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Inverse identification of flow stress in metal cutting process using Response Surface Methodology

Amir Malakizadi[a,*], Stefan Cedergren[a,b], Ibrahim Sadik[a,c], Lars Nyborg[a]

[a] Chalmers University of Technology, Department of Materials and Manufacturing Technology, SE412 96 Gothenburg, Sweden
[b] GKN Aerospace Engine Systems, Research and Technology Centre, 46181 Trollhättan, Sweden
[c] AB Sandvik Coromant, R&D Materials and Processes, SE126 80 Stockholm, Sweden

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ABSTRACT

In this study, a methodology was presented to determine the flow stress behaviour of the work material within the range of strain, strain rate and temperature encountered during chip formation process by means of inverse modelling of orthogonal cutting operations. This approach was based on the concept of Design of Experiments (DOEs) and Response Surface Methodology (RSM). Initially, an extension of Oxley's machining theory incorporating the Johnson–Cook material model was integrated with RSM to accomplish a fast assessment of the material parameters. Having provided the material parameters by Oxley's machining theory, the optimum set of friction coefficients were determined through evaluation of the Finite Element (FE) simulation results. The final step involved direct integration of 2D FE models incorporating the optimum frictional boundary conditions with RSM to reassess the optimum set of material parameters. This approach was implemented to determine the constitutive parameters for wide range of materials including Inconel 718 in aged condition, AISI 1080 plain carbon steel and AA6082-T6 aluminium alloy. The calibration of material models using the presented inverse methodology led to a significant improvement in simulation results. The reasons for the robustness of the proposed inverse methodology were discussed.

1. Introduction

In recent years, Finite Element Method (FEM) has been widely used to cope with difficulties in simulation of machining operations. Yet, implementation of a proper constitutive model provided with well-defined parameters remains as a main challenge to attain reliable simulation results [1]. Due to severe material deformation during chip formation process, it is common to reach shear strains as high as 10, strain rates between 10^4–10^6 s^{-1} and temperatures up to 1000 °C [2]. High strain rate experiments such as Taylor's impact and Split Hopkinson Pressure Bar (SHPB) tests have generally been used to simulate the deformation conditions during metal cutting process. Calibrated constitutive models using those experimental data have been used by several authors [3–6] for metal cutting simulations. However, some studies showed poor simulation results incorporating the flow stress data attained from high strain rate experiments. Chandrasekaran et al. [7] showed that the flow stress properties obtained from SHPB test may lead to 2–3 times higher shear stress at the primary shear zone

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[*] Corresponding author. Tel.: +46 31 772 12 45; fax: +46 31 772 13 13.
E-mail address: amir.malakizadi@chalmers.se (A. Malakizadi).

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as compared with the experimental measurements [7]. This deviation was believed to be due to the limited attainable range of plastic strain in those experimental setups. The other limitations of SHPB test were explored by Guo [2].

To overcome these limitations, a number of studies have been dedicated to inverse identification of constitutive data using the measured responses during orthogonal cutting tests as a reference. In this approach, the constitutive data are constantly modified during orthogonal cutting simulations until the difference between the experimental and simulated responses is minimised. Sartkulvanich et al. [8] developed a programme named OXCUT based on Oxley's machining theory. In this programme, the cutting forces and the relative thickness of primary and secondary shear zones were used as the criteria for inverse identification of material parameters. Özel and Zeren [9] extended the Oxley's machining theory [10] by improving the frictional distribution along the tool–chip interface. The modified model was then used for inverse identification of the constitutive data and the friction coefficient. Pujana et al. [11] instead used the analytical model proposed by Tounsi et al. [12] to calculate the shear stress on the primary and secondary shear zones as inputs for inverse identification of material parameters. Shi et al. [13] developed an analytical model, referred to as distributed primary zone deformation (DPZD) model, to accomplish a better prediction of stress, strain and strain rate distribution within the primary shear zone. They later used this model for inverse identification of Johnson–Cook (JC) material parameters. However, despite rigorous efforts, these analytical models involved a number of assumptions to simplify the deformation field in the vicinity of the cutting edge. Hence, the FE models provided with the constitutive data determined based on those analytical models often showed poor prediction results [11,13]. Direct implementation of FEM was instead suggested by several authors [14–16] to overcome this limitation. In this approach, the FE models provided with updated set of constitutive data were solved iteratively until the difference between the FE simulation results and the corresponding experimental measurements was minimised. However, computational cost of iterative FE simulations may also lead to an inefficient inverse modelling scheme.

