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Effect of TiC whisker addition on properties of YG10F alloy

LU De-ping(陆德平), LIU Ke-ming(刘克明), LU Lei(陆 磊),
CHEN Zhi-bao(陈志宝), ZENG Wei-jun(曾卫军)

Institute of Applied Physics, Jiangxi Academy of Sciences, Nanchang 330029, China

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Abstract: The cemented carbide material (YG10F) with different additions of TiC whisker (0%, 0.3%, 0.6%, mass fraction) was prepared by different techniques. The effect of TiC whisker addition on the density, microhardness and toughness of the experimental material was investigated. The results indicate that after the wet-milling for 8 h and sintering in vacuum at 1 440 ℃, the toughness of YG10F is remarkably improved and meanwhile higher microhardness is obtained by 0.3% TiC whisker addition. Preliminary analysis suggests that the main toughening mechanism of TiC whisker in YG10F is whisker pull-out and bridging phenomena.

Key words: TiC whisker; cemented carbide; toughness

1 Introduction

The cemented carbide is widely used as tool and die material for its excellent hardness and good resistance to wear. However, the fracture toughness of cemented carbide tool is usually deficient, which makes it difficult to meet the requirement of complicated and severe load. In order to improve the combination property of cemented carbide material, scientists have done massive research by means of thinning grain, coating, surface nitriding and boriding, adding rare metal and rare-earth, and so on[1−4], but the results are still not very satisfactory. So far, the research of whisker-reinforced material has mainly concentrated on SiC whisker-reinforced ceramic material and SiC whisker-reinforced Al-matrix composites, etc, while there are few reports about TiC whisker-reinforced cemented carbide [5−7].

In this work, a novel TiC/YG10F composite with good toughness was developed, and the effect of different TiC whisker contents and preparing techniques on the density, microhardness and toughness of YG10F material was investigated. The expectation is to improve the toughness and extend the application of whisker-reinforced cemented carbide.

2 Experimental

Submicron close grain YG10F (WC90%-Co10%) was used as the matrix. The diameters of the TiC whiskers were between 0.5 and 2.5 μm, and the mean diameter was about 1.0 μm. The lengths of the TiC whiskers ranged from 5 to 70 μm and most of them were between 20 and 30 μm.

TiC whiskers with big slenderness ratio are easy to aggregate, therefore pre-dispersion must be conducted before mixing. The method was to add a proper quantity of dispersant agent (alcohol) into the whiskers, and then disperse and stir them by an ultrasonic cleaning machine. The addition of TiC whisker was 0%, 0.3% and 0.6%, respectively. The mixed powders were dry-milled for 2 h or wet-milled for 8 h, and then extruded into massive samples by unidirectional die press. The massive samples were sintered at 1 420 ℃ in hydrogen atmosphere, 1 420 ℃ and 1 440 ℃ in vacuum atmosphere, respectively.

Porosity was tested with a metallomicroscope (OLYMPUS−BX51/BX51M). Density was measured using a gravimetry instrument (METTLERTOLEDO AB−104N). Microhardness was measured by a numeral

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Corresponding author: LU De-ping; Tel: +86-791-8176237; E-mail: ludeping61@163.com

micro Vickers hardness tester (HXD−1000). Impact toughness was carried out by an impact machine (JB30A). Microstructures and fracture surfaces were observed using the Quanta 200 environmental scanning electron microscope. Micro-area chemical analysis was conducted using an energy spectrometer (OX-FORD EDXS). All samples for performance testing and constituent analyzing were cut from the massive samples with a linear cutting machine.

3 Results and analysis

3.1 Density

The effect of TiC whisker addition on the density of YG10F dry-milled for 2 h and wet-milled 8 h respectively, and sintered in vacuum at 1 420 ℃ is shown in Fig.1. The density of YG10F drops with the increase of the content of whiskers, especially for dry-milled 2 h. The explanation is that mixing equiaxial WC and Co particles and rod-like TiC whisker lead to the increase of the porosity. In addition, the low density of TiC whisker is also one of the reasons for the density drop. The density of the experimental material wet-milled for 8 h is larger than that of the experimental material dry-milled for 2 h (Fig.l), which indicates that more uniform distribution of whiskers and compact material could be obtained by the condition of wet-milling for 8 h.

