An alternative grinding wheel regenerative mechanism: distributed grit dullness

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Summary. This work focuses on the dynamics and stability of grinding operations. Surface regeneration, which is a well-known and widely accepted cause of regenerative chatter in machining, affects grinding in a unique way as it can occur not only on the workpiece but on the wheel as well. The vast majority of relevant publications consider only distributed radial wear or physical surface waves around the circumference of the grinding wheel in order to account for surface regeneration on the wheel. This research presents an alternative regenerative mechanism, namely the distributed dullness of the cutting edges captured by the specific energy, which is a fundamental quantity in grinding, similar to the cutting-force coefficient in conventional machining. The new chatter theory, which is validated experimentally, predicts stable grinding conditions with respect to wheel regeneration for a certain set of cutting parameters. This is atypical as far as the relevant literature is concerned, i.e., grinding is reported to be typically unstable with regard to wheel regeneration.

Introduction

Grinding is a widely used machining process with a significant 20-25% share of the manufacturing sector in developed countries [1]. The main difference between grinding and conventional machining lies in their respective cutting tools. While conventional processes (e.g. turning and milling) employ geometrically well-defined machine tools, grinding relies on a geometrically ill-defined wheel for material removal. Owing to its unique cutting tool, grinding has a number of advantages and disadvantages. Abrasive processes are known for producing excellent surface quality and dimensional accuracy, cutting difficult-to-machine materials with relative ease, and achieving high material removal rates. The downside of abrasive machining is excessive tool wear, significant heat generation, and – from a theoretical point of view – the complexity of process modelling and prediction due to the inherent randomness of the wheel geometry. This last disadvantage makes it especially complicated to accurately capture an already intricate phenomenon in grinding, which harmfully affects virtually all machining operations, namely regenerative machine tool vibration or chatter. The consequences of self-excited relative vibration between the workpiece and the cutting tool are serious: inadequate surface finish, inaccurate dimensions, reduced tool life, unpleasant noise, etc. Since machining under unstable conditions is highly unfavourable, chatter is to be avoided for the sake of product quality and manufacturing efficiency.

Literature review

Chatter modelling in conventional machining has been the topic of extensive research since Taylor published his famous work at the beginning of the 20th century, asserting that chatter is the most obscure of all machining problems, and there are probably no rules that can guide the machinist in maximising productivity and avoiding chatter at the same time [2]. Taylor's initial concerns have been allayed in the world of conventional processes by chatter theories that are capable of accurately predicting the onset of unstable vibrations [3,4]. However, grinding has been lagging behind the results of conventional theories, because the inherently random nature of its cutting tool makes regenerative chatter more difficult to model and predict. Nevertheless, grinding chatter has been the subject of active and diligent research since the middle of the 20th century [5,6].

Grinding is often a finishing operation responsible for the final surface quality and dimensional accuracy of the machined part. Therefore, in the case of grinding, unstable relative vibration between the wheel and the workpiece can be especially detrimental, because it can destroy a product on which a number of costly machining operations have already been performed. The uniqueness of grinding lies not only in its cutting tool but also in the fact that surface regeneration can occur not only on the workpiece but on the grinding wheel as well, introducing the possibility that the two phenomena happen simultaneously and influence one another in real time. This idea is often referred to as double regeneration in the literature, and has been meticulously studied ever since wheel-related instability was first measured in practice [7].

Surface regeneration on the grinding wheel has usually been modelled as distributed radial wear or physical surface waves around the circumference of the grinding wheel. While this is a perfectly reasonable approach to considering wheel-related instability, Li and Shin claimed that such a description is incomplete, as distributed radial wear alone cannot account for a number of experimental observations reported in the literature [8]. Therefore, they formulated a new theory based on a regenerative mechanism that combines distributed radial wear with distributed grit dullness (i.e. the distribution of the dullness of the cutting edges around the circumference of the grinding wheel). They characterised grit dullness by the specific energy, which quantifies the amount of grinding energy required to remove a unit volume of workpiece material, or equivalently, the amount of grinding power necessary to sustain a unit material removal rate. That is because a sharper/duller grain corresponds to a lower/higher specific energy, respectively. Therefore, Li and Shin considered not only physical surface waves but also specific energy waves on the grinding wheel.

Nevertheless, the current literature tends to model wheel regeneration as a result of uneven radial wear alone. The present study seeks to overcome this by investigating the approach taken by Li and Shin from an analytical and experimental perspective.

