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Progress and Challenges Related to Thermal Fatigue Research of Super-hard Cutting Tools

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Abstract. A large number of super-hard tools literature has been studied, most of which aimed at tool wear patterns and mechanisms. Researches on thermal lord affecting tools wear are carried out insufficiently and achievements about thermal cracks initiation, propagation are little reported. As existing of elevated temperature and intense heat during cutting processes, super-hard cutting tools thermal fatigue problems are obliged to be faced and some fundamental and unresolved issues need to be answered.

1. Introduction

As one kind of advanced machining technologies, high-speed cutting using super-hard cutting tools (including natural diamond tools, polycrystalline diamond tools (PCD), monolithic polycrystalline cubic boron nitride tools (PCBN), cubic boron nitride (CBN) composite tools) content themselves with high-speed, high-efficiency, low cost and environment friendly machining.

But their working conditions are very hostile, like undergoing loop-impacting loads and elevated temperatures, which would give rise to fluctuating stresses and strains and could eventually result in emergence of tools' thermal fatigue and fracture.

2. Researches Review

2.1. Researches on Tools Wear Patterns and Mechanisms

Researches on super-hard tools' wear patterns and mechanisms have been carried out widely both at home and aboard.

Fatih conducted a research to address wear performance of the CBN and TiN based coated CBN inserts when face milling tool steel. Results showed that macro chipping governing mechanism was responsible for tool wear under all cutting conditions [1].

Zhong investigated micro cutting of pure tungsten with PCD micro slotting tools experimentally. Compared with the flank face, the wear degree of the rake face was more severe. Furthermore, on the rake face micro chipping and flaking emerged, which made up the main wear patterns [2].

With self-developed PCD micro end mills, Bian investigated the tool behaviour in ductile milling of ceramic. During the machining process, diamond particles kept peeling off periodically, which formed the main tool wear pattern [3].

Professor Bai conducted many experiments on 2A12 micro-part with PCD tools. Results showed the predominant features in the damage region of PCD tools were still abrasive, adhesive, and oxidative wear [4].

Priarone compared CBN and PCD tools to carbide tools, indicating that the tool life of the former two kind of tools was clearly longer than that of carbide ones. Because of tool wear, machined surface quality dropped and micro-cracks appeared [5].

Only wear patterns and wear mechanisms, and cutting parameters, mechanical shock and tool material composition effects on tool wear are involved in above researches, little are touched upon influences of cutting temperature and amount of heat on tool wear.

2.2. Studies about Influences of Heat and Thermal Lord

Professor Liew studied the wear features of PCBN tools during machining STAVAX with and without coolant. Results showed that both the tool edge and the rake face were apt to broken. The fracture on the rake face would be resulted from high thermal stresses [6].

Huang investigated lots of CBN tool wear studies and then came to conclusion that abrasion, adhesion, and diffusion would still dominate the CBN tool wear, with each functioning differently, depending on mechanical and thermal load, CBN amount, binder type and quality, chemical stability and parts material, etc. [7].

Professor Ghan did experiments to study CBN tools in hard turning of hardened tool steel. The tool wear, however, under both cutting speeds (υ_c=144.26m/min, and 288.52m/min), was dominated by chipping, which would be alleviated greatly through limiting the heat flow into the tool [8].

With parts possessing both successive and intermittent surfaces, Manu Dogra used CBN and coated carbide tools to finish turning them. Because of high temperature on the tool edge at high cutting speed (190m/min) during turning of continuous surface, the CBN tools tore out quickly, where thermally activated wear was dominant [9].

Doctor Li carried out high-speed milling tests on Ti-6Al-4V with PCD tools, finding that the PCD tool possessed kinds of serious chipping and spalling when υ_c was greater than 375m/min. If υ_c was increased still higher, thermal–mechanical impacts would be intensified and the flank wear and breakage became even terrible [10].

With the CBN tool in continuous cutting operations on material Inconel 718, Tatsuya Sugihara did orthogonal machining experiments (υ_c =20~300 m/min) to analyse the tool wear mechanisms. It considered that the trouble lied in the thermal wear originated from the elevated temperature rather than the mechanical wear [11].

Professor Grzesik intended to analyse the changing progress of tool wear using chamfered CBN cutting tools. Results showed that mechanical wear played an important role when υ_c was low, whereas thermal wear when υ_c was high [12].

As far as stresses and temperature were concerned, Li developed and validated evaluation models of PCD tools. What controlled the wear process were still adhesion, abrasion and diffusion, with each wear mechanism functioning at different tribological region [13].

Temperature, Heat quantity, thermal impact and thermal-mechanical coupling are discussed in above documents, but few on initiation, effects and development rules of thermal cracks of super-hard tools.