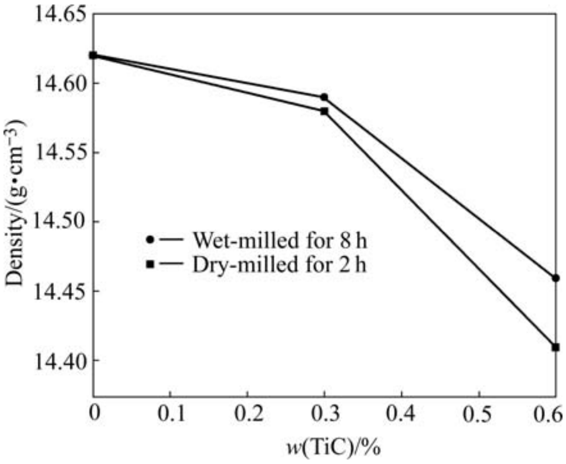

Fig.1 Effect of TiC whisker content on density of YG10F sintered in vacuum at 1 420 ℃

3.2 Microstructure

Fig.2 shows the SEM micrograph and EDS of TiC (0.3%)/YG10F composite wet-milled for 8 h and sintered in vacuum at 1 420 ℃. There is a rod-like phase in the YG10F matrix(Fig.2(a)). The EDS analysis of the rod-like phase reveals that this phase is TiC whisker. There is no conglobation and aggregation phenomenon of TiC whiskers, and the slenderness ratio of the whiskers does not change obviously after milling and

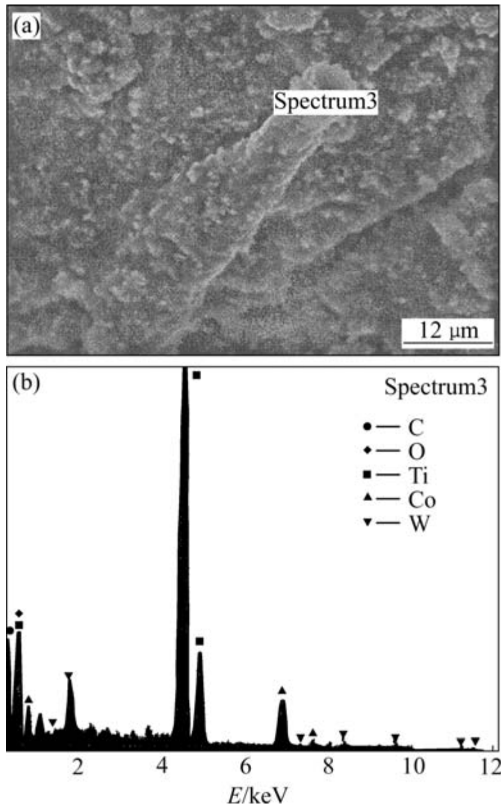

Fig.2 SEM image (a) and EDS (b) of TiC(0.3%)/YG10F wet-milled for 8h and sintered in vacuum at 1 420 ℃

sintering, which is advantageous to the toughening of the composite.

3.3 Microhardness

The effect of TiC whiskers on the microhardness of YG10F sintered in vacuum at 1 420 ℃ and 1 440 ℃ is shown in Fig.3. Fig.3 indicates that the microhardness of the YG10F rises gradually with the increase of TiC whisker content, which is attributed to that the microhardness of TiC whiskers is higher than that of YG10F matrix. Meanwhile, the microhardness increases slightly with sintering temperature. The explanation is that to rise the sintering temperature will increase the density of the experimental material, which results in the increase of microhardness. Nonetheless, the excessive sintering temperature will cause the crystal grains of matrix to grow up unusually.

