



Mechanical characterization and modelling of Inconel 718 material behavior for machining process assessment



A. Iturbe^{a,*}, E. Giraud^b, E. Hormaetxe^a, A. Garay^a, G. Germain^b, K. Ostolaza^c, P.J. Arrazola^a

^a Faculty of Engineering, Mondragon University, Loramendi 4, Arrasate 20500, Spain

^b Arts et Métiers ParisTech, CER Angers, Laboratoire LAMPA, 2 Bd du Ronceray, 49035 Angers Cedex 1, France

^c ITP, Parque Tecnológico, Edificio 300, 48170 Zamudio, Bizkaia, Spain

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ABSTRACT

Nickel based alloys are extensively used in the aerospace industry due to the excellent corrosion resistance and high mechanical properties that are maintained up to elevated temperatures (600–800 °C). However, these superalloys are classified as difficult-to-cut and therefore modelling and simulation of the machining processes has become a key in the machinability assessment of nickel based alloys. The reliability of Finite Element Models (FEM) largely depends on the quality of input parameters, one of the most relevant being the constitutive material model representing work material behavior under high strain, strain rate and temperatures.

In order to develop a reliable material model, the present work deals with a complete characterization of Inconel 718. Uniaxial compression tests at testing temperatures close to those found in machining (21–1050 °C) and high strain rates (10^0 – 10^2 s^{−1}) were performed on the Gleeble 3500 testing machine. Moreover, the microstructural analysis and microhardness measurements of the testing samples were performed, in order to correlate the microstructural state with the mechanical properties of the Inconel 718. Based on this experimental work, a new coupled empirical model is proposed to describe the particular behaviour of nickel based alloys at elevated temperatures and high strain rates. This material behaviour model introduces softening phenomena as well as the coupling between the temperature and the strain rate known to occur experimentally, for machining FEM simulations with Inconel 718 superalloy.

1. Introduction

Nickel based alloys are extensively used in the aerospace industry due to their high corrosion and oxidation resistance, high strength and long creep life at elevated temperatures [1]. Inconel 718 is the most widely used nickel based alloy in the aerospace industry owing to the remarkable machinability and welding capability of this alloy in comparison with other superalloys [2]. Nickel based alloys, have a relatively high yield (700–1200 MPa) and tensile (900–1600 MPa) strength at room temperature [3]. The most remarkable property of nickel based alloys is that they maintain their mechanical properties within a wide range of temperatures (up to 600–800 °C) [1]. Therefore, these alloys are commonly used in the hot section of jet engines [4].

The mechanical properties of nickel based alloys greatly depend on the chemistry and the microstructural features of the superalloy, such as grain size, γ'/γ'' size and distribution, carbide and boride size and content, and grain boundary morphology [5]. Inconel 718 exhibits a face-centred cubic (FCC) structure γ matrix where the remaining

phases reside. The main strengthening phase of this superalloy is the thermodynamically metastable phase γ'' . After long term thermal exposure, this metastable phase may eventually transform into the stable phase δ (Ni₃Nb) at temperatures above 650 °C, leading to a loss of properties of Inconel 718 above this temperature.

Concerning the machining performance, nickel based alloys are classified as difficult-to-cut. This is due to their special characteristics such as high strength at elevated temperatures, tendency to work hardening, poor thermal conductivity, the presence of hard abrasive carbides on their microstructure and the high chemical reactivity with the tool material and coatings [6,7]. These characteristics, lead to high power consumption and frequent tool changes that reduce productivity [8]. Considering the high workpiece material and experimentation cost, modelling and simulation of machining processes has become a key factor in the machinability assessment of nickel based alloys [9].

Nevertheless, the success and reliability of FEM modelling depends on the quality of input parameters such as the constitutive model representing the dynamic behavior of the workmaterial, the physical

* Corresponding author.

