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A novel relaxation-free analytical method for prediction of residual stress induced by mechanical load during orthogonal machining

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ABSTRACT

Prediction of the residual stresses in machining is significant for the manufacturing of high performance components. This paper presents a novel relaxation-free analytical method for residual stress prediction in orthogonal machining based on the inclusion theory. First, a semi-analytical approach is employed for incremental analysis of the elastic–plastic deformation of the subsurface material. Both the mechanical loads on the shear plane and the flank face are considered in the contact model of orthogonal machining. Then, one-dimension distributed inclusion theory is deduced to achieve the closed-form solution of the residual stresses based on the plastic strains obtained in the foregoing analysis. Using the proposed method the boundary conditions encountered in the solution of the residual stress are satisfied in nature and the relaxation procedure is no longer required. A widely used orthogonal machining test is adopted to verify the residual stress derived from the proposed method. As a result the residual stress predicted by the proposed method is identical with the one from the relaxation procedure. Moreover, the proposed relaxation-free method is valid against the experimental measurement and the existing numerical simulation. In addition to the high computation efficiency inherited from analytical approach, the relaxation-free method provides a more concise solution with clear physical mechanism, which reveals the unique linear mapping relationship between the biaxial in-plane plastic strains and residual stresses in machining for the first time.

1. Introduction

Residual stress induced by machining process plays an important role in the functional behavior of the machined components. The distribution of the residual stresses in the subsurface layer of components might enhance or impair fatigue life, corrosion resistance and dimension accuracy, etc., depending on their attributes (tensile or compressive). Therefore, understanding of residual stress and applicable model for prediction are needed for the optimization of process parameters so as to achieve high performance machined components at shop floor.

The residual stress in machining is a classic topic which has been widely investigated in the past nearly 70 years since the pioneer work of Henriksen [1]. Although a large number of experimental and theoretical investigations have been reported on the mechanism of residual stress, it is in the recent 20 years that quantitative models for prediction are proposed. In summary, they can be classified into empirical models, numerical models and analytical models [2]. The empirical models based on statistical method, such as the response surface methodology [3], regression analysis [4] and ANOVA method [5], etc., can provide a good knowledge about the outcomes with similar input parameters. Without understanding of the mechanism, however, these models are *black-boxes* which depend on a large amount of cumbersome experiments and measurements. With the rapid development of computation techniques, the numerical models based on finite element method (FEM) technique are emerging as powerful tools. Once the material constitutive model is calibrated accurately, these methods generally obtain predictions that conform to the experimental values [6]. In spite of their ability to simulate complex physical phenomenon in machining process with specific subroutine of material constitutive, they are too much time consuming for the parameter study of machining process in industry, which might take as long as dozens of hours. In comparison, the analytical methods are promising candidates with high computation efficiency and scientific understanding of the mechanism [7].

Several analytical models for residual stress in machining had been proposed since the early work of Liu et al. [8–10], which illustrated an idealized qualitative model with a small line element subjected to elastic–plastic loading and unloading process for the interpretation of residual stress. Matsumoto et al. [11,12] employed Merwin and Johnson's analytical method for rolling contact

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[13] to analysis the effect of workpiece hardness on residual stress. Similarly, Jacobus et al. [14] developed a plane-strain thermo-elastic–plastic model for orthogonal machining following the modeling technique in [13] and accurately predicted the biaxial residual stress profiles beneath the newly machined surface. Recently, Liang and Su [15] proposed a predictive model for residual stress in orthogonal cutting considering the effect of shear plane and the edge hone, in which the hybrid algorithm proposed by McDowell [16] is adopted. Based on the superposition of thermal and mechanical stresses, Lazoglu et al. [17,18] presented an enhanced analytical model for residual stress prediction in orthogonal machining using the analytical approach for rolling/sliding contact developed by Jiang and Sehitoglu [19]. It is noted that all the analytical methods mentioned above must tackle the 'pseudo' residual stresses and strains which do *not* satisfy the equilibrium conditions after the incremental analysis of elastic–plastic deformation. Hence, an artificial incremental relaxation procedure is required to achieve the real residual stress after the loading and unloading process.

In this paper, we present a relaxation-free analytical method based on inclusion theory to predict the residual stress in orthogonal machining. Inheriting the high efficiency of analytical model, the proposed method provides a more concise result with clear physical meaning, which can simplify the computation procedure and enhance the applicability of the analytical models at present. To the best of our knowledge, the proposed method based on inclusion theory from the perspective of micromechanics has never been reported in the prediction of residual stress in machining. The methodology of inclusion theory is introduced to tackle the one-dimension distributed residual stress in orthogonal machining so that the problem of 'pseudo' residual stresses and strains is eliminated in nature. Instead of the relaxation procedure, a closed-form solution for residual stress is achieved in our method, which can be employed to enhance the analytical methods mentioned above. For the first time, the proposed method reveals the unique linear mapping relationship between the biaxial in-plane plastic strains and residual stresses, providing a deep insight into the scientific understanding of residual stress generation in machining.