2.3. Literatures on Thermal Cracks

When milling GG-25 with CBN tools, König discovered continuously enlarged groove wear and thermal cracks at the CBN tool flank face, and there were still chipping and fine grooves distributed on the CBN rake and crater wear faces while cutting Cf53 steel. The latter defect would originated from thermal cracks emerged at the cutting region [14].

Davies discovered that a fine scale attrition governing the wear progress with the low CBN tools. If both CBN and work carbide particle sizes decreased, tool wear rate would be reduced, indicating that the proceeding of micro-fractures was the governing mechanism contained in this kind of tool wear action [15].

Chou investigated microstructure of low CBN content tools in finish hard turning, demonstrating that the key wear reason was fine scale attrition caused by micro-fracture and fatigue [16].

Nabhani employed CBN and PCBN tools to cut titanium alloy and setup a temperature equation, above which the signed adhesion and welding occurred in the contacting surface of tool-part. The

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failure appeared in the main part of the tool material in all cases, and its pattern was discussed to build the crack propagation route. [17].

In a PCD cutting experiments with laminated flooring with Al_2O_3 overlay, it was found that inter-granular wear and partial cleavage fracture were tool wear mechanisms, among which the micro-cracks played an important role [18].

Professor Cui carried out face milling experiments of AISI H13 steel with CBN tools with high υ_c values. It was found that defects resulted from mechanical load changed reversely with υ_c , while those of adhesion, oxidation, and thermal cracks boosted by elevated temperature transformed identically [19].

Bushlya presented studies of super-alloy machinability with PCBN tools, on which the crack length was remarkable and stretched beyond the wear region. Experiments told that cracks were not on the surface but extended deep into the tool bulk [20].

From the above papers it is known that the emergence of thermal cracks is one of dominant tool wear mechanisms, but what about cracks initiation characteristics, influence factors and evolution patterns also remain unclear.

3. Challenge

Many researches about super-hard tools mainly concern cutting force, temperature, and tool wear patterns and mechanisms; few are about thermal lord on their wear rules. Literature related to thermal cracks initiation, propagation and evaluation criteria are limited. Many questions remain open

3.1. Cracks Initiation Conditions being not Ascertained

Ding studied the wear behaviour of CBN tools with different grain sizes and various CBN/TiN ratios in ultra-precision cutting of STAVAX. In the machining process, fine-scale cavities appeared on the rake face resulting in cracks formation [21].

Milling of AISI H13 hardened steel with high υ_c values, Professor Cui studied the influences of cutting parameters on tool life and wear. Under conditions of elevated temperature and hostile thermal impact, thermal cracks were easily initiated. When υ_c=400 m/min, with the following parameter combinations, a_e=15mm, f_z=0.24m/z or a_e=75mm, f_z=0.048m/z, thermal cracks would be found on the rake face with the propagation direction vertical to the cutting edge [22].

Pan studied tool life, tool wear, and causes led to tool failure when end milling of Ti6Al4Vwith PCD tools, indicating that brittle chipping and fatigue were the two controlling failure patterns. One of the possible reasons would be stress concentration [23].

Guangxian Li investigated PCD tools manufactured by electrical discharge grinding (EDG) and common grinding in turning titanium alloy. The initial fragmentation at the cutting stage indicated that interior cracks appeared, which expedited flank wear and tool nose wear and intensified tools fracture [24].

The above researches all attributed tools thermal cracks to stress, temperature, thermal impact and materials hardness, but the individual effect of each factors and their inter-relationships are unknown.

3.2. Thermal Cracks Initiation and Propagation Rules Being Little Stated, Nothing about Thermal Fatigue Evaluation Criteria

Pan established a Finite Element Model to simulate cracks initiation under various loading cycles. Results showed that cracks propagation path was perpendicular to the cutting plane. But whether there existed initiation law, what affected their quantity and growing, how many propagation related factors were there, all related questions waited to be answered [23].

A tool life equation was established by Poulachon when machining hardened steel with CBN tools, which showed that the tool life laid dependence on tool material hardness, cutting parameters (υ_c, f, $a_{p)}$, among which υ_c was of the most importance [25].

The above functions are only related to tool life, tool flank and rake wear rates, nothing about thermal fatigue evaluation criteria. If there existed thermal cracks initiation or growth results, they were almost all concerned about metals other than super-hard cutting tool materials.

4. Conclusion
Super-hard cutting tools own a number of benefits over traditional ones. Therefore, they are of great importance to both business and scientific personnel. Towards better understanding and application of super-hard tools, many works need to be done, like thermal cracks initiation, propagation and governing laws, thermal fatigue evaluation criteria, etc.

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