8M-11 standard. Uniaxial isothermal tensile tests are carried out on a computer controlled universal tensile testing machine (UTM) with high temperature contact type extensometer. Tensile test experiments were conducted from room temperature to 400°C at an interval of 100°C and strain rates 10^{-4}, 10^{-3} and 10^{-2} s^{-1}. A computer control system is used to record the load versus displacement which are converted into true stress versus true strain curves.

3. Development of Khan–Huang–Liang (KHL) constitutive models
The material constants for the KHL are determined based on the experimental data. Predicted Flow stress is given by equation (2) as expressed in the KHL Model.

\[
\sigma = A + B \left(1 - \frac{\ln \dot{\varepsilon}}{D_p} \right)^{n_1} \varepsilon_p^{n_0} \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_*}\right)^c \left(\frac{T_m - T}{T_m - T_{ref}}\right)^m
\]

where, \(\sigma\) is the true (Cauchy) stress and \(\varepsilon_p\) is the true plastic strain. \(T_m, T, T_{ref}\) are melting, current, and reference temperatures, respectively. \(D_p = 10^{-6} \ s^{-1}\) known as deformation rate (arbitrarily chosen upper bound strain rate) and \(\dot{\varepsilon}_* = 0.01 \ s^{-1}\) (reference strain rate, at a reference temperature of \(T_{ref}\), usually room temperature, at which material constants A, B and \(n_0\) are determined). \(n_0, n_1, c, m\) and m are additional material constants. For Inconel alloys, the melting temperature were taken to be 1350°C (for Inconel 625) and 1330°C (for Inconel 718). The reference temperature was taken as the initial temperature (27°C) for experiments. The detailed procedure for evaluating the material constant is mentioned by previous work done by Khan et al., [9]. The calculated material constant for Inconel 718 and 625 alloys is mentioned in Table 1.

Table 1. Material constants for Inconel 718 and 625 alloys

| Parameter   | A (MPa) | B (MPa) | \(n_0\) | \(n_1\) | C   | m   |
|-------------|---------|---------|---------|---------|-----|-----|
| Inconel 625 | 605.4   | 450.06  | 0.3042  | 0.3742  | 0.01957 | 1.073 |
| Inconel 718 | 828.9   | 580.06  | 0.62    | 1.3417  | 0.0135  | 1.385 |

4. Comparison of constitutive models:
The prediction capability of constitutive models has been evaluated by statistical measures viz. correlation coefficient (\(R\)), average absolute error (\(\Delta\)) and its standard deviation (\(\delta\)). \(R\) value may be biased towards higher or lower values. Therefore, average absolute error and its standard deviation are used to check the accuracy of the predictions [10]. The representative graphs comparing constitutive model predictions at higher (400°C) and lower temperature (Room temperature) with two different strain rates are shown in Figure 1. The correlation coefficient (\(R\)) with average absolute error and its standard deviation is shown in Figure 2. The R values are found to be 0.9559 and 0.9626 for Inconel 625 and 718.
alloys respectively. The average absolute error values are to be 3.99 and 7.06. Based on the statistical measures, it can be concluded that KHL model is very well suited for the prediction of flow behavior of Inconel 625 and Inconel 718 alloy at elevated temperatures.

Figure 1. Representative graphs comparing constitutive model prediction (a) Inconel 625 alloy (b) Inconel 718 alloy

Figure 2. Correlation for Khan–Huang–Liang (KHL) Model for (a) Inconel 625 (b) Inconel 718 alloys
5. Conclusion:
KHL constitutive model has been developed for Inconel 625 and Inconel 718 alloy at various temperatures and strain rates. In both the cases, the correlation coefficient is found to be above 0.95. Also, the average absolute error and its standard deviation is less than 7.65% which signifies the suitability of the KHL model for flow stress prediction of Inconel alloys at elevated temperatures.

Future work involves FE analysis of tensile test simulation using KHL constitutive model.

Acknowledgments
The financial support received for this research work from Science and Engineering Research Board (SERB – DST ECR) Government of India, ECR/2016/001402, is gratefully acknowledged.

References
[1] S.S. Satheesh Kumar, T. Raghu, Pinaki P. Bhattacharjee, G. Appa Rao, Utpal Borah, Strain rate dependent microstructural evolution during hot deformation of a hot isostatically processed nickel base superalloy, Journal of Alloys and Compounds 681 (2016) 28-42.
[2] D.-G. He, Y.C. Lin, M.-S. Chen, J. Chen, D.-X. Wen, X.-M. Chen, Effect of pretreatment on hot deformation behavior and processing map of an aged nickel-based superalloy, J. Alloys Compd. 649 (2015) 1075-1084.
[3] KS Prasad, SK Panda, SK Kar, M Sen, SVSN Murty, SC Sharma, Microstructures, Forming Limit and Failure Analyses of Inconel 718 Sheets for Fabrication of Aerospace Components, Journal of Materials Engineering and Performance 26 (4), 1513-1530.
[4] N Kotkunde, AD Deole, AK Gupta, SK Singh, B Aditya, Failure and formability studies in warm deep drawing of Ti–6Al–4V alloy, Materials & Design, 2014, 60, 540-547.
[5] Y.C. Lin, X.M. Chen, A critical review of experimental results and constitutive descriptions for metals and alloys in hot working, Mater. Des. 32 (2011) 1733-1759.
[6] N Kotkunde, HN Krishnamurthy, P Puranik, AK Gupta, SK Singh, Microstructure study and constitutive modeling of Ti–6Al–4V alloy at elevated temperatures, Materials & Design, 2014, 54, 96-103.
[7] Y.Huang, M Strangwood "Superplastic Behaviour of Inconel 718 alloys sheet,” Journal of Materials Science and technology, 16(2000), 1309-1313.
[8] Y C Lin, F Q Nong, X M Chen, D D Chen, M S Chen, “Microstructural evolution and constitutive models to predict hot deformation behaviors of a nickel-based superalloy”, Journal of Vaccum, 137(2017), 104-114.
[9] Akhtar S.Khan, Rehan Kazmi, Babak Farrokh, Multiaxial and non-proportional loading responses, anisotropy and modeling of Ti–6Al–4V titanium alloy over wide ranges of strain rates and temperatures, International Journal of Plasticity, Volume 23, Issue 6, June 2007, Pages 931-950.
[10] N Kotkunde, AD Deole, AK Gupta, SK Singh, Comparative study of constitutive modeling for Ti–6Al–4V alloy at low strain rates and elevated temperatures, Materials & Design, 2014, 55, 999-1005.