Mechanical Property and Cutting Performance of Yttrium-Reinforced Al_2O_3/Ti(C,N) Composite Ceramic Tool Material

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(Submitted 19 June 2000)

Effects of yttrium on the mechanical property and the cutting performance of Al_2O_3/Ti(C,N) composite ceramic tool material have been studied in detail. Results show that the addition of yttrium of a certain amount can noticeably improve the mechanical property of Al_2O_3/Ti(C,N) ceramic material. As a result, the flexural strength and the fracture toughness amount to 1010 MPa and 6.1 MPam$^{1/2}$, respectively. Cutting experiments indicate that the developed ceramic tool material not only has better wear resistance but also has higher fracture resistance when machining hardened #45 steel. The fracture resistance of the yttrium-reinforced Al_2O_3/Ti(C,N) ceramic tool material is about 20% higher than that of the corresponding ceramic tool material without any yttrium additives.

Keywords ceramic tool material, fracture, mechanical property, rare earth, wear

1. Introduction

With the development of ceramic tool materials, they are more and more widely used in the field of metal cutting, because their mechanical properties and cutting performances have been greatly improved. Now, Al_2O_3-based ceramic tool material is one of the most widely used in practices. The mechanical properties of the particle-reinforced alumina-based ceramic tool materials have been improved notably with the hard materials, including TiC, TiN, TiB_2, SiC, (W,Ti)C, and Ti(C,N), working as the reinforcement phases, through various toughening mechanisms such as crack deflection, crack branching, crack bridging, microcracking, and the synergism toughening mechanism.[1,2,3] However, the intrinsic brittleness is a fatal weakness for ceramic tool materials. In order to reduce the brittleness and to increase the strength and the fracture toughness of the ceramic tool materials, various research has been done and progresses has been achieved to some extent[4, 5]. Until now, rare earth elements working as a kind of effective additive have found widespread applications in various ceramic materials.[6, 7] It is one of the important fields in the current research of ceramic composite materials. In the present study, an advanced Al_2O_3/Ti(C,N) composite ceramic tool material reinforced by rare earth yttrium is reported, and both the mechanical property and the microstructure are analyzed.

Major failure mechanisms of ceramic tools are tool wear and tool fracture. Usually, failure by tool wear dominates under continuous machining, while failure by tool fracture controls in intermittent machining. Therefore, in order to tend the application of this advanced ceramic tool material, cutting performances and failure mechanisms are studied further in the present study.

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2. Experimental Procedures

High-purity and ultrafine alumina and Ti(C,N) particles are used as the starting materials with sizes of 0.8 and 1 μm, respectively. The raw materials are blended with each other according to certain proportions and doped with different amounts of yttrium containing rare earth additives in a specific way. The mixtures are subsequently homogenized with alcohol media in a ball mill for 100 h. After milling, the slurry is dried in vacuum and screened under nitrogen atmosphere. Samples are then formed by hot pressing with parameters of 1720 °C $\times$ 20 min $\times$ 35 MPa.

The three-point-bending method is used to measure the flexural strength with a span of 20 mm and a crosshead speed of 0.5 mm/min. Flexural bars are carefully ground and polished into the size of 3 mm $\times$ 4 mm $\times$ 30 mm with the surface roughness less than 0.1 μm. Fracture toughness is determined by the indentation method. Samples are indented with a Vickers indenter HV-120 with a load of 196 N and holding time of 15 s. Microstructural characterizations of the material are performed with a scanning electron microscope (Hitachi S-570) and a transmission electron microscope (TEM, Hitachi H-800).

