A REVIEW OF STABILITY IN TURNING FOR NICKEL BASED SUPERALLOYS

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Abstract

With the wide application of nickel-based superalloys, problems related with the cutting chatter processing have become a serious problem affecting the processing efficiency and the machining accuracy. Therefore, a review study on the influence of cutting parameters on chatter to improve the processing properties of nickel-based superalloys and the surface quality of workpieces by analyzing the machinability of chatter generation is very crucial**.**

In this review research, a research study of chattering stability for high-speed turning of nickel-based super alloy has been studied from the following considerations: Research Background and Significance; Research Methods Compared with Previous Research Studies which includes Research Status and Mechanism of Cutting Chatter, and Control and Prevention Methods for Cutting Chatter which in turn includes Passive Chatter Control, Active Control of Chatter, Online Monitoring Chatter Control, Predictive Chatter Control; Research Status of High-Speed Machining of Nickel-Based Superalloys; and The Major Problems Currently in Existence.

Keywords: Significance of the study; Research Background; Chatter Stability; Turning; Nickel-Based Super Alloy

مستخلص

مع التطبيق الواسع للسبائك الفائقة القائمة على النيكل، أصبحت المشاكل المتعلقة بمعالجة قطع الإصطكاك مشكلة خطيرة تؤثر على كفاءة المعالجة ودقة التصنيع. ولذلك، فإن إجراء دراسة مراجعة حول تأثير متغيرات القطع على الإصطكاك لتحسين خصائص معالجة السبائك الفائقة القائمة على النيكل وجودة سطح قطع العمل أو الشغلات من خلال تحليل قابلية توليد الإصطكاك هو أمر بالغ الأهمية.في هذا البحث الاستعراضي، تم عمل دراسة بحثية عن ثبات أو إستقرار الإصطكاك للخراطة عالية السرعة للسبائك الفائقة القائمة على النيكل من الإعتبارات التالية: خلفية البحث وأهميته؛ طرق البحث مقارنة مع الدراسات البحثية السابقة والتي تتضمن حالة البحث وآلية قطع الإصطكاك ، وطرق التحكم والوقاية لقطع الإصطكاك والتي تتضمن بدورها التحكم السلبي في الإصطكاك ، والتحكم النشط في الإصطكاك ، ومراقبة الإصطكاك عبر الإنترنت المباشر، والتحكم في الإصطكاك التنبؤي ؛ الحالة البحثية للتصنيع عالي السرعة للسبائك الفائقة القائمة على النيكل؛ وأهم المشاكل الموجودة حاليا.

1. Research Background and Significance

The rapid development of science and technology in the twentieth century has led the development of aerospace industry from the initial exploration stage into strategic stage of industries in the today's world. In this field, due to the harshness and complexity of the working environment, the mechanical properties of engineering materials are required to be very high quality [1] – [5]. Nickel-based superalloys are one of these materials which are widely used in many industrial applications due to their good structural, physical, chemical, and mechanical properties. In addition, they have strong work hardening tendency, low-thermal conductivity and severe tool wear under high temperature and corrosion conditions [6] and [7]. Therefore, nickel-based superalloy has become one of the most superiorly used material in this field, especially it is used to process the core components in the aerospace field, such as axles in rocket, aircraft and other spacecraft engines [8] and [9].

However, nickel-based superalloys have special physical properties that make them difficult to prepare for the final uses, but these difficulties of preparing can be handled with special technics. Because the main causes of the poor cutting performance of superalloy is that the cutting force is relatively high and the cutting temperature is extremely high during the processing. In this regard many experts and scholars paid special attention to these issues of how to process the preparation of these materials. This was achieved through high efficiency and precision during the process of cutting. The machining of metals is often accompanied by a violent relative motion between tool and workpiece which is called chatter vibration. Chatter is a wide range of self-excited vibration caused by dynamic cutting forces existing in tool and workpiece systems; also, chatter is considered from the most obscure and delicate of all problems facing the machinist [10]. In the machining process, chatter is a highly unstable and complex mechanical vibration phenomenon generated, which significantly affect the production efficiency as well as reduces machining accuracy, and produces noise. When high-hardness tools such as ceramics and PCBN are used, they are highly brittle and can be easily chipped after being affected by chatter vibration, and as a result the process cannot be completed [11] – [13]. Therefore, analyzing the mechanism of chattering and studying the influence of cutting parameters stability has important practical significance for processing properties of nickel-based superalloys and the surface quality of workpieces [14].