Recently, Malakizadi et al. [17] proposed an inverse methodology based on the concept of experimental design and Response Surface Methodology (RSM) to avoid the need for running FE models iteratively during optimisation process. In the current study, different aspects of the proposed inverse algorithm are addressed in detail and its credibility is assessed for a wider range of materials. This approach involves two steps. Initially flow stress properties for each material are determined by integration of Oxley's machining theory and RSM. The aim is to accomplish a fast assessment of the constitutive data for the work materials using a relatively simple analytical model. Having provided the potential set of material parameters, a number of 2D FE simulations are carried out to determine the optimum set of friction coefficients for each tool–work material combination. The final step involves direct integration of 2D FE models with RSM to reassess the material parameters. This inverse methodology is applied to determine the JC constitutive parameters for Inconel 718 in aged condition, AISI 1080 plain carbon steel and AA6082-T6 aluminium alloy. The creditability of identified material parameters is evaluated by comparison of the 2D and 3D FE simulation results with experimental measurements at a wide range of cutting conditions.

2. Materials and experimental details

Orthogonal machining tests for AISI 1080 eutectoid steel were performed under dry condition using Sandvik grooving inserts N151.2-650-50-3B-H13A uncoated carbide. A cylindrical bar with 60 mm diameter and 55 mm length was heat up to 865 °C for 1 h followed by 10 min holding time at 590 °C within a salt bath and air cooled to room temperature. The heat treating cycle resulted in a fully pearlitic structure with 274 μm mean true lamellar spacing. All machining tests were performed in a EMCO 365 CNC lathe equipped with a Kistler 9275A three component dynamometer to measure the cutting forces. Transverse machining of 2 mm flanges ensured that the orthogonal cutting condition was held during cutting experiments. Each cutting test was repeated three times with fresh inserts to ensure reproducibility of the results. A Leitz DMRX light optical microscope equipped with AxioVision digital image processing software was used to measure the thickness of randomly selected chips at each cutting condition. The chip–tool contact lengths were also measured by means of EDS (Energy Dispersive Spectroscopy) analysis on the rake face of the inserts after machining using Iron elemental map.

The experimental measurements for Inconel 718 in aged condition were taken from Malm and Hagberg [18]. The orthogonal cutting tests were carried out under dry condition using Greenleaf ceramic inserts WG-6218-2A, grade WG-300, with 0° rake angle. The material was heat treated using standard aging cycle of 8 h at 718 °C followed by 10 h holding time at 620 °C [19]. The heat treatment resulted in a Vickers hardness of 445, measured with 10 kg load. The average grain size of the samples were 16 μm, measured according to E112 ASTM standard.

The experimental data for AA6082-T6 aluminium alloy was taken from [20]. K10 uncoated carbide with 6° rake angle and without chip breaker was used for orthogonal cutting tests. The orthogonal cutting tests were performed on tubular samples with cutting width at least ten times larger than the uncut chip thickness (i.e. feed rate). Table 1 shows the cutting conditions used for inverse identification of JC parameters and also the verification of the flow stress properties of the workpiece materials.

Face turning was also carried out for Inconel 718 to assess the reliability of the identified constitutive data for modelling of the machining process under operational conditions. The work material was taken from the same batch as the ones used for the orthogonal cutting tests and was heat treated in similar way. Machining tests were conducted under wet condition, using mineral oil based emulsion Blaser Swisslube Blasocut BC25-MD with 7% concentration. The cutting forces were measured using a Kistler type 9275A three component dynamometer. Uncoated standard cemented carbide tools without