Cutting conditions are as follows. First, continuous turning experiments are carried out on a CA6140 lathe equipped with a 75° lead angle, 5° negative inclination, 5° negative rake tool holder, 5° clearance, and dry cut. The geometry of the tool inserts is SNGN160603 with an edge chamfer of 0.2 mm at 20°. The work material is a 0.45% C mild carbon steel (#45 steel) with a hardness of 45 to 46 HRC in the form of round bars. Second, intermittent turning is performed on the same lathe with the same tool geometry and the same work material. Tools used in the cutting experiments are yttrium-reinforced

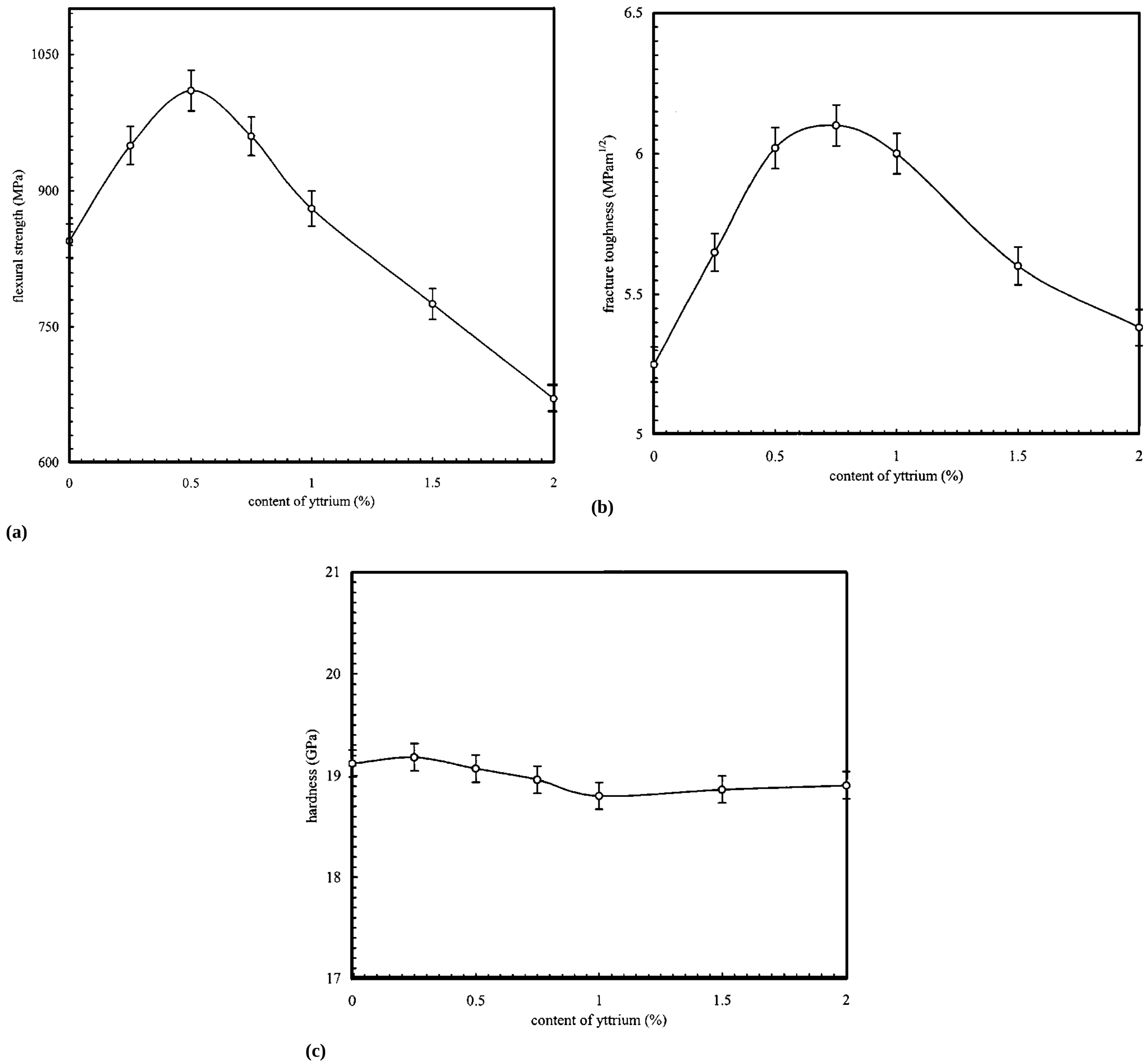


Fig. 1 (**a**) to (**c**) Effects of yttrium on the mechanical properties of Al_2O_3/Ti(C,N) ceramic tool materials

Al_2O_3/Ti(C,N) composite ceramic tool materials. Here, TCN1, TCN2, and TCN0 indicate the ceramic tool material with the addition of 0.5% Y and 2% Y and the tool material without any yttrium addition, respectively.

