THE EFFECTS OF ZrO$_2$ or TiC ON THE PERFORMANCE OF THE ALUMINA-BASED CERAMIC CUTTING TOOLS

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Abstract   Two types of alumina-based cutting tools with compositions of 90 vol.% Al$_2$O$_3$+10 vol.% ZrO$_2$ and 80 vol.% Al$_2$O$_3$+20 vol.% TiC are produced by isostatic pressing and sintering technique. The effects of these additives on the mechanical properties and cutting performance of these materials are investigated. The tool life in both materials is examined under identical conditions on cutting a grey cast iron of grade 14. At a cutting speed of 550 m/min., a feed rate of 0.25 mm/rev., and a cutting depth of 2 mm, the material containing TiC with an optimal tool life of 27 minutes, is found to be superior to the ZrO$_2$ containing material which had an optimal tool life of 25 minutes. The possible role of these additives on the performance of these materials are discussed.

چکیده   دونوع ابزار برش آلومینائی با ترکیبات حجمی   10%ZrO$_2$+90% Al$_2$O$_3$ و 20% TiC+80% Al$_2$O$_3$ به روش پرس کردن ایزواستاتیکی و عملیات سینتر کردن متعاقب تولید گردیده است. تاثیرات این افزودنیها در خواص مکانیکی و کارآیی برشی این ابزارها مورد مطالعه قرار گرفته است عمر ابزارهای ساخته شده از هردو ماده تحت شرایط یکسان در برش چدنی با گرید 14 بررسی شده است. تحت سرعت برشی برابر 550 متر در دقیقه، نرخ تغذیه ای برابر 0/25 میلیمتر در دور، وبک عمق براده برداری برابر 2 میلیمتر ماده محتوی TiC با عمر بهینهٔ 27 دقیقه، نسبت به ابزار محتوی ZrO$_2$ عمر بهینهٔ 25 دقیقه برتر تشخیص داده شده است. رل ممکن این افزودنیها درکارآیی این مواد برشی بحث خواهد شد.

INTRODUCTION

Technological developments have shown a substantial increase in use of advanced technical ceramics as cutting tool materials[1]. The current worldwide usage of ceramic cutting tools is estimated to rise from about $ 75 million at present to about $ 150 million in 1995[2]. Thus accurate data for composition of the material, processing of a tool, and its performance under specific cutting conditions are all necessary to optimize the overall performance of a cutting tool. Among the ceramic cutting materials, alumina and alumina-based composites have shown to have a high industrial potential as cutting inserts[3]. The effects of various additives on the performance of the alumina-based cutting tools have been reviewed and among these additives, the role of ZrO$_2$ or TiC has been reported to be outstanding[4].

The addition of a small amount of ZrO$_2$ or TiC (up to 2000 ppm) to alumina promotes the densification process and inhibits the grain growth through the formation of solid solutions and introducing lattice defects[5]. However, increasing the amount of ZrO$_2$ up to 15 vol% or TiC up to 25 vol% has been shown to modify the mechanical properties of the alumina-based composites by the formation of a

distinct phase which does not form a solid solution within the alumina[6].

The present work has been undertaken to study the effects of addition of 10 vol.% ZrO_2 or 20 vol.% TiC on the mechanical properties and performance of the alumina-based ceramic tool materials. The possible reasons for the observed behaviour are discussed.

MATERIALS AND EXPERIMENTAL PROCEDURES

The Al_2O_3, ZrO_2, and TiC powders used in this experiment were supplied by B.D.H. Ltd. and Magnisum Electron Ltd. (U.K.). The mean particle size of Al_2O_3, ZrO_2 and TiC powders were 1,2, and 2 μm respectively: The purity of the powder materials was of the order of 99.6%.

Slurries containing 90 vol% Al_2O_3+10 vol% ZrO_2 (hereafter sample A) or 80 vol.% Al_2O_3+20 vol.% TiC (hereafter sample B) were produced using distilled water. These slurries were then mixed by a magnetic mixer for two hours before milling with alumina milling balls for 3 hours to remove large agglomerates and enhance the homogeneity. A Coulter particle size analyser was used to analyse the particle size in the milled slurries prior to drying. The mean particle size in the slurries of samples A and B was found to be 4 and 3 μm respectively. The slurries were dried on a hot plate with the magnetic mixer in operation to sustain composition uniformity of the powders. The dried powders were placed in a flexible tube of ~20 mm diameter and were then isostatically compacted at a pressure of around 140 MPa. The green compacts were sintered at 1500°C for 3 hrs with a ramp rate of 3°C/min. The cylindrical sintered compacts with a diameter of ~18 mm and a length of ~40 mm were precisely cut into disks of 5 mm thickness using a low-speed diamond saw. The tool inserts were then cut out of these disks.