The effect of TiC whiskers on the microhardness of YG10F dry-milled for 2 h and wet-milled for 8 h is shown in Fig.4. Fig.4 indicates that the microhardness of the experimental material prepared by wet-milled for 8 h is higher than that dry-milling for 2 h. The reason is that the better dispersion of TiC whiskers is obtained by wet-milling for 8 h, which results in the higher density and microhardness. Meanwhile, Fig.4 shows that there is

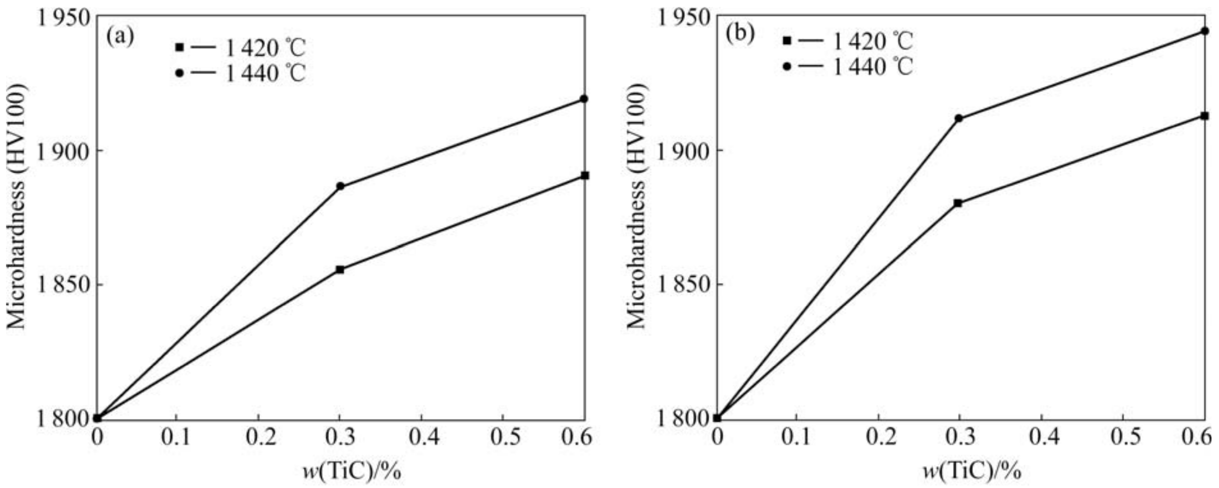

Fig.3 Effects of TiC whisker content on microhardness of YG10F sintered at different temperatures: (a) Dry-milled for 2 h; (b) Wet-milled for 8 h