3. Results and Discussion

3.1 Mechanical Property and Microstructure

Figure 1 shows the effects of yttrium on the mechanical properties of the Al_2O_3/Ti(C,N) ceramic cutting tool material. It can be seen that, when the yttrium content is less than 1%, the flexural strength of the material increases to a different extent (Fig. 1a). The maximum increment reaches 20% and the highest flexural strength is about 1010 MPa when 0.5% yttrium is added. Above 1% yttrium, however, the flexural strength decreases with the increase of yttrium content. Under the experimental conditions, the addition of yttrium plays a notable role in the improvement of the fracture toughness of the ceramic tool material (Fig. 1b). The fracture toughness of the material with 0.75% Y is 6.1 $MPam^{1/2}$, while that of the material without yttrium is 5.25 $MPam^{1/2}$. So the former is 15% higher than the latter. However, the addition of yttrium has little effect on the hardness of the Al_2O_3/Ti(C,N) ceramic tool material (Fig. 1c).

Microstructure of the Al_2O_3/Ti(C,N) ceramic tool material with 0.5% yttrium addition under a TEM is given in Fig. 2. It is found that all the strengthening phases are distributed homogeneously with fine particles in the Al_2O_3 matrix and the grain size remains around 1 to 2 μm. Further studies indicate

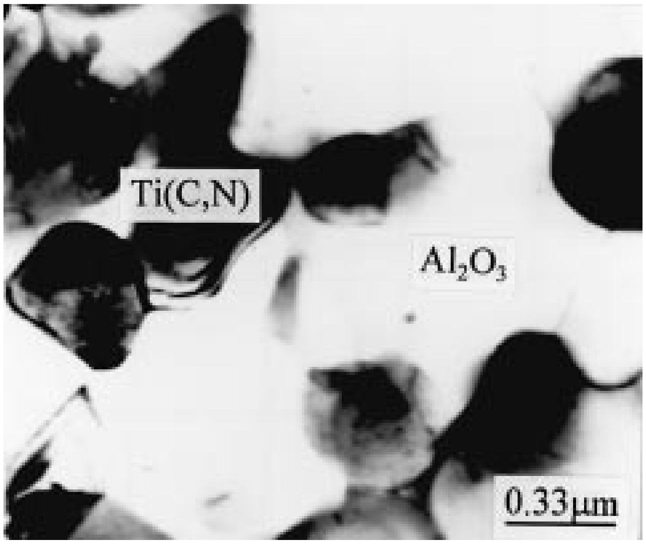


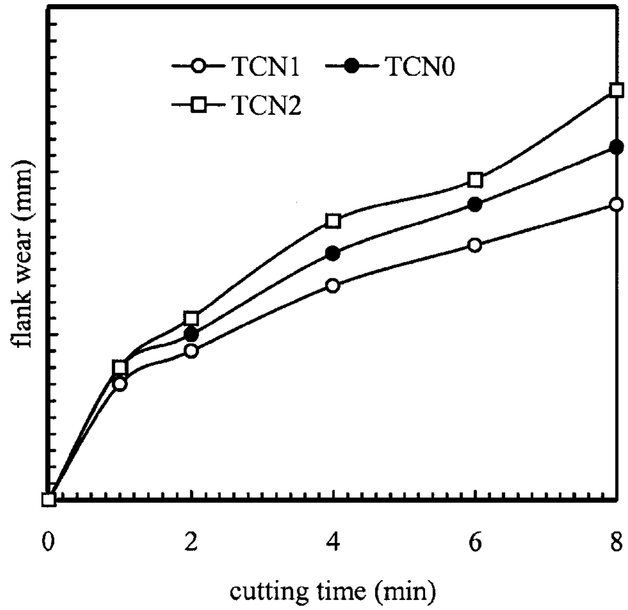
Fig. 2 Microstructure of yttrium-reinforced Al_2O_3/Ti(C,N) ceramic tool material