Model

A two-dimensional, single-degree-of-freedom model of single-pass surface grinding has been developed by the authors, where the distributed dullness of the cutting edges is quantified by the variation of the specific energy around the circumference of the wheel. The governing equation of motion of the system is linear in its primary variable, which is the specific energy (u), and contains two time delays – a point delay (T_g) and a distributed delay (τ, between 0 and $\tau_{c,0}$):

$$\ddot{u}(t) + 2\zeta\omega_n\dot{u}(t) + \omega_n^2 u(t) = \ddot{u}(t - T_g) + 2\zeta\omega_n\dot{u}(t - T_g) + \omega_n^2 u(t - T_g) - \frac{\mu_x \delta_0 w C_d v_w^2 \tau_g}{m\tau_{c,0} v_g}\int_0^{\tau_{c,0}} u(t - T_g + \tau_{c,0} - \tau)\, d\tau.$$

The point delay is equal to the rotation period of the grinding wheel, and the upper limit of the distributed delay describes the total time necessary for an individual grit to pass through the grinding zone. It can be seen that T_g is significantly larger than $\tau_{c,0}$ for practical values of the nominal depth of cut (δ_0). The mathematical complexities of the stability analysis introduced by these two time delays are dealt with in the frequency domain. Taking the Laplace transform of the equation of motion, the open-loop transfer function between the nominal depth of cut and the resulting wheel vibration reads

$$T_o(s) = \frac{\mu_x \delta_0 w C_d v_w^2 \tau_g e^{-T_g s}(e^{\tau_{c,0} s} - 1)}{m\tau_{c,0} v_g s(1 - e^{-T_g s})(s^2 + 2\zeta\omega_n s + \omega_n^2)}.$$

Having transformed the two time delays into a number of complex exponentials, it is possible to apply the Nyquist criterion to the open-loop transfer function above, in order to determine the stability properties of the system.

Results

The proposed theory predicts stable machining conditions for a certain, practically feasible set of grinding parameters (see black lines in Fig. 1). This is an unusual yet fascinating result, as grinding is reported to be typically unstable with respect to wheel regeneration in the literature [5,6]. Furthermore, a number of grinding trials have been performed by the authors as well, which present a strong case for the validity of the new model (see coloured circles in Fig. 1). The primary aspects of comparison were stability diagrams and, in the case of instability, chatter frequencies, which indicate a good correspondence between the theoretical predictions and the experimental data.

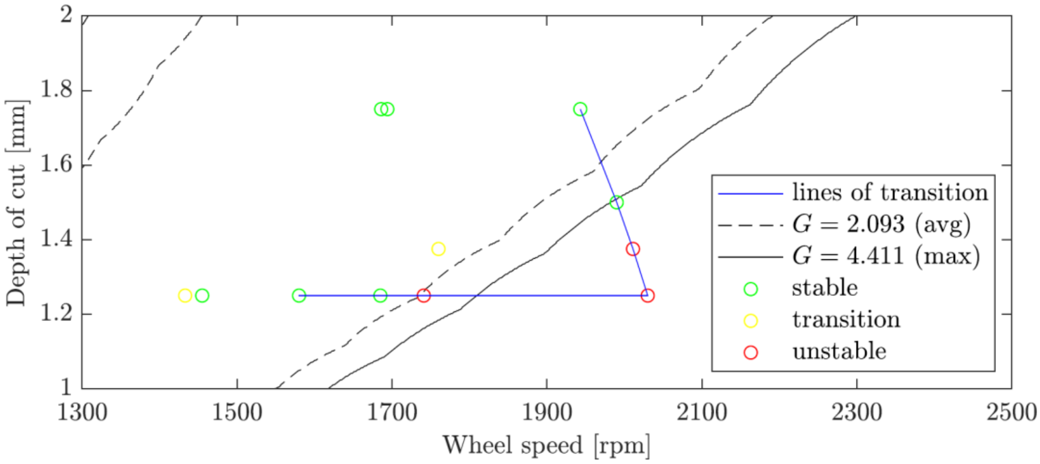

Figure 1: Comparison between theoretical and experimental stability boundaries with a good agreement between the two

Conclusions

The new chatter model proposed in this work is not only reliable in its own right, but also has a much broader area of application, calling for the alternative wheel regenerative mechanism of distributed grit dullness to be included in sophisticated grinding chatter models. Practically speaking, the new theory suggests that previously unknown regions of stability exist and can be utilised in the pursuit of avoiding chatter vibrations in grinding processes, which is the main and most promising outcome of this research.

References

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