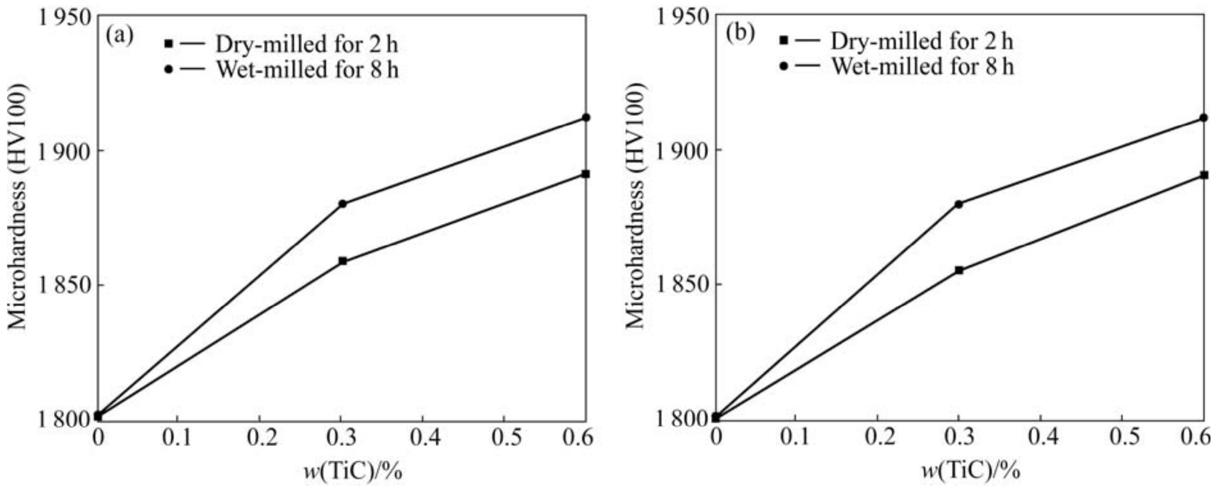

Fig.4 Effects of TiC whisker content on microhardness of YG10F sintered in different atmospheres: (a) Vacuum; (b) Hydrogen

little microhardness difference between the experimental materials sintered in hydrogen and in vacuum.

3.4 Toughness and toughening mechanism

The impact toughness data of experimental material with different TiC whisker additions (0%, 0.3% and 0.6%) are listed in Table1. The experimental material was wet-milled for 8 h and sintered in vacuum at 1 440 ℃. The impact toughness of TiC(0.3%)/YG10F composite increases by approximately 4 times than that of the YG10F matrix, while the impact toughness of TiC(0.6%)/YG10F composite is lower than that of the YG10F matrix.

Fig.5 shows the SEM micrograph of the fractural surface of impact toughness specimen of TiC(0.3%)/ YG10F composite wet-milled for 8 h and sintered in vacuum at 1 440 ℃. It can be seen from Fig.5 that the fracture surface of the specimen is uneven, and there is no such big and smooth cleavage plane as brittleness

Table 1 Impact toughness data of experimental material wet-milled for 8 h and sintered in vacuum at 1 440 ℃

w(TiC)%	Fracture dimension/mm^2	Impact energy/J	α_k/(J·cm^{-2})
0	6.96×7.89	1.5	2.70
0.3	6.90×8.20	8.1	14.32
0.6	6.96×8.04	0.9	1.60

cleavage fracture. Moreover, bassets of whiskers and holes remained by the whiskers that had been pulled out were observed, which indicates that there is the pull out phenomenon of TiC whiskers during the fracture of experimental material. Different diameters and depths of the holes suggest that TiC whiskers are uniformly distributed in the YG10F matrix. The whisker pull out phenomenon will increase the energy of crack spreading and material fracture, so preliminary analysis suggests that the main toughening mechanism of TiC whisker in YG10F is whisker pull out phenomena. The whisker pull out phenomenon often occurs with the whisker bridging phenomenon. When crack is narrow and short, the whisker bridging phenomena will play an important role. While with the crack enlarging, the whisker at the tip of crack will be damaged, and then the whisker pull-out phenomena will become the main toughening mechanism.

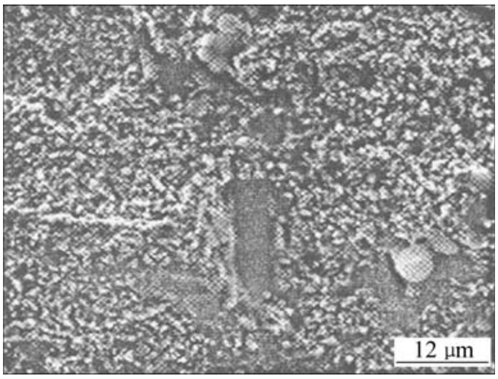

Fig.5 SEM micrograph of fracture surface of impact toughness specimen of TiC(0.3%)/YG10F wet-milled for 8 h and sintered in vacuum at 1 440 ℃