In the recent time, researchers' attention on nickel-based superalloys mainly includes a cutting mechanism, processing performance, tool wearing, and so on. However, there is less attention on the problems of chatter stability that generated during the cutting process, therefore, in this work, we will investigate the chatter stability prediction, and chatter control techniques during the cylindrical turning of nickel-based superalloy GH4169. firstly, the status of the previous search results was summarized. Then the following procedures were carried out: a theoretical analysis for the cutting chatter mechanism and the cutting stability, the vibration mechanics model and a simulation model of turning regenerative vibration which established in some studies. Through the modal hammering and cutting test, the kinetic parameters required for the simulation of the system are obtained, and the limit cut width is predicted. The turning test of the nickel-based superalloy GH4169 is analyzed, the influence of cutting parameters on stability and surface quality of workpiece is obtained. The obtained results provide a reference for improving process efficiency and improving the actual process quality.

2. Research Methods Compared with Previous Research Studies

The difficulties faced in the materials cutting and the wide range of its application has brought the researchers attention to study the influences of the chatter on the efficiency of the materials cutting quality, many experts and scholars across the world have been conducting active researches in this field. However, there are still sub-problems and deficiencies. According to the reviewed and summarization of reported previous research studies in the field and therefore the current research we aimed to provide a comparable study with the previous researches in three aspects: a model of cutting chatter mechanism, chatter control and prevention, and cutting process of nickel base superalloy.

2.1 Research Status and Mechanism of Cutting Chatter

In the cutting process for the machine tool, the cutting vibration is generated by the interaction between the tool and workpiece. That is, which divided into four categories according to vibration characteristics differences: free vibration, self-excited vibration, forced vibration, and random vibration. The self-excited vibration is the strongest, and this vibration refers to the vibration generated by the change of the dynamic force of the cutting system. This leads to the cutting chatter despite the absence of external influences regarding the cutting process.

Research on the problem of cutting chatter can be traced back to the early part of the last century. Taylor E. W. proposed in 1907 that the main cause of chatter is that the generation period of discontinuous chips is the same as the vibration period of a certain part of the machine tool [11]. Although the cause of chatter cannot be simply attributed to this reason, the theory for the studying of cutting chatter has laid a good groundwork. In the past century, according to the physical causes of chatter, cutting chatter has been classified into three main mechanisms: mode coupling effect, friction effect, and regeneration effect. Regeneration effect is considered to be ubiquitous in the machining process, and its theoretical application is the most extensive [15].

The chatter theory based on mode coupling effect was proposed by J. Tlusty in 1981, its mechanism constitutes two actuators of the system that vibrate at two degrees of freedom perpendicular to each other. In this theory, the modal coupling will cause chatter [16]. Gasparetto [17], studied the stability and instability of model trajectories of the tool and obtained the conditions for stable cutting. Kong Fansen [18], and others studied the influence of uncertainties in coupled modes by fuzzy mathematical analysis and obtained distribution law based on the chatter mode coupling effect.

Friction-type chatter, firstly was proposed by R. N. Arnold in 1946 and provided an experimental result in wide range of speed. Thus, with increase of the cutting speed and decrease of the main cutting force in the direction of cutting speed, the negative friction of the main cutting force will decrease the cutting speed and cause self-excited vibration between the tool and the workpiece [19]. Based on that, many scholars have achieved results in the study of friction chatter [20]. Chen Hualing et al. established a model based on the nonlinear theory and determined the equivalent limit stability of the model by using the equivalent linearization method [21]. In addition, the chatter model created by N. Stelter, which simplifies the tool into a cantilever beam simulated the change of cutting force and cutting speed, and the first two models of the system have been introduced to the diffusion and were verified by experiment [22].