that, when the yttrium content increases, the coarse particles can then easily be observed.[8] It seems that the kind of particle coarsening is one of the dominant reasons for the decrease of the flexural strength. According to the analyses of the toughening mechanisms of Al_2O_3/Ti(C,N) ceramic tool material,[8] yttrium can purify the interfaces between the ceramic phases by reacting with the impurities in the material to form the complex rare earth compounds and thus increase the binding strength of the interfaces. As a result, the crack propagation resistance is enhanced, and both the flexural strength and the fracture toughness are improved.

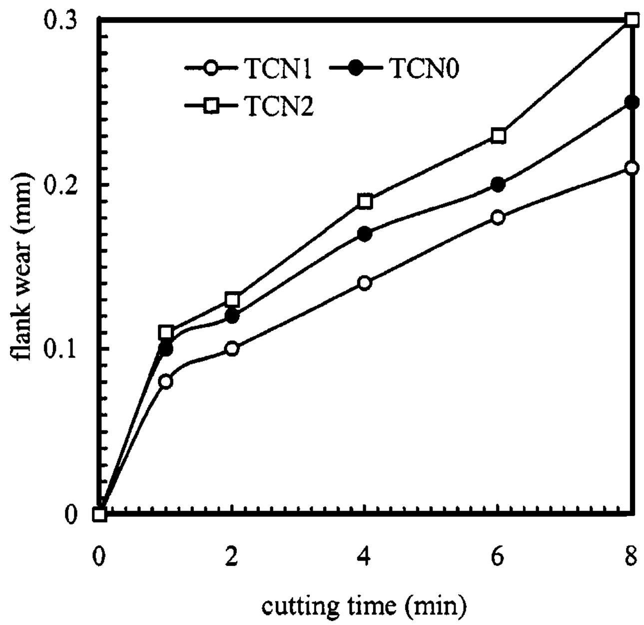
3.2 Cutting Performance

Figure 3 indicates the wear resistance of Al_2O_3/Ti(C,N) series ceramic tool materials when turning hardened #45 steel under the cutting conditions of cutting speed $v = 150$ m/min, feed rate $f = 0.2$ mm/rev, depth of cut $a_p = 1$ mm (Fig. 3a), $v = 220$ m/min, $f = 0.15$ mm/rev, and $a_p = 0.8$ mm (Fig. 3b). It suggests that, under the two kinds of experimental conditions, the wear resistance of the TCN1 ceramic tool, which contains 0.5% yttrium, is higher than that of the other two kinds of ceramic tools, TCN2 and TCN0. On the other hand, wear resistance of the TCN0 ceramic tool, which does not contain any yttrium additives, is higher than that of TCN2 containing 2% yttrium. Differences in the wear resistance become more obvious when compared with that under higher cutting speed (Fig. 3b). In the present study, the sequence of the wear resistance of the Al_2O_3/Ti(C,N) series ceramic tool materials is TCN1 $>$ TCN0 $>$ TCN2, which coincides with that of the mechanical properties according to the results of measurement.

Failure modes of Al_2O_3/Ti(C,N) series ceramic tool materials when machining hardened #45 steel are nearly the same and are mainly the crater wear, the flank wear, and the slight edge chipping. In the crater wear field, traces of obvious hard particle scratching and adhesion exist, while adhesion wear and ploughing grooves and slots can also be found in the flank wear field.



(a)