Grinding of peripheral and bearing surfaces on the inserts were carried out prior to chamfering. The features of the chamfered tools given in Table 1, have been prepared according to ISO 1832 and ISO 5608: 1977.

A number of tests to evaluate the mechanical properties of the tool materials such as hardness, bending strength, and fracture toughness were carried out on the disks.

The microhardness measurements were performed according to ASTM, E384 using a Vickers microhardness machine with a load of 0.5 kg. The bending strength of the

TABLE 1. Features of the Tool Holder and Chamfering.

Features of the tool holder(°)		Chamfer of the tool tips
Approach Angle	45	
Slide Rake Angle	-6	$0.2 \times 20°$
Back Rake Angle	0	
Clearance Angle	5	

specimens was evaluated according to ASTM F417 using the four-point test. For this, the cylindrical sintered compacts were cut along the axes of the cylinders and the test samples were taken from the central part of these compacts with a thickness of around 5mm. The fracture toughness of the specimens were measured according to ASTM E23 by using the four-point bend test on a single-edge notch specimen.

A final visual inspection of the tool was carried out using an optical microscope of ×10 prior to engagement of the tools with the workpieces. The machining experiments were carried out on a Boehringer DM 640 lathe with a speed range of 5-2500 rpm and a feed range of 0.05-1.8 mm/rev. A constant speed was maintained in all experiments using a tachometer. The cutting and feed forces were measured using a Kistler dynamometer type 9263.

The feed rate and the depth of cut were 0.25 mm/rev. and 2 mm respectively. The surface roughness was measured perpendicular to the feed marks and its average value was obtained by measuring three different radial positions.

A grade of grey cast iron with a designation of G-14 or 220(14) has been used in testing the life of the tools in this experiment. The tensile strength in this cast iron is 220 MPa and its 0.2%-proof stress corresponds to 140 MPa. The hardness varied between 228-248 HV and this was measured using a Vickers Hardness tester under a load of 50Kgf. This cast-iron represents one of the most widely used materials in automotive industries and it has a good machinability behaviour.

After every 5 minutes of cut, the tool insert was washed in a 50-50 HCl for 10 minutes to remove all the adhering metal from its flank and rake faces. The tool wear was then measured under a travelling microscope with a magnification of ×10 on the rake face, flank face, and the notch depth. When a crater was observed on the tool, it was measured by a Talysurf-4.

Termination of a tool's life was decided on the basis of

one of the following parameters; thus a tool was rejected:
- if the average flank wear reached 0.4 mm. or the maximum
  flank wear reached 0.7 mm.
- if the notch depth reached ~1mm either at the depth of cut
  or at the nose of the tools.
- if the crater depth reached 0.14 mm.
- if surface finish on the grey cast iron exceeded 6μm.
- if flaking or fracture occurred.

RESULTS AND DISCUSSION

Typical microstructures of samples A and B prior to cutting
are shown in Figures 1 and 2 respectively. As can be seen
the microstructure of sample B is remarkably finer in
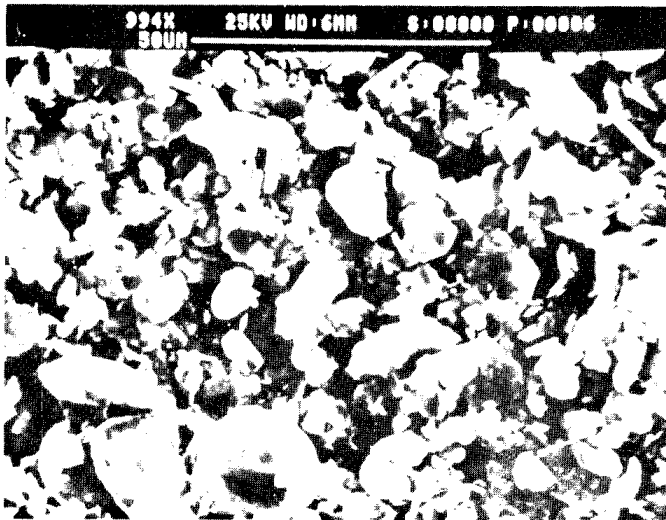comparison to that of sample A. This could be due to the

effect of TiC in modification and refinement of the
microstructure of alumina during sintering which seems to
be more significant than the effect of ZrO_2.

