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Material loading in inverse surface integrity problem solution of cemented carbide component manufacturing by surface modification

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Abstract

The inverse surface integrity problem could be effectively solved if the generation of a desired surface integrity be quantitatively correlated to process parameters or process loads. Possibility of establishing such a correlation is studied by employing a surface modification technique of high-intensity pulsed ion beam with well controlled thermo-mechanical load to manufacture WC-Ni cemented carbide component with enhanced wear resistance. The multiple surface integrity parameters including phase, microstructure and composition in addition to surface microhardness should be taken into account for establishing the correlation between process loads and surface integrity, since the interactions between the surface integrity parameters determine the wear performance of surface modified cemented carbides. The different process parameters can be quantitatively distinguished by material loading, i.e. the temperature and/or stress field evolution in the surface layer of cemented carbide under the different thermo-mechanical loads, while the material loading can be further correlated to the resultant changes in surface integrity. In this way, identification of material loading enables establishing a process-independent correlation between process loads and surface integrity for solving the inverse surface integrity problem.

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Keywords: Surface integrity; Surface modification; High-intensity pulsed ion beam; Material loading; High performance manufacturing

1. Introduction

Surface integrity of a component are being widely recognized and concerned as a principal factor determining the functional performance of components [1-3]. However, the desired surface integrity of high performance components is still generated by an iterative process during practice in industry. The required process parameters cannot be deduced from a given desired surface integrity merely based on the iterative way by trial and error. Therefore, the inverse problem may be solved if a correlation between process parameters and surface integrity could be established. In order to solve the inverse surface integrity problem in machining processes, Brinksmeier et al. [4,5] proposed a new concept, process signature, with emphasis on establishing a process-independent correlation between process loads within the component material and resultant materials modification. It is implied that, systematic investigations are still necessary to verify the feasibility to establish a process-independent correlation linking process parameters to surface integrity. It is revealed in our recent study that, the various parameters of surface integrity such as surface morphology, chemical composition, roughness, phase structure, residual stress, microhardness etc. should have a combined effect on the final component performance [6,7]. Consequently, the interactions between the multiple surface integrity parameters should be taken into account for the correlation to be established between process loads and surface integrity.

Generation of a surface integrity with controllable multiple surface integrity parameters is indispensable for achieving a desired high performance of components, which also facilitates the investigation to establish a process-independent correlation between the process loads and the surface integrity thus generated. It is demonstrated that surface modification techniques can be considered as an effective manufacturing approach by which the controlled multiple surface integrity parameters with active interactions are achievable according to desired high performance, from well-defined external

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process loads of thermal, mechanical, chemical or a combination of them in the surface layer of manufactured component, as reducing the geometrical, physical and chemical constraints from base material [7,8].

In this work, the surface modification technique based on high-intensity pulsed ion beam (HIPIB) is employed with controlled external process load of thermo-mechanical nature, termed ion beam shock processing (IBSP), for manufacturing cemented carbide components with improved wear performance. A particular case study is presented for surface integrity parameter change with an identical enhancement in surface microhardness of the cemented carbides, achieved by controlling different process parameters. Under the controllably different process parameters, the material loading and its variation in the components can be readily confirmed and compared. The material loading, i.e. the temperature and/or stress field evolution in the surface layer of cemented carbide under the thermo-mechanical load, thus can be explored to interpret multiple surface integrity parameters generation, leading to different wear performance. Identifying of material loading is discussed and considered as an effective way to correlate the surface integrity change of not only hardness alternations but also phase transformation, composition and microstructure variations etc., to the process parameters, for high performance manufacturing toward desired surface integrity.

2. Experimental

The IBSP surface modification of WC-Ni cemented carbide with bulk composition of 87 wt.% WC and 13 wt.% Ni and average WC grain size of 2 μm was carried out in TEMP-6 HIPIB equipment. The detailed description of this equipment and controlling of ion beam parameters have been reported previously [9,10]. The IBSP process parameters in this study are as follows: ion beam composition of 30% C ions and 70% proton, ion accelerating voltage of 300 kV, ion current density of 50-300 A/cm^2 with 70 ns pulse width (FWHM), irradiation of 1-10 shots. Due to the short pulse duration in the tens nanoseconds range, an energy density of 1-6 J/cm^2 per shot can be delivered adiabatically into the surface layer of a few micrometers in depth. The thin surface layer of material is thus rapidly heated, remelted and/or ablated followed by a rapid cooling due to thermal conduction into substrate, with ultra-fast heating and cooling rates typical of 10^8-10^{11} K/s. The recoil impulse due to ablation of a thin top layer typically of hundreds nm depth and generation of thermal shock in the heat affected zone can lead to strong compressive stress that may further develop to a shock wave propagating inwards. The coupled thermal-mechanical load from the IBSP result in a shock hardening layer in depth typically of several hundreds micrometers for metallic materials along with amorphous and/or nanostructure, submicron nonequilibrium microstructures in the heat affected top layer of a few micrometers. During the process, the thermo-mechanical load is well controlled by the energy input practically by adjusting the ion current density while fixing the other parameters [11,12].

