Available online at www.sciencedirect.com
ScienceDirect
Trans. Nonferrous Met. Soc. China 26(2016) 1105−1111
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Identification of constitutive model parameters for nickel aluminum bronze in machining

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Received 27 May 2015; accepted 4 November 2015

Abstract: The material of nickel aluminum bronze (NAB) presents superior properties such as high strength, excellent wear resistance and stress corrosion resistance and is extensively used for marine propellers. In order to establish the constitutive relation of NAB under high strain rate condition, a new methodology was proposed to accurately identify the constitutive parameters of Johnson−Cook model in machining, combining SHPB tests, predictive cutting force model and orthogonal cutting experiment. Firstly, SHPB tests were carried out to obtain the true stress−strain curves at various temperatures and strain rates. Then, an objective function of the predictive and experimental flow stresses was set up, which put the identified parameters of SHPB tests as the initial value, and utilized the PSO algorithm to identify the constitutive parameters of NAB in machining. Finally, the identified parameters were verified to be sufficiently accurate by comparing the values of cutting forces calculated from the predictive model and FEM simulation.

Key words: nickel aluminum bronze; constitutive parameter; Johnson−Cook model; identification method

1 Introduction

As a copper-based alloy, nickel aluminum bronze (NAB) presents great advantages of high strength, and corrosion resistance, and thus is extensively used for marine propellers [1]. These optimum characteristics are mainly controlled by the thermo-mechanical behaviors in the cutting process. Many researches on NAB have mainly focused on microstructural evolution, corrosion properties [1−4], flow behavior under conventional material tests [5], and no regarding the plastic deformation behavior in machining. However, the material behavior encountered in conventional material tests could not be applied to metal cutting. Therefore, developing the accurate constitutive model and identifying the involved parameters are urgently needed to explain the material properties that influence the cutting process in both FEM simulation and analytical modelling of process variables.

Generally, for a constitutive model, the reliable flow stress data and the corresponding mathematical equation are required. Flow stress data are mainly obtained from three methods [6], i.e., material compression test [7−9], cutting experiment [10−13] and FEM [14−16]. SEDIGHI et al [7] investigated an approach in parametric identification of the high strain rate constitutive model using SHPB tests, and determined the model parameters by Levenberg−Marquardt method. PUJANA et al [10] proposed a reverse method to determine the constitutive model based on the variables in primary shear zone (PSZ) and second deformation zone (SDZ), and successfully identified the constitutive parameters of the steel 42CrMo4 and 20NiCrMo5. SHATLA et al [11] and SARTKULVANICH et al [12] used the orthogonal slot milling to obtain the variables in PSZ, and the constitutive parameters were derived from the iteration method by matching OXCUT output with the experimental cutting force. TOUNSI et al [15] and OZEL [16] obtained the constitutive parameters by matching FEM prediction with the measured cutting force in orthogonal cutting. However, these three

Foundation item: Project (2014CB046704) supported by the National Basic Research Program of China; Project (2014BAB13B01) supported by the National Science and Technology Pillar Program of China
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DOI: 10.1016/S1003-6326(16)64207-3

methods have still some drawbacks. For SHPB method, strains were less than 1, the strain rates were not higher than 2×10^4 s^{-1} [7], and the experimental equipment was relatively complex and high-cost. Cutting experiment method needed numerous cutting experiments and was time-consuming, and the identified results were not unique [12]. For FEM method, the adjustment of flow stress every time required many iterations to match predictive and measured value of cutting force, and each iteration needed more than 5 h [12].

Considering the previous review and the vast advantage of Johnson−Cook constitutive model in describing the material plastic flow behavior in machining [14,17], a methodology was proposed to identify the constitutive parameters of Johnson−Cook model for NAB material in machining. This was based on the combination of SHPB tests, predictive cutting force model and orthogonal cutting experiment. The method set up an objective function of the predictive and experimental flow stresses, put the identified values of SHPB tests as the initial value, and adopted the PSO algorithm to derive the constitutive parameters in machining. The identified parameters were verified by comparing the values of cutting forces obtained from the predictive model and FEM simulation.

2 Johnson−Cook constitutive model

The Johnson−Cook constitutive model is used widely in the simulation and analytical prediction of cutting process due to its high accuracy and mathematical simplicity, which can also describe the material behavior at high strains, high strain rates and high temperatures. So, it is chosen here to describe the plastic deformation behaviors of the material NAB, as given in Eq.(1):

$$\sigma=(A+B\varepsilon^n)\left[1+C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left[1-\left(\frac{T-T_r}{T_m-T_r}\right)^m\right] \tag{1}$$

where σ is the flow stress, ε is the plastic strain, $\dot{\varepsilon}$ is the strain rate and T is the temperature. The material flow behaviors are defined by five parameters A, B, C, n and m, which are yield strength, strain hardening modulus, strain rate hardening coefficient, strain hardening exponent and thermal softening exponent, respectively. In addition, $\dot{\varepsilon}_0$, T_r and T_m respectively represent reference strain rate, room temperature and melting temperature. For NAB, the melting temperature is 1058 °C.

3 SHPB tests and results

The material used in the tests was NAB alloy, ZCuAl9Fe4Ni4Mn2, and its chemical composition (mass fraction) is: 80.30% Cu, 9.28% Al, 4.45% Fe, 4.24% Ni, 1.42% Mn, 0.0076% Zn, 0.011% Sn and 0.022% Pb, which is accordance with the standard GB1176−74 ISO484.

SHPB tests were used to obtain the true stress−strain curves at various temperatures and strain rates. In order to increase uniformity in deformation, the interfaces among the bars and specimen were lubricated with grease. Heating furnace was used to warm up the specimen and made the temperature reach the set value. The strain gages pasted on the bars can be used to measure and collect the strain signal. What is more, the initial diameter and height of the cylindrical specimens were 2 mm and 2 mm, respectively. And special treatment of the parallelism, flatness and roughness was made for the reliability of the experimental results.

The designed temperatures and desired strain rates for SHPB tests are listed in Table 1. Since actual strain rate was not a constant, all the tests were repeated three times, and the data had good repeatability.

Table 1 Designed parameters of SHPB tests

Temperature/°C	25	200	400	600	800
Desired strain rate/s^{-1}	2000	2000	2000	2000	2000
	6000	6000	6000	6000	6000
	16000	16000	16000	16000	16000

The experimental results of SHPB tests are shown in Figs. 1 and 2. Figure 1 gave the true stress−strain curves of NAB at different temperatures and the same desired stain rate, while Fig. 2 represented ones at different desired stain rates and the same temperature. As seen in Figs. 1 and 2, the flow behaviors of NAB had the effect of obvious strain rate strengthening and thermal softening, i.e., at the same temperature, when strain rate increased, the flow stress increased. While the flow stress decreased with temperature rise under the same strain rate. This phenomenon can be attributed to: high strain rates forced the crystal movement at the grain boundary and resulted in the increase of flow stresses; at high temperatures, the thermal activation effect increased the dislocation slip plane and slip direction, and led to crystal plastic deformation easily, thus the flow stresses decreased along with the temperature rise.

Furthermore, quasi-static compression tests were also conducted using the Gleeble 3500 machine at a stain rate of 0.001 s^{-1} and room temperature. The cylindrical specimens used were 5 mm in diameter and 5 mm in height. Load and displacement of loading head were recorded. Then, true strain and stress of specimens could be calculated. The results of quasi-static compression test are shown in Fig. 3.