When cutting under orthogonal conditions, flank, rake
and end clearance faces come into contact with the moving
workpiece resulting in the appearance of wear in all these
surfaces and bands of worn area. Figures 3 and 4 show the
general view of typical worn areas on the tool tips in
samples A and B respectively under identical cutting
conditions. The relative comparison of the wear behaviour
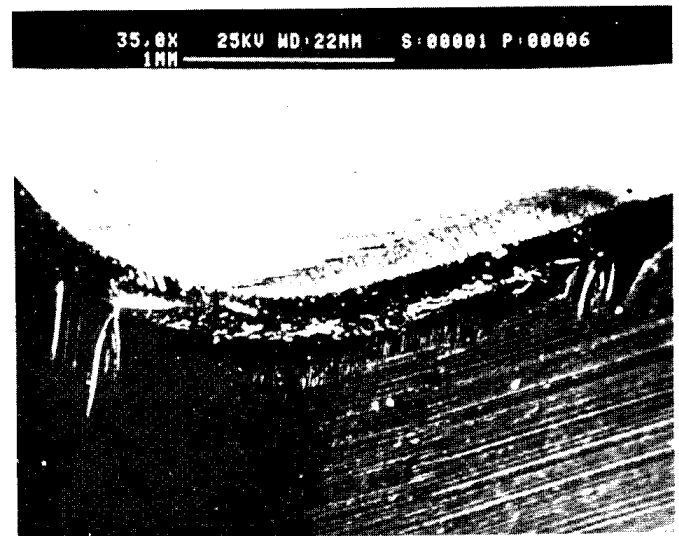on flank and rake faces of samples A and B shows that there

Figure 3. General view of a typical worn area in sample A after 25
minutes of cut at 550 m/min. with a feed rate of 0.25 mm/rev.
and depth of cut of 2 mm.

Figure 1. Typical SEM microstructure of sample A.
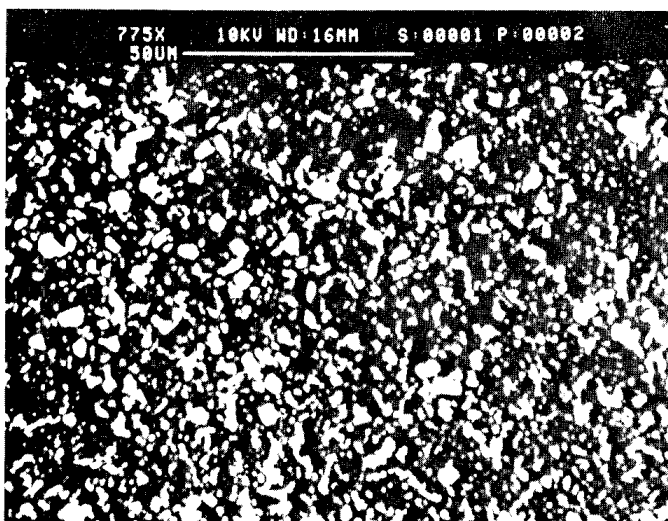
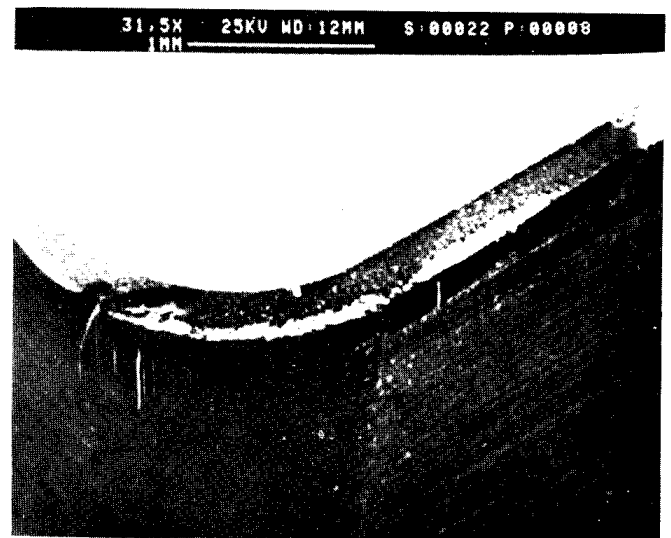Figure 2. Typical SEM microstructure of sample B.

Figure 4. General view of a typical worn area in sample B after 27
minutes of cut at 550 m/min. with a feed rate of 0.25 mm/rev.
and depth of cut of 2 mm.

is a more significant and uneven wear associated with sample A. The difference in the wear behaviour in these tools can be related to different modifications imparted by addition of the ZrO. or TiC to the alumina.

The wear and cracking behaviours at a tool tip are of the main factors which could affect the tool life. It is generally known that the wear and cracking of a tool can be affected by its hardness and toughness. These mechanical properties can be influenced significantly by composition and the microstructure of the tool.

The presence of tetragonal ZrO_2 as a distinct phase in the alumina matrix and its transformation into a more stable monoclinic structure under applied stresses, during the metal-cutting processes is known to modify the structure of sample A and enables the tool to absorb higher stresses during the metal-cutting operations[6]. This transformation is associated with a volume expansion and shear strain which enhances the toughness of the tool A. This structural modification prevents cracking and even when cracks exist, the required energy for their propagation will be increased. However, the increase in toughness could also be produced by other mechanisms such as microcrack toughening, compressive surface stress and crack deflection[7]. The addition of zirconia to alumina can also retard the plastic deformation of the alumina-based tools and increase the wear resistance[7].