For wear performance evaluation, a series of block samples were prepared by electrical wire machining, followed by ground using diamond abrasive powders and SiC abrasive paper. The polished surfaces were then treated by IBSP. The wear tests were carried out on a MM200 block-on-ring tribometer under dry sliding condition. The block WC-Ni samples were fixed and pressed under normal load of 98 N contacting with a rotating GCr15 bearing steel ring with 45 mm outer diameter and 10 mm in width at a constant sliding speed of 0.47 m/s up to 2100 s. The wear performance of WC-Ni cemented carbides was evaluated by specific wear rate, i.e., the wear volume loss of the cemented carbide block with respect to the normal load and the sliding distance. The changes in surface integrity parameters including phase transformation, chemical composition, and metallographic microstructure variations in addition to microhardness change after IBSP surface modification, was comprehensively examined concerning the material loading caused by the thermo-mechanical load.

3. Wear performance

The surface hardness, coefficient of friction and specific wear rate of cemented carbide components by the selected IBSP parameters are listed in Table 1. It is shown that, identical surface hardness of the IBSP processed WC-Ni cemented carbides can be obtained by controlling the process parameters of energy density per shot and shot number, i.e. 1 J/cm^2 and 4 J/cm^2 with 10 shots, and 6 J/cm^2 with 1 shot, respectively.

Table 1 Surface hardness, coefficient of friction (COF) and specific wear rate (SWR) of cemented carbide components by ion beam shock processing with the selected parameters by which identical surface microhardness is obtained.

Energy density (J/cm^2)	*N* Shot number	$HV_{0.2}$ (GPa)	COF	SWR $\times10^{-7}$ mm^3/N m
0	0	11.80	0.54-0.78	11.71
1	10	14.72	0.50-0.69	8.55
4	10	14.87	0.50-0.66	4.95
6	1	14.92	0.56-0.71	8.78

It is shown that, the microhardness value of top surface increased notably from the original 11.80 GPa of base material to 14.72-14.92 GPa by the IBSP surface modification. Although the effect of surface hardening is the same, the coefficients of friction and specific wear rates differed greatly and then the optimized parameters can be selected as 4 J/cm^2 with 10 shots for processing cemented carbide mechanical seal rings to achieve a better tribological and wear performance in pump applications. A typical mechanical seal ring is presented in Fig. 1 where the outer diameter of ring is 150 mm.

Fig. 1. Photo of IBSP processed WC-Ni cemented carbide mechanical seal where the outer diameter is 150 mm.

4. Multiple surface integrity parameters assessment

To explore the effect of material loading on the surface integrity determining the wear performance, the surface integrity change of IBSP processed WC-Ni cemented carbides was examined including phase transformation, chemical composition, metallographic microstructure variations in addition to the microhardness change, corresponding to the resultant multiple surface integrity parameters.

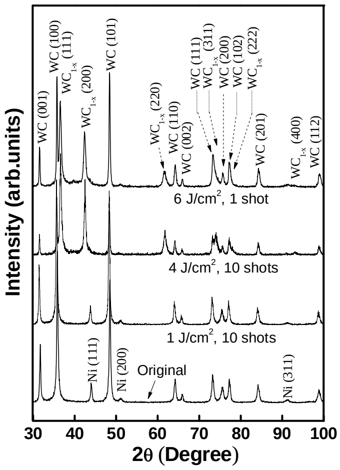

Fig. 2. X-ray diffraction patterns of original and IBSP processed WC-Ni cemented carbides with the selected process parameters at energy density per shot of 1-6 J/cm2, respectively.

Fig. 2 shows XRD patterns of original and IBSP processed WC-Ni cemented carbides with the selected three combinations of parameters leading to identical surface mirohardness. In addition to the hexagonal α-WC and cubic Ni phases for the original WC-Ni cemented carbides, the phase transformation to β-WC_{1-x} is confirmed in the both cases of 4 and 6 J/cm^2 while no noticeable phase change could be detected for 1 J/cm^2. Moreover, the relative intensity of β-WC_{1-x} diffraction peaks at 4 J/cm^2 with 10 shots is higher that of 6 J/cm^2 with only 1 shot.

Based on a quantitative method, the relative volume ratio between β-WC_{1-x} and α-WC can be estimated from the XRD results [13] and the content of Ni binder phase and carbide phase is summarized in Fig. 3 for all the samples. It is clearly revealed that, reduction in Ni binder content is in accordance with increase in β-WC_{1-x} phase transformation under the IBSP thermo-mechanical load, contributing to generation of the identical surface hardness.