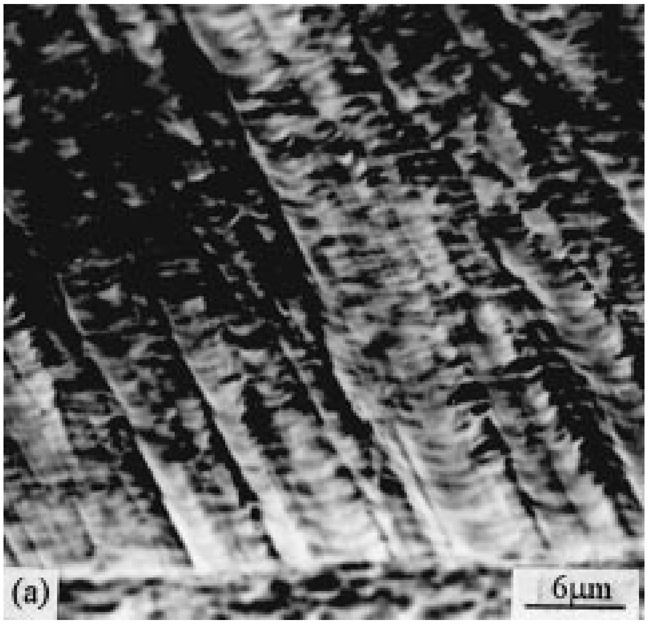


(b)

Fig. 3 (**a**) and (**b**) Flank wear curves of Al_2O_3/Ti(C,N) series ceramic tool materials when turning hardened #45 steel

However, it should be noticed that the flank wear of the TCN1 ceramic tool material, which contains 0.5% yttrium, is slighter than that of the other two kinds of ceramic tool materials, TCN2 and TCN0.

The adhesion between the tool material and the workpiece material is intensified with the increase in the cutting speed, which results in the increase in the crater wear. In the flank wear area, the dominant wear mode is changed from the abrasive wear at low speed to the adhesive wear at high speed. The ploughing grooves and slots become shallower, while the adhe-



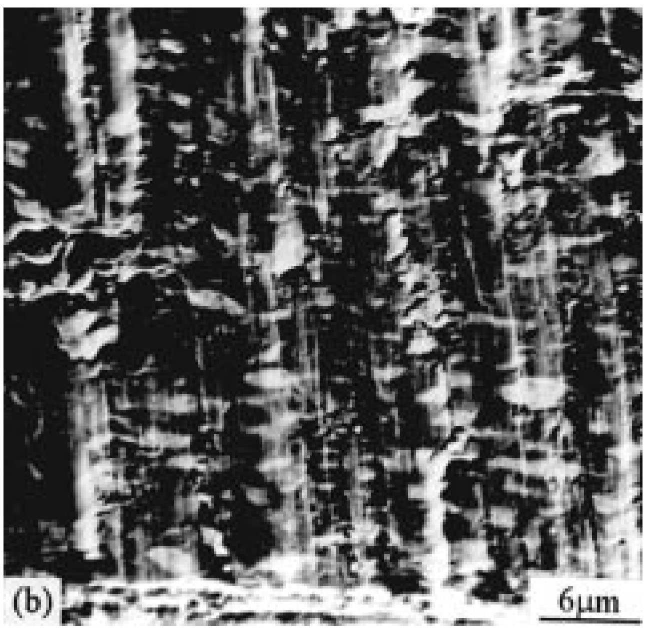


Fig. 4 (**a**) and (**b**) Morphology of the flank wear of TCN1 and TCN0 ceramic tools at high speed

sive phenomenon becomes more and more obvious. Furthermore, phenomena of the peeling off of some grains can even be observed in the TCN0 and TCN2 ceramic tool materials. Generally, the adhesion wear in the TCN1 ceramic tool material is slighter than that of the other two tool materials, which can be proved further with the comparison of the wear morphology of TCN1 (Fig. 4a) and TCN0 (Fig. 4b) ceramic tool materials.

The failure form of the used ceramic tools in intermittent cutting is mainly tool fracture. Figure 5 shows that the fracture resistance of the TCN1 ceramic tool containing 0.5% yttrium is the highest among the three kinds of Al_2O_3/Ti(C,N) series ceramic tool materials used in the present study. Under the