The effect of TiC in alumina is to reduce the grain size and act as a hard abrasive phase within the alumina matrix and this can retard the wear associated with the tool tips. The addition of TiC to alumina can also result in microcracking which in contrast to the microcrack-toughening mechanism in Al_2O_3-ZrO_2 composites, weakens

FLANK WEAR (mm)

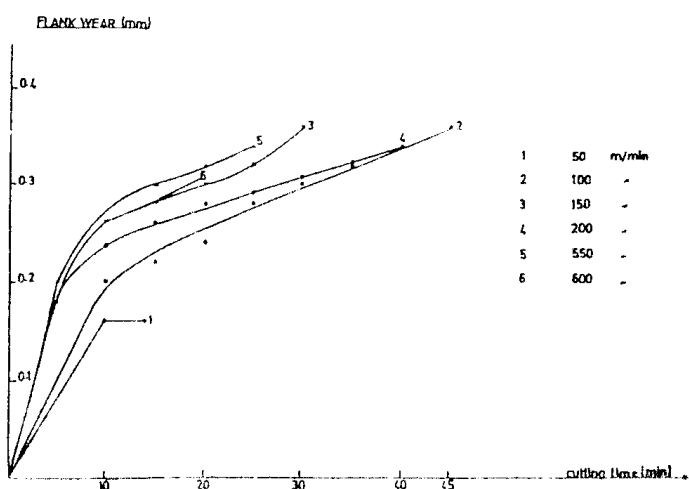| | 50 | m/min |
1	50	m/min
2	100	"
3	150	"
4	200	"
5	550	"
6	600	"

Figure 5. The average flank wear vs cutting time for sample A.

the tool tip.

Figures 5 and 6 show the average flank wear vs. cutting time at different cutting speeds in samples A and B respectively. As can be seen in Figure 5, at a very low speed of 50 m/min. the flank wear is increased uniformly and flattens off, and then the tool is discarded due to workpiece surface finish. At cutting speeds of 100 to 200 m/min. the flank wear is uniform and has a low rate. However, at speeds of 200 to 400 m/min. no flank wear could be measured due to catastrophic failure of the tool bits at an early stage of cut. Higher speeds of 500 to 600 m/min. showed a reasonable rate of flank wear and an optimum tool life of 25 min. is recorded for the cutting speeds of 550 m/mm.

Figure 6 shows that at lower cutting speeds of 50 to 200 m/min, the rate of flank wear is relatively low, however it increases as the cutting speed is increased. At cutting speeds of 200 to 400 m/min. the rate of flank wear increases repidly. However, at 550 m/min. the rate of wear is reduced significantly and an optimum tool life of 27 min. was obtained at this cutting speed. Thus the cutting speed of 550 m/min. was selected to compare the cutting life in samples A and B.

The variations in surface finish of the workpiece vs. cutting time at different cutting speeds using samples A and B are shown in Figures 7 and 8 respectively. These figures show that at a speed of 550 m/min. the surface finish of the workpiece was within the acceptable limits of 6 µm after a cutting time of 25 min. with sample A and 27 min. with sample B.

FLANK WEAR (mm)

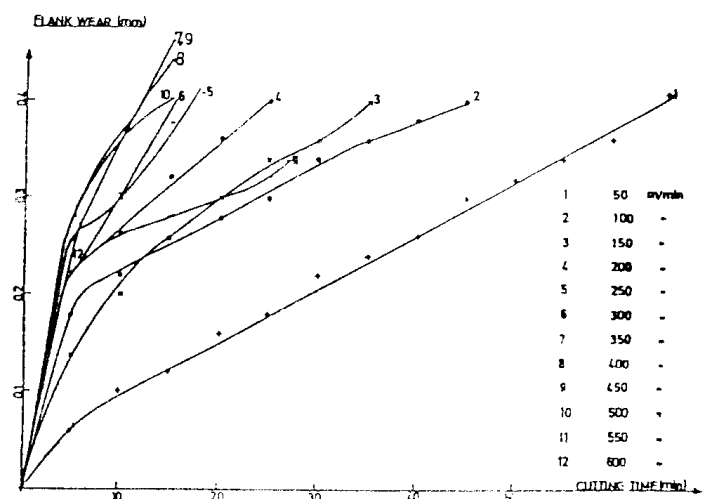| 1 | 50 | m/min |
2	100	"
3	150	"
4	200	"
5	250	"
6	300	"
7	350	"
8	400	"
9	450	"
10	500	"
11	550	"
12	600	"

Figure 6. The average flank wear vs cutting time for sample B. The termination of the tool's life has been determined on the basis of the average flank wear of 0.4 mm.