Theoretical analysis suggests that in order to achieve better toughening effect of whisker pull-out, the coefficient of thermal expansion of whisker α_w should be slightly larger than that of the matrix α_m. Otherwise, whiskers will suffer large radial compression stress provided by the matrix, and the shearing strength and the friction force between whisker and matrix will increase, which increases the resistance to the whisker pull out. In addition, if the tensile stress withstood by the matrix surpasses the matrix's ultimate strength, meshy crack will generate in the matrix plane vertical to the axes of whiskers, which decreases the relative strength of the matix, so as to weaken whisker pull-out effect[8]. The residual stress in the matrix can be expressed as[9]

$$\sigma_o = \frac{(\alpha_m - \alpha_w) E_w \varphi_w \Delta T_g}{1 + \varphi_w (E_w / E_m - 1)} \tag{1}$$

where σ_o is the residual stress; E_m and E_w represent the elastic modulus of the matrix and the whisker, respectively; φ_w is the volume fractions of the whisker; ΔT_g represents the temperature difference that causes thermal stress. The residual stress can be calculated approximately by Eqn.(1). When the coefficient of thermal expansion of whisker α_w is slightly larger than that of the matrix α_m, the matrix will suffer compression stress and the whisker will suffer tensile stress, which causes the energy consumption in the process of whiskers pull-out due to the friction of the interface of whisker and matrix. The energy consumption is advantageous to the improvement of the toughness of experimental material.

According to the compound law, the coefficient of thermal expansion of YG10F α_m can be expressed simply as

$$\alpha_m = w_{WC}\alpha_{WC} + w_{Co}\alpha_{Co} \tag{2}$$

where w_{WC} and w_{Co} are the mass fraction of WC and Co in YG10F respectively, α_{WC} and α_{Co} are the coefficients of thermal expansion of WC and Co respectively. In YG10F, w_{WC}=90%, w_{Co}=10%, α_{WC}= 6.2×10^{-6}/K, α_{Co}=12.5×10^{-6}/K, so the coefficient of thermal expansion of matrix can be worked out by Eqn.(2), that is α_m=6.8×10^{-6}/K. While the coefficient of thermal expansion of TiC whisker α_w is 7.4×10^{-6}/K. The value of α_w is slightly larger than α_m, which is consistent with the above theory and further confirms that the pull-out phenomenon of TiC whiskers is the main toughening mechanism of the experimental material.

However, when the addition of TiC whisker increases to 0.6%, the impact toughness of experimental materials decreases obviously (Table 1). The explanation is that excessive addition of TiC whisker causes difficulty in whisker scattering, and thus decreases the density and increases the porosity of matrix. In addition, the mismatch of thermal expansion between whisker and matrix produces residual tensile stress in the matrix, and it increases with the increase of whisker content. Excessive residual tensile stress results in cracks in matrix, which decreases the toughness of the experimental material.

The maximum residual tensile stress σ_{Tmax} caused by the thermal expansion of two parallel whiskers can be calculated by the following formula[10]:

$$\sigma_{Tmax} = 2\sigma_o(2r/L)^2 \tag{3}$$

where σ_o is expressed by Eqn.(1); r is the radius of whisker; L is the distance between two parallel whiskers. The increase of whisker content leads to the decrease of L. Eqn.(3) indicates that the decrease of L enlarges the maximum residual tensile stress σ_{Tmax}. So the superfluous whiskers not only cause the decrease of the density of experimental material, but also increase the tendency of cracking, both reduce the toughness of the experimental material dramatically.

4 Conclusions

1) There is no whisker conglobation and aggregation in the TiC(0.3%)/YG10F composite wet-milled for 8 h and sintered in vacuum at 1 420 ℃.

2) The impact toughness of YG10F is increased by about 4 times and higher microhardness is also obtained

by 0.3% TiC whisker addition with wet-milled for 8 h and sintered in vacuum at 1 440 ℃.

3) The whisker pull-out phenomenon can be seen in the fracture surface of impact toughness specimen of TiC(0.3%)/YG10F wet-milled for 8 h and sintered in vacuum at 1 440 ℃. The main toughening mechanism of TiC whisker in YG10F is whisker pull-out and bridging phenomena.

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