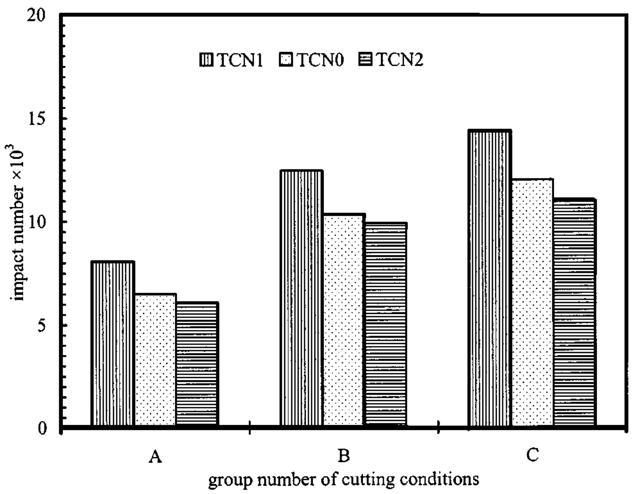


Fig. 5 Fracture resistance of Al_2O_3/Ti(C,N) series ceramic tool materials

three groups of cutting conditions (group A: cutting speed $\nu = 118$ m/min, feed rate $f = 0.1$ mm/rev, depth of cut $a_p = 0.5$ mm; group B: $\nu = 188$ m/min, $f = 0.1$ mm/rev, $a_p = 0.3$ mm; and group C: $\nu = 264$ m/min, $f = 0.1$ mm/rev, $a_p = 0.1$ mm), the fracture resistance of the TCN1 ceramic tool is 24, 20, and 21% higher than that of TCN0 tool, while it is 32, 26, and 31% higher than that of the TCN2 ceramic tool. It denotes that wear resistance and fracture resistance of Al_2O_3/Ti(C,N) ceramic tool material can eventually be increased through the increase in the mechanical properties as a result of the addition of yttrium.

It is found with cutting experiments that the fracture forms of the ceramic tools vary with the cutting conditions. Under group A conditions, peeling off in the rake face and tool fracture in the flank area dominate, while under group B and C conditions, flank fracture and thermal fracture in the rake face are the dominant fracture modes.

Under group A cutting conditions, the ceramic tools bear mainly the mechanical stresses, since the cutting speed is low and the depth of cut is large. However, the ceramic tools dominantly undertake the thermal stresses and the combination of mechanical and thermal stresses, respectively, under group B and C conditions. Figure 6(a) shows the morphology of a crack observed in the TCN2 ceramic tool under group A conditions. It seems that it is a macrocrack left after the peeling off in the rake face. It is relatively short and far from the cutting edge, which implies that it is not this crack that causes the failure by fracture and it is only one of the possible cracks that cause the tool fracture. Some smaller cracks can also be found near the macrocrack. In Fig. 6(b), a fatigue crack of about 0.2 mm in length, which is nearly propelled to the main cutting edge, is observed to exist in the fractured area of the rake face of the TCN1 ceramic tool under group B conditions. It terminates at the interface between the fractured area and the nonfractured area and extends into the material of the other side. Under group C cutting conditions, some radial net-shaped and comb-like cracks can be obviously observed as a result of the thermal shocks and thermal stresses (Fig. 6c)). Thus, it suggests that both mechanical and thermal stresses have extreme effects on