E-mail address: aiturbei@mondragon.edu (A. Iturbe).

and thermal properties of the workpiece and tool materials and tool-chip contact conditions, such as friction and heat transfer coefficients [9]. Of this inputs, one of the most relevant to the model, is the constitutive material law representing workpiece material behavior under high strain, strain rate, and temperatures [10]. A major difficulty to describe the material behavior in the cutting process is the severe deformation that takes place at high temperatures and high strain rates in a very small area: the primary and secondary deformation zones [11]. Strain levels ε (1–7), strain rate $\dot{\varepsilon}$ (0 – 10^6 s $^{-1}$) and heating rates (close to 10^6 °C s $^{-1}$) can be encountered in metal cutting [11]. These unique features of deformation in metal cutting result in material behavior that is markedly different from that encountered in conventional material testing.

The identification of material constitutive laws for machining is generally carried out through direct experimental methods such as Split Hopkinson pressure bar (SHPB) tests [12], shear tests [13,14] and uniaxial compression tests at high temperatures and strain rates [15,16].

Mechanical properties of Inconel 718 superalloy were mainly studied through uniaxial quasi-static compression tests at room and high temperatures and low strain rates ($\dot{\varepsilon} \leq 1$ s $^{-1}$), which focused on the optimization of hot forming processes. Yuan and Liu characterized the mechanical properties of Inconel 718 in the temperature range between 900–1080 °C and strain rates in the range of 10^{-3} – 10^0 s $^{-1}$ [17]. More recently, Si et al. also utilised the hot compression technique to determine the mechanical properties of Inconel 718 in the temperature range between 900–1060 °C and strain rates in the range of 10^{-3} – 0.5 s $^{-1}$ [18]. Wang et al. carried out hot compression tests on the Gleeble-1500 machine at temperatures in the range of 950–1100 °C and strain rates ranging from 10^{-3} to 10^0 s $^{-1}$ to understand the dynamic recrystallization behaviour of Inconel 718 superalloy [19].

At closer conditions to those found in machining, Soo et al. carried out hot compression tests on Inconel 718 superalloy on the Gleeble 3500 thermo-mechanical simulator at temperatures in the range of 20–850 °C and strain rates ranging from 10^0 to 10^2 s $^{-1}$ [16]. Nevertheless, only strains up to 30% were reached on this study. Wang et al. utilised SHPB testing method to characterize Inconel 718 at higher strain rates, from 5000 to 11000 s $^{-1}$, but on a narrower temperature range, from 500 to 800 °C [12]. Therefore, the material behaviour of Inconel 718 in conditions close to those found in machining has not been well addressed yet. Moreover, there is a lack of insight into interactions between strain, strain rate and temperature on this processing range.

The Johnson-Cook Material model [20] is the most widely used material constitutive law for simulating metal cutting processes. This empirical model (Table 1), considers isotropic hardening, strain rate hardening and thermal softening as three independent phenomena that can be isolated from each other (uncoupled). The equivalent flow stress σ is calculated by multiplying these three phenomena: (i) $[A + B\varepsilon^n]$, isotropic hardening (ii) $\left[1 + C \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]$ strain rate hardening and (iii)

$\left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right]$ thermal softening where ε is the equivalent plastic strain, $\dot{\varepsilon}$ is the plastic strain rate, $\dot{\varepsilon}_0$ is the reference equivalent plastic strain rate, T is the workpiece temperature, T_m is the material melting temperature and T_0 is the reference temperature. Regarding the model parameters that need to be calibrated for each material, A is the yield strength of the material at the reference temperature and strain rate, B is the strain hardening constant, n is the strain-hardening exponent, m is the thermal softening exponent and C is the strain-rate sensitivity parameter.

The Johnson-Cook model parameters utilised in the literature as an input for FEM simulation with the Inconel 718 are summarized in Table 2. It is noteworthy that JC model parameters, mostly A , C , n , highly depend on the heat treatment. It is also appealing that various authors did not consider the thermal softening effect ($m=0$).

Table 1

Different coupled material constitutive equations.