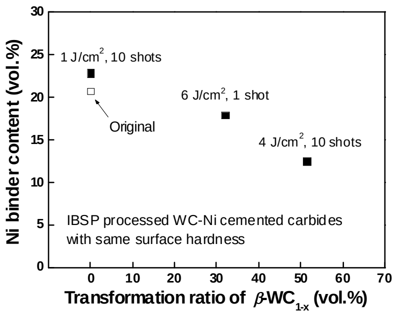

Fig. 3. Phase and chemical composition of IBSP processed WC-Ni cemented carbides with respect to the β-WC_{1-x}/α-WC ratio and the Ni binder content.

Moreover, the microhardness profiles along the depth in the surface layer of IBSP processed WC-Ni cemented carbides are also measured as shown in Fig. 4. The profiles in the top surface layer within 20 μm are similar except that the higher energy density and the larger shot number can result in a deeper and higher level of hardness profiles.

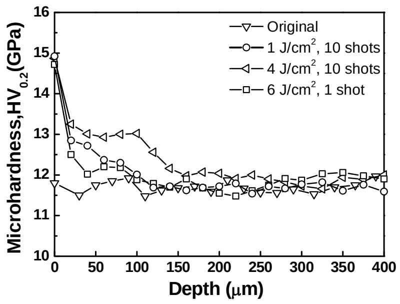

Fig. 4. Microhardness profiles of IBSP processed WC-Ni cemented carbides with the selected process parameters of 1-6 J/cm^2, respectively.

5. Material loading identification

Surface integrity of identical surface hardness profiles within a limited surface layer of 10-20 μm on cemented carbide components can be generated by IBSP surface modification as varying the process parameters with a combination of energy density and shot number. However, wear performance of samples varied significantly with identical surface hardness and one from three combinations of parameters can be selected with the best wear performance of lowest coefficient of friction and specific wear rate. Therefore, the present experimental result confirms that, on one hand, the surface modification is capable of controlling process loads in a wide range independent of base material, i.e. external thermo-mechanical load by IBSP in this case, to cause a material loading in the component; on the other hand, identifying the material loading to interpret the generated surface integrity is critical to solution of inverse surface integrity problem since the strong interactions between the surface integrity parameters determine the final performance.

The material loading of IBSP process is temperature field and stress field evolution in the surface layer of processed components, and note that, the stress field is intrinsically associated with the temperature field since the heat source due to ion energy deposition is origin of the compressive stress wave under the thermal shock by rapid heating and cooling as well as the recoil impulse by surface ablation. Typical temporal temperature evolutions of IBSP processed flat component surface are compared for different energy density 1-6 J/cm^2, demonstrated in Fig. 5, obtained by heat transfer and dissipation modeling with heat source of ion energy deposition in the surface layer and thermophysical properties of component material [13,14]. With identifying the material loading, the thermo-mechanical process load can be thus correlated to the resultant multiple surface integrity parameters. Under 1 J/cm^2, both WC phase and Ni binder phase could not be melted if the surface is ideally flat. As a matter of fact, the processed surface is preferably remelted by selective melting of high points dependent on the surface morphology before IBSP treatment, as previously observed in metallic materials as well as ceramic materials [14,15]. With increasing the energy density per shot, the maximal value of surface temperature is increased and simultaneously the duration of high temperature state is prolonged in the surface layer. Therefore, under the higher energy densities of 4-6 J/cm^2, surface temperature readily reaches the melting and boiling points of Ni phase, and the melting points of WC phase. Considering the surface morphology of treated surfaces, the notable ablation is expected during the IBSP at the higher energy density, which leads to strong compressive stress propagation inwards [11,12].

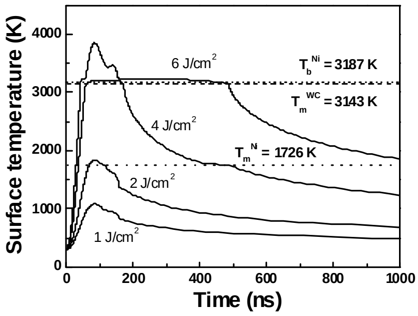

Fig. 5. Calculated surface temperature evolution on the IBSP processed WC-Ni cemented carbides with selected process parameters at energy density per shot of 1-6 J/cm^2, respectively.

The changes in multiple surface parameters can be thus interpreted by the material loading that, the identical surface hardness is resulted virtually from superimposition of the other surface integrity parameter alternations including phase, microstructure (densification due to surface remelting) and composition (selective ablation of Ni phase). The β-WC_{1-x} formation may reduce the hardness, while the densification and the selective ablation of Ni phase could enhance the hardness. Therefore, the material loading identification is unique for establishing process-independent correlation between process parameters and surface integrity change on which the desired multiple surface integrity parameters are thus possibly created by exclusively pre-selecting a process with process loads corresponding to the material loading.

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