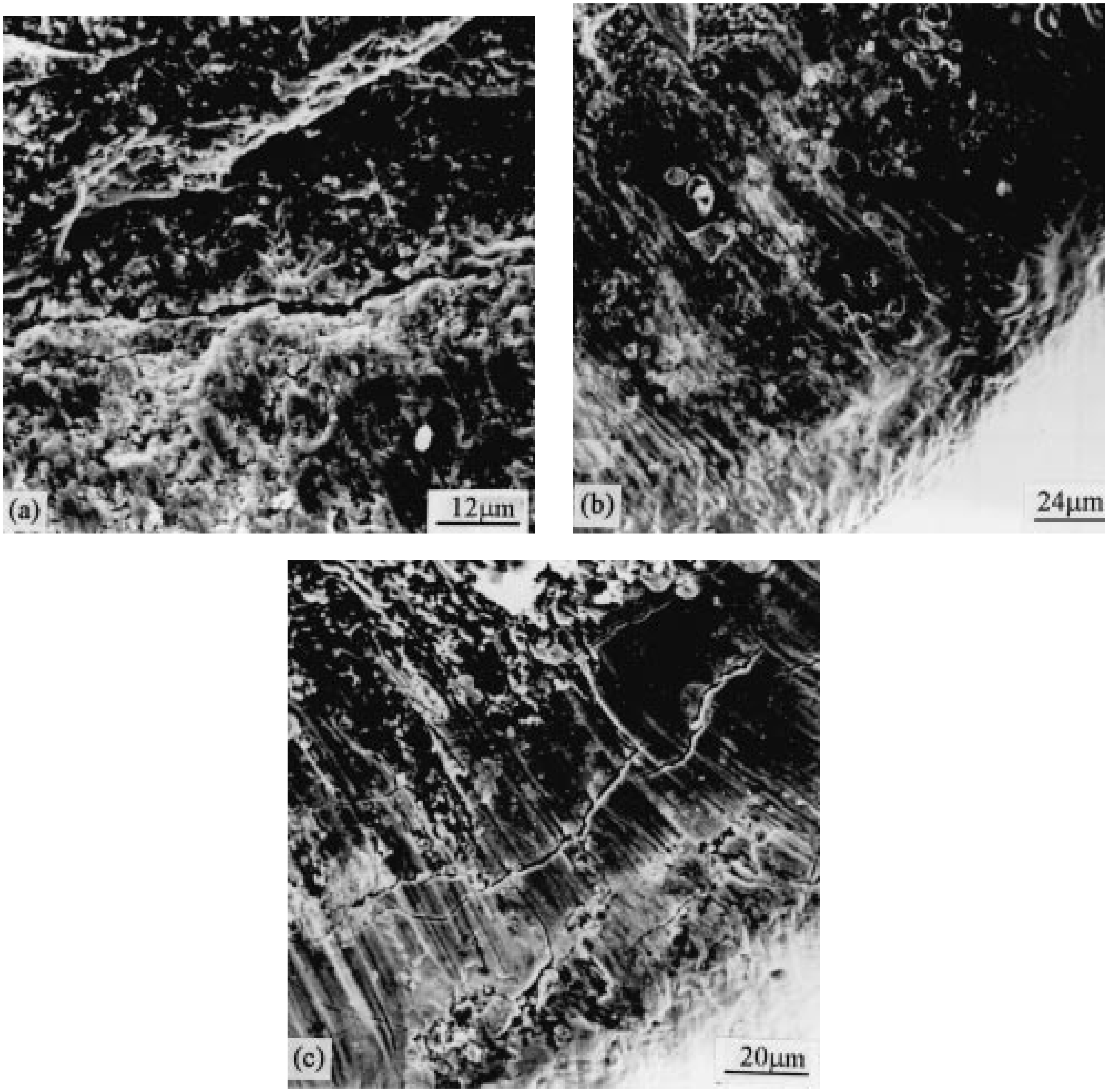


Fig. 6 (**a**) to (**c**) Fatigue cracks in Al_2O_3/Ti(C,N) ceramic tool materials in intermittent machining

tool fracture of the ceramic tool materials in the interrupted turning of hardened #45 steel regardless of whether they are at low or high cutting speed. The resulting fatigue cracks play an important role in the tool failure by fracture.

4. Conclusions

The addition of the rare earth element yttrium of a certain amount can noticeably improve the mechanical properties of the Al_2O_3/Ti(C,N) ceramic tool material. The flexural strength and the fracture toughness amounts to 1010 MPa and 6.1 $MPam^{1/2}$, respectively, when the volume content of yttrium is 0.5 and 0.75%. High wear resistance and fracture resistance have been found with cutting experiments for the yttrium-reinforced ceramic tool material when turning hardened #45 steel. Under three different groups of cutting conditions, the fracture resistance of the TCN1 ceramic tool, which contains 0.5% yttrium, is 24, 20, and 21% higher than that of the TCN0 tool, while it is 32, 26, and 31% higher than that of the TCN2 ceramic tool, respectively. It denotes that wear resistance and fracture resistance of the Al_2O_3/Ti(C,N) ceramic tool material can eventually be increased through the increase of mechanical properties as a result of the proper addition of yttrium.

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