Johnson-Cook [20]	$\sigma_{JC} = [A + B\varepsilon^n] \cdot \left[1 + C \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right] \cdot \left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right]$
Modelling strain softening Calamaz [21]	$\sigma = \sigma_{JC} \left[D + (1 - D) \tanh\left(\frac{1}{\varepsilon + \varepsilon_a}\right) \right]$ $D = 1 - \left(\frac{pe^r}{1 + pe^r} \right) \tanh\left[\left(\frac{T - T_0}{T_{rec} - T_0} \right)^q \right]$
Sima & Ozel [10]	$\sigma = \sigma_{JC} \left[D + (1 - D) \left(\tanh\left(\frac{1}{\varepsilon + S^j}\right) \right)^S \right]$
Lurdos [22]	$\sigma = \sigma_s + (\sigma_0 - \sigma_s + A\varepsilon^n) \exp(-re)$
Modelling the coupling between the temperature and strain rate Lin [23]	$\sigma = (A_1 + B_1\varepsilon + B_2\varepsilon^2)(1 + C_1 \ln \dot{\varepsilon}^*) \exp[(\lambda_1 + \lambda_2 \ln \dot{\varepsilon}^*)(T - T_{ref})]$
Arrhenius model [18,24,25]	$\sigma = \frac{1}{a} \ln \left\{ \left(\frac{Z}{A} \right)^{\frac{1}{n}} + \left[\left(\frac{Z}{A} \right)^{\frac{2}{n}} + 1 \right]^{\frac{1}{2}} \right\}$ $Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right)$ Zenner-Hollomon parameter
Wang [12]	$\sigma_{JC} = [A + B\varepsilon^n] \cdot \left[1 + C(T) \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right] \cdot \left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right]$ $C(T) = 0.0232 - \left(0.00372 + 0.0021 \sin\left(\frac{\dot{\varepsilon} - 5000}{3000}\pi\right)\right) \sin\left(\frac{T - 500}{150}\pi\right)$

Even if Johnson-Cook Material model is the most widely used strength model in metal cutting simulations, this equation (Table 1) describes strain hardening as an increasing function that diverges to infinity with strain and does not consider strain-softening phenomena. However, it has been reported that softening phenomena is essential for the initiation and amplification of strain localization, which causes the formation of adiabatic shear bands in simulation of machining operations [21]. Thus, several authors have developed modified versions of the Johnson-Cook model in order to consider softening phenomena. Calamaz et al. proposed a TANH model that adds a new term to the conventional Johnson-Cook equation to take into account strain softening at elevated temperatures and strain rates [21]. In the TANH model (Table 1), flow softening is defined as a decreasing behavior in the flow stress with increasing strain beyond a critical strain value. The main advantage of this model is that the previously identified Johnson-Cook model parameters can be used (A , B , C , n , m) to predict the flow behavior of the material. Nevertheless, five new parameters need to be identified in order to consider softening: p , q , T_{rec} , r , ε_0 . Sima & Ozel further modified the TANH material model by introducing an S exponent to better control tangent hyperbolic (tanh) function for thermal softening [26]. Another approximation to consider flow softening was developed by Lurdos et al. [22] by adding a supplementary strain hardening term $A\varepsilon^n$ to the conventional Voce model [27]. The fundamental difference with the Johnson-Cook equation is the occurrence of steady state behavior in the Voce equation when compared to a divergent behavior of the strain hardening in Johnson-Cook equation. The strain rate and temperature sensitivity in this model are accounted by the variation of the five model parameters σ_s , σ_0 , r , A , n as a function of the temperature and the strain rate, where σ_0 is the initial yield strength and σ_s the steady state stress.

Furthermore, Johnson-Cook model neglects the coupling between the strain, strain-rate and temperature known to occur experimentally [28]. For most metals, the strain rate sensitivity parameter is low near room temperature but increases with temperature [29]. On a sensitivity analysis of flow stress carried out by Fang, it was concluded that below the temperature of 500 °C Inconel 718 is not sensitive to strain rate hardening [30]. Therefore, several models have tried to describe the coupling of the effects of temperature and strain rate on the flow stress

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