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Prediction about ground hardening layers distribution on grinding chatter by contact stiffness

Cong Sun, Jinchao Duan, Dongxue Lan, Zhenxin Liu, Shichao Xiu *

Northeastern University, China

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ABSTRACT

The grinding hardening is an integrated manufacturing technology which combines the surface hardening theory and the grinding technology. However, the grinding chatter accompanies with the whole grinding hardening process. It is the existence of the grinding chatter that makes the transformation unsteady. To this end, the paper presents a three-hybrid model to investigate the relationship between the grinding chatter and the grinding hardening layers distribution. The dynamic grinding force with the analytic and numerical method is calculated firstly. Then the finite difference method (FDM) is used to obtain the dynamic temperature distribution accordingly. Thirdly, the cellular automata (CA) method is applied to calculate the transformed microstructure distribution under different chatter strengths. The study shows that the thickness of the grinding hardening layers goes up with the increase of the grinding chatter. However, the quality of the grinding hardening layers reduces with the increase of the chatter strength. In addition, the martensite content varies with different hardening layers since each layer has its own unique temperature distribution. Moreover, metallurgical experiments are conducted to validate the proposed model. The model is anticipated to be meaningful for the improvements of workpiece's mechanical properties by controlling the chatter strength in the industry manufacturing.

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1. Introduction

Grinding hardening is a new technology on account of its excellent surface integrity, complex machining and green manufacturing characteristics [1–4]. The grinding hardening layer is a result of workpiece's microstructure transformation. It should be noticed that the transformed microstructure distribution decides the final workpiece's surface mechanical properties directly [5,6]. Therefore, it is of significance to investigate the factors which affect the transformed microstructure distribution.

Generally, the dynamic temperature distribution is the key factor which affects the transformed microstructure distribution. Moreover, the generated thermal load is superimposed by the mechanical load, which can be calculated in the form of

* *Corresponding author.*
E-mail addresses: a20082051@163.com (C. Sun), 510015993@qq.com (J. Duan), 1426828248@qq.com (D. Lan), 2273846547@qq.com (Z. Liu), a20082051@163.com (S. Xiu).

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Hertzian contact between the workpiece and the grinding wheel [7,8]. The Hertzian stress is obtained by calculating the grinding force. It is true that the grinding force always varies with the macro time due to the grinding chatter. According to the previous research, the grinding system's parameters can result in different chatter strengths [9,10]. To note that the researches on the grinding chatter are focused on the dynamic characteristics of the grinding system itself. However, the research on the details of workpiece's mechanical properties after grinding is limited. To this end, more and more investigations are mentioned to evaluate the influence of the grinding parameters on the workpiece's hardening layers.

Since the grinding process enabling the surface hardening of the steel parts is described by Brinksmeier and Brockhoff, the heat generated within the contact zone is considered to be a positive factor instead of the negative one before [11]. Nguyen et al. investigated the microstructure transformation process and the mechanical properties of the hardening layers with the FEM (finite element method) and the experiments [2]. Zarudi et al. stated the grinding hardening layers distribution and studied the mechanical and tribological properties according to the grinding hardening experiments [6]. Wang et al. and Liu et al. evaluated the depth of the grinding hardening layers and meanwhile investigated the influence of the grinding parameters on the grinding hardening layers [12,13]. Xiu et al. combined the pre-stress with the grinding hardening to research the transformation mechanism and the residual stress after grinding [14]. The above researches are deep enough on the mechanism of grinding hardening layer formation and most analytic model are based on the temperature of the FEM. Generally, these analytic models are mostly obtained in the static or quasi-static state. However, the actual dynamic transformation is a transient unsteady process, which may lead to inhomogeneity transformed microstructure distribution due to different chatter strengths. Therefore, it is essential to establish a mathematical model to quantify the whole grinding hardening process under different chatter strengths.

To get the better grinding hardening effect, the grinding system's dynamic parameters should not be neglected. Therefore, a new model should be established and is made up of three parts: the dynamic grinding characteristics between the wheel and the workpiece, the FDM for the grinding temperature distribution and the CA method for the transformed microstructure distribution. Meanwhile, the dynamic characteristics are obtained by analyzing the grinding system's chatter strength. The FDM is an efficient method to deal with the transient temperature in multiple situations [15,16]. The CA method is a platform in the analysis of the material transformation by discretizing the calculation domain into cells according to the current physical conditions. Su et al. and Zheng et al. applied the CA method in the hot rolling during the heating process [17,18]. Sherman et al. calculated the steel's martensite content by the CA method during the cooling heat treatments [19]. Although the CA method is widely used in the above material simulations, a new model should be re-established to consider the inhomogeneity of the microstructure distribution due to different chatter strengths and workpiece's spatial depth.

Based on the above, the critical need for obtaining a better hardening layer has become increasingly pronounced. Therefore, a new three-hybrid model is established to consider the effect of in-completed transformation and the difference of the chatter strength. Meanwhile, the dynamic grinding force is deduced on the basis of the single grit's analytic and the numerical solution of the dynamic equations. In order to obtain the depth of the grinding hardening layers under different chatter strengths, the dynamic temperature distribution is calculated according to the FDM. Afterwards, coupled with the dynamic grinding temperature distribution and the dynamic grinding force, the austenite distribution and the martensite distribution under different chatter strengths are obtained respectively. Furthermore, the effect tendency of grinding chatter on the transformed microstructure distribution is validated by the grinding experiments. Consequently, the hybrid model can be applied to study the relationship between the grinding chatter and the ground workpiece's transformed microstructure distribution. Based on the above, the critical need for obtaining the better workpiece's mechanical properties by controlling grinding chatter would be increasing pronounced when the specific demanding requirements (aerospace, automotive, robotic, etc.) are taken into consideration. Moreover, the proposed model is not only believed to be able to considerably promote the realization of the relationship between grinding hardening technology and the grinding chatter, but also provides a new reference for better workpiece's mechanical properties in all the grinding enterprises.

2. Force modeling with grinding process and dynamics

Generally, grinding is characterized by numerous cutting grits with relative large rake angles to efficiently remove materials. The high efficiency results are caused by dynamic grinding force, which is regarded as the input of the dynamic temperature distribution and the material's microstructure transformation. Actually, the dynamic grinding force can be represented as the sum of each grit's grinding force. What is more, the present single grit force model are decomposed as chip formation, ploughing, and rubbing forces according to Malkin's study [20]. Therefore, a single grit model is established firstly based on the above analysis.

2.1. *Single grit's force model*

The single grit's force model is based on the theory and experiment of Shao and Liang's research [21]. The single grit's force is decided by this three components which are the chip formation, the ploughing and the rubbing force respectively. In order to obtain this three components, a geometric model of the single grit is proposed in this paper, whose shape is considered to be conical with a rounded tip and a flat area. When the conical grit is confirmed, the geometric model between the workpiece and the single grit is shown in Fig. 1.

In Fig. 1, the single grit's grinding force of the three components is defined as the chip formation force, the rubbing force and the plowing force respectively, which can be written

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