Regenerative chatter which is a troublesome problem nowadays for machine operators to obtain high accuracy and acceptable surface finish, was proposed by R. S. Hahn in 1954. One of the reasons for the occurrence of regenerative chatter was the self-excited vibration caused by the phase difference between the previous cutting and the current cutting in one workpiece [23]. Continuous development of in this field was due to the efforts of many scholars such as Tobias, Tlusty, Merrit. In 1958, Tobias [24] studied the regenerative chatter of the drilling process, and mapped the chatter stability lobe diagram. This extended the research method for milling and turning machines, and laid a theoretical foundation for the research in this field. Tlusty [16], proposed the theory of cutting chatter generated by the regeneration effect and pointed out that the cutting width is one of the factors affecting the regenerative chatter. According to the principles of control theory, Merrit [25] introduced the feedback effect model of machining process. In addition to the linear model of regenerative chatter effect, Hanna [26] studied the nonlinear factors of the cutting process and machine tool structure. Tlusty et al. [16] considered that the increase in vibration causes the workpiece to separate from the tool and causes nonlinear factors. Shi Hanmin et al. [27] studied nonlinear systems by using time-delay differential-difference equations. Wu Ya [28] introduced the theory of forced vibration into regenerative chatter and proposed the theory of forced regenerative chatter by the frequency characteristics of vibration.

2.2 Control and Prevention Methods for Cutting Chatter

Based on the in-depth study of cutting chatter mechanism, the effective control, and prevention against the occurrence of cut, the chatter has become an important topic. In recent years, scholars across the world have carried out much research on this topic, which includes the following four aspects:

2.2.1 Passive Chatter Control

In early studies on chatter prediction, it has been observed that machining stability can be enhanced by increasing damping of the whole system. Therefore, passive vibration control techniques generally aim to increase damping [29] and [30]. Several kinds of dampers are used, such as Lanchester dampers [31], impact dampers [32] and [33], tuned mass dampers [34] – [36], or vibration absorbers [37] – [41]. As an example, in reference [37] a passive vibration control system using a dynamic vibration absorber mounted on a cutting tool has been developed to suppress vibrations in turning operations. The dynamic vibration absorber has to satisfy two conditions: 1) the natural frequency of the dynamic vibration absorber should be close to the natural frequency of the tool and 2) the dynamic vibration absorber should have a larger damping ratio than the tool. Whereas in most cases a single damper is used. Yang et al. [36] presents an optimization strategy for multiple tuned mass dampers to maximize the minimum value of the real part of the tooltip frequency response function, which is beneficial for stability, see references [42] and [43]. In [44] and [45], the development of a so-called multi-fingered centrifugal damper, which is inserted inside a hollow tool, is discussed. As a result of centrifugal forces, the flexible fingers press against the inner surface of the hollow tool which constrains the bending of the tool.

Passive dampers are relatively cheap and easy to implement and do not require external energy. More importantly, passive control methods never destabilize the system. However, drawbacks regarding the use of passive damping techniques are the fact that the amount of damping which is practically achievable is rather limited. Furthermore, vibration absorbers needed to be accurate. Consequently, lack robustness with respect to changing machining conditions and some other deficiencies with machine tools lead to less promotion and popularization of the method.

2.2.2 Active Control of Chatter

Chatter mitigation by active controller design is a growing research field. Active control of chatter in machining processes has been proposed in different ways.

Firstly, different control laws are used. Examples are model-based control procedures based on linear quadratic Gaussian (LQG) and/or optimal control [46] – [51], H_∞-norm based control [52] – [54], and μ-synthesis [55] – [58], and non-modal based active damping procedures, see reference [59], based on positive position feedback [60], acceleration feedback [61] and [62], and velocity feedback [63] and [64].

Secondly, several kinds of actuators are applied, such as active vibration absorbers [49], [53], and [65], active magnetic bearings [55], [56], and [66], piezo-electric actuators [48], [60], [67] and [68], Tefenol-D actuators [61], [62], [69] and [70] and electro-rheological fluids [71] – [73]. An extensive overview of the use of active materials in machining processes can be found in the literature of reference [74].