The rest of the paper is organized as follows. In Section 2, mechanism of residual stress in orthogonal machining is introduced and the incremental sliding contact model of elastic–plastic deformation due to mechanical load in machining is provided. Section 3 proposes the relaxation-free method, in which the closed-form solution of residual stress is deduced based on one-dimension distributed inclusion theory. Section 4 provides the numerical verification and results comparison. Section 5 give a discussion on the similarity and the discrepancy of the results achieved by the proposed method. Conclusions are drawn in Section 6.

2. Contact model of orthogonal machining

The generation of residual stress in the machined surface depends on the mechanical–thermal contact between the cutting edge and the surface to be formed, as shown in Fig. 1. Despite the significance of thermal stress in some process, such as grinding and EDM, it has been demonstrated that mechanical effect dominates the generation of residual stress for orthogonal machining of some material at relatively low cutting speed [10,20,21], when the thermal effects on the subsurface plastic deformation are trivial. Therefore, we focus on the analysis of mechanical load during orthogonal machining in the subsequent sections and the thermal effects are not to be considered for simplification.

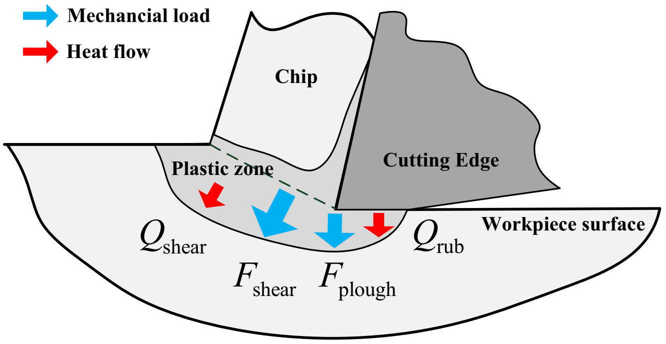

Fig. 1. Mechanical–thermal contact in orthogonal machining.

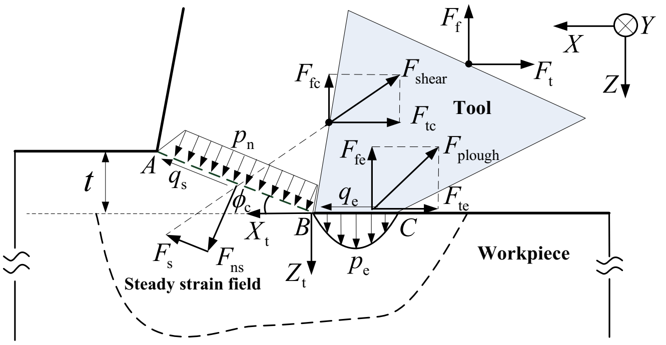

Fig. 2. Mechanical loading with flank wear in orthogonal machining.

2.1. Mechanical loading during orthogonal machining

The geometry of orthogonal machining and the coordinate system used for analysis are described in Fig. 2. The mechanistic cutting force model with shearing and ploughing mechanism is adopted, in which the forces in the tangential and feed directions F_t, F_f are expressed as superposition of the components of the shearing force F_{tc}, F_{fc} due to the primary deformation zone and the components of the ploughing force F_{te}, F_{fe} due to the tertiary deformation zone:

$$F_t = F_{tc} + F_{te}$$
$$F_f = F_{fc} + F_{fe} \tag{1}$$

The shearing force is in proportion to the uncut chip thickness t, while the ploughing force is determined by the cutting width b:

$$F_t = K_{tc}bt + K_{te}b$$
$$F_f = K_{fc}bt + K_{fe}b \tag{2}$$

where the cutting coefficients K_{tc}, K_{fc} and the edge coefficients K_{te}, K_{fe} can be calibrated by linear regression of the forces measured in several orthogonal cutting tests with different feed rates [22]. Moreover, based on the orthogonal cutting theory, the cutting coefficients can be expressed as functions of the shear stress τ_s, shear angle ϕ_c, friction angle β_a and rake angle α_r:

$$K_{tc} = \tau_s \frac{\cos(\beta_a - \alpha_r)}{\sin\ \phi_c\ \cos(\phi_c + \beta_a - \alpha_r)}$$
$$K_{fc} = \tau_s \frac{\sin(\beta_a - \alpha_r)}{\sin\ \phi_c\ \cos(\phi_c + \beta_a - \alpha_r)} \tag{3}$$

Liu and Barash's work [9] indicates that the shear plane length is the governing parameter of the plastic deformation of the subsurface layer in orthogonal cutting with a sharp tool. It is thus reasonable to take the distribution of load on the shear plane as a part of boundary conditions for contact analysis. Without