However, compared with the passive chatter control methods, the active control method is more effective. However, the structure of the machine cutting system is relatively complicated. Due to the need to introduce an external device, and the accurate identification of the control signal the difficulty of control increases. In addition, the additional device vibrates before the control signal, this will increase the instability of the system [50], [75], and [76]. Therefore, the application of the active control method has been very scarce.

2.2.3 Active Control of Chatter Online Monitoring Chatter Control

This method refers to the direct measurement and collects vibration signals during the cutting process by using computer technology, sensor technology, and artificial intelligence system. After analyzing the characteristic parameters, the cutting chatter can be controlled early by adjusting cutting parameters online. Variable cutting parameters method can be classified as a semi-active control method, which can suppress the chatter vibration by changing the cutting parameters cutting speed [77], feed rate [78], depth of cut, and the tool angles [79]. Theoretically, the main purpose of the method is to increase the area of the stable cutting area or change its shape by changing the cutting parameters, which can quickly and directly supplement the deficiencies of theoretical analysis. In this regard, a lot of research on the mechanism of chatter and the strategy of changing cutting parameters have been conducted [80]. However, this method has high requirements for the machine feed drive system and the motor servo system, and the versatility of the key equipment is poor, and many related technologies have not been solved. Hence, the promotion of this method has been very limited.

2.2.4 Predictive Chatter Control

This method initially predicts the limit of stability of the system by using the chatter theory and then determines the working state at the stable cutting area of the system by adjusting the cutting parameters. Thus, it achieves the suppression of the chattering effect. This method is different from the variable parameter method, in which the range of the stable cutting is changed by changing the cutting parameters, while in this method it remains unchanged, it only works in the stable area. Since this method only needs to adjust the cutting parameters, it has the widest applicability and reflects the important application value. In this respect, Weck M [81], obtained an adaptive control method for face milling by automatically adjusting and setting the cutting parameters. In another research Sata T. [82], obtained a method for predicting and controlling chatter based on the analysis of the influence of dynamic characteristics on cutting stability, the control strategies of cutting speed, feed rate and tool working angle. Bason [83], established a cutting dynamics model based on three-dimensional cutting force in turning process and carried out experimental verification. The results showed that the chatter of the system was the weakest in the direction of cutting speed. Davies [84], implemented computer simulation, which proved that, the analysis of prediction results of intermittent cutting stability is better than continuous cutting. However, their results lack experimental verification. Fofana et al. [85], found that the wear of the tool occurs at the limit or marginal stability of the turning system, and concluded that the stability decreases as the wear amount increases. Zhao Hongwei [86], used the theoretical formula for calculating the change of spindle speed of the lathe with the limit cutting width of the system of regenerative chatter at a single-degree-of-freedom turning and proposed a method for predicting the limit stability of lathe cutting system. On this basis, Li Jinhua [87], developed a special software package for chatter analysis of turning by using numerical simulation technology, and carried out the simulation analysis with relevant test data, and obtained the influence of spindle speed, direction coefficient, coincidence degree, and cutting stiffness on the ultimate cutting width. Zhang Yong, et al. [88], used MATLAB/Simulink software to simulate the regenerative chatter turning model of two-degree-of-freedom, and analyzed the limit cutting width of the system from the point of view of energy supplement. However, the influence of cutting parameters on the regenerative chatter was not considered comprehensively in the model, and no experimental verification was carried out. Based on the regenerative chatter model, Huang Qiang et al. [7], conducted a variable a depth-cut test on 45 steel and found that the chatter occurred at the natural frequency of the tool and workpiece.

2.3 Research Status of High-Speed Machining of Nickel-Based Superalloys

A nickel-based superalloy is one of the four high-temperature alloys (iron-based, iron-nickel-based, nickel-based, and cobalt-based), it is ranked first among the four superalloys. The GH4169 alloy (American brand Inconel 718) is one of the most widely used nickel-based superalloys [49]. According to the material properties, they are characterized by great cutting force, large deformation, high cutting temperature, serious hardening phenomenon and easy wear of cutting tools, which results in poor processing performance and low machining accuracy. In the thirties of the twentieth century, Salomon [89], proposed the theory of high-speed turning, pointing out that when the cutting speed is increased to a certain extent, the cutting force, and cutting temperature, etc. are decreased. At present experimental research on the cutting performance of nickel-base superalloy and cutting tools is still an area of interest for many researchers.

For nickel-based superalloy cutting tools, it is usually required to have high strength, high hardness, good chemical stability and wear resistance. Common tools are carbide tools, high-speed steel tools, coated tools, ceramic tools and polycrystalline cubic boron nitride tools. Because they have different mechanical properties of materials, and they show different characteristics in processing.

High-speed steel tools were first used to process nickel-based superalloys, and their strength and toughness were good, however they have some disadvantages such as poor workability and low efficiency [90]. Ceramic tools and carbide tools come in the second stage. Ceramic tools are characterized by strong wear resistance, high hardness, good chemical stability, and are not easily bonded at high temperatures. Altin [91] used different types of ceramic tools to carry out cutting experiments on GH4169, pointing out that circular blades can withstand higher cutting speed than square blades in cutting. Kitagawa T. [92], compared the cutting performance of two different tools Al_2O_3-Ti_3C and Si_3N_4 and found that when the cutting speed reached 250 m/min, the cutting performance of the former tool was much better than the latter tool. Generally, In the ceramic tools study, their high fragility restricted their widespread application. Although cemented carbide tools are widely used, they can produce large cutting force and high heat during cutting nickel-base superalloy and are prone to plastic deformation and severe collapse. Deng Jianxin et al. [93] compared the cutting performance, and tool wear of Al_2O_3/TiB_2/SiCW ceramic tools and YG8 cemented carbide tools on nickel-base superalloys, they concluded that there was little difference in the wear resistance of the two tools at low cutting speed; while at the high speeds, the latter was less than the previous one. In an experimental investigation carried out Luca Stetner [94], revealed that, the cemented carbide cutters are suitable for low-speed cutting and found that when the cutting speed exceeds 50 m/min, the wear increased by the sharp increase of temperature. They concluded that the coated tools can relieve the wear of carbide tools. Ducros C. [95], compared between uncoated and coated tools, their results showed that the TiN/AlTiN coatings relieved the wear of tools effectively. Arunachalam et al. [96] compared the cutting performance of PVD and CVD coated tools for cutting nickel-based superalloys, they concluded that the hardness of PVD coated tools was higher than that of CVD coated tools and are more suitable for finishing and semi-finishing. Polycrystalline cubic boron nitride (PCBN) is an advanced ceramic tool material which appeared in the mid-1970s principally for the machining of hardened steels (turning, milling etc.). It can also be employed as an advantage for the finishing turning of some nickel-based alloys. PCBN is the second super-hard tool material, and its crystal structure is similar to diamonds, and it is appropriate for cutting, and its characteristics include, high hardness and abrasive resistance, high heat stability, excellent chemical stability, large coefficient of heat conductivity and low friction coefficient etc., [79].

Over the last 15 years, the range and variety of PCBN products increased dramatically. Significant benefits in terms of tool life and surface roughness have been seen with PCBN inserts in the machining of hardened steels and cast iron [97] – [102]. The key advantage and/or benefit associated with PCBN tooling is the possibility of enhancing productivity by employing higher cutting speeds, i.e., within the range of 300-600 m/min, also has a good physical and chemical stability when cutting temperatures reaches 1500 °C [103]. Even at this temperature, it maintains good mechanical property for a long time. It has considerable plasticity, mechanical fatigue and thermal fatigue resistance and corrosion resistance etc., [104]. Compared with the Turning Nickel-based Superalloy GH4169 Using PCBN Cutting Tool, most research on cutting nickel-base superalloy with PCBN tools are mainly focused on cutting force, tool wear, tool life, and cutting temperature etc. This suggests that there are considerable scope and potential for a wider evaluation of cutting nickel-base superalloy with PCBN tools. RS Pawade, et al. [105], used a PCBN tool to test-cut a nickel-base superalloy GH4169. They found that when the cutting force is $v = 125{\sim}475 m/min$, feed rate $f = 0.05{\sim}0.15 mm/r$, cutting depth $ap = 0.15{\sim}1.0 mm$, the radial force and the feed force were approximately equal, and tangential force was $1/3{\sim}1/2$. Peng Ruitao, et al. [106], proposed a method for active control of cutting force, chip shape and surface quality by using different prestressing conditions through the development of the axial prestressing device. Barry and Tiffe [101] and [107], studied the chips generated during machining and indicated that when the cutting speed increases within a certain range, the chip shape changes to serrated, and the chips become more serrated with the increasing feed rate and cutting depth. Costes et al. [96], studied the wear process of PCBN cutting tools in detail through energy spectrum analysis, they found that the elements of the tool and the workpiece were overlapping with each other, and the tool wear was mainly diffusion and bonding.

In summary, the studies on Nickel-based Superalloy mainly includes cutting mechanism, machining performance, tool wear and other aspects, however the studies on the influences of the chatter on the efficiency of the materials cutting quality and the problems of chatter stability that is generated during the high-speed cutting process are scarce. Therefore, it is very important to analyze the mechanism of chatter, study the influence of cutting parameters on the chatter stability, improve the machining performance and improve the machining quality and surface finish.

2.4 The Major Problems Currently in Existence

Although experts and researchers across the world have achieved satisfactory results in the research of cutting chatter and nickel-based superalloy processing, there still exists the following problems and deficiencies:

(1) At present, the research on cutting nickel-base superalloy mainly focuses on the cutting mechanism, tool wear and surface quality, however there is lack of relevant research experiment on the chattering problem when cutting nickel-base superalloy at high-speed using high-hardness cutting tools such as PCBN tools, and also there are no clear conclusions on the influence of cutting parameters on cutting vibration.

(2) In the current regenerative turning chatter model, most of the researches were based on a single-degree-of-freedom system that only considers the radial feed direction. However, in actual machining, the vibration of the tool system in the axial feed direction will also have a significant effect on the machining quality of the workpiece surface, and there is still a large possibility for the occurrence of cutting chatter. However, the determination of the direction of the main vibration of the cutting tool system has not been thoroughly studied.

(3) In the prediction of the turning chatter stability limit, a fast and effective simulation prediction method has not been established, which would help to obtain the stability characteristics of the cutting system quickly and intuitively according to the cutting parameters, and thus the optimization of the cutting parameters can be realized.

In view of the aforementioned problems, this research focused on the numerical and experimental analysis of evaluation of regenerative chatter stability of high-speed turning of nickel-based superalloy GH4169 using PCBN cutting tool.

3. Conclusions

The term Superalloy was first used shortly after World War II to describe a group of alloys developed for use in turbo-superchargers and aircraft turbine engines that required high performance at elevated temperatures. The range of applications for which superalloys are used has expanded to many other areas and now includes aircraft, gas turbines, rocket engines, chemical, and petroleum plants. They are particularly well suited for these demanding applications because of their ability to retain most of their strength even after long exposure times at temperatures above 650 °C. Their versatility stems from the fact that they combine this high temperature strength with good low-temperature ductility (and/or formability) and excellent surface stability.

The review paper concludes with current challenges in chatter stability of machining which remains to be the main obstacle in increasing the productivity and quality of manufactured parts.

This paper reviews the dynamics of machining and chatter stability research since the first stability laws were introduced by Tlusty and Tobias in the 1950s. The paper aims to introduce the fundamentals of dynamic machining and chatter stability, as well as the state of the art and research challenges, to readers who are new to the area. The strong demand for increasing productivity and workpiece quality in high-speed milling make the machine-tool system has to operate close to the limit of its dynamic stability. This requires that the chatter stability is predicted accurately to determine the optimal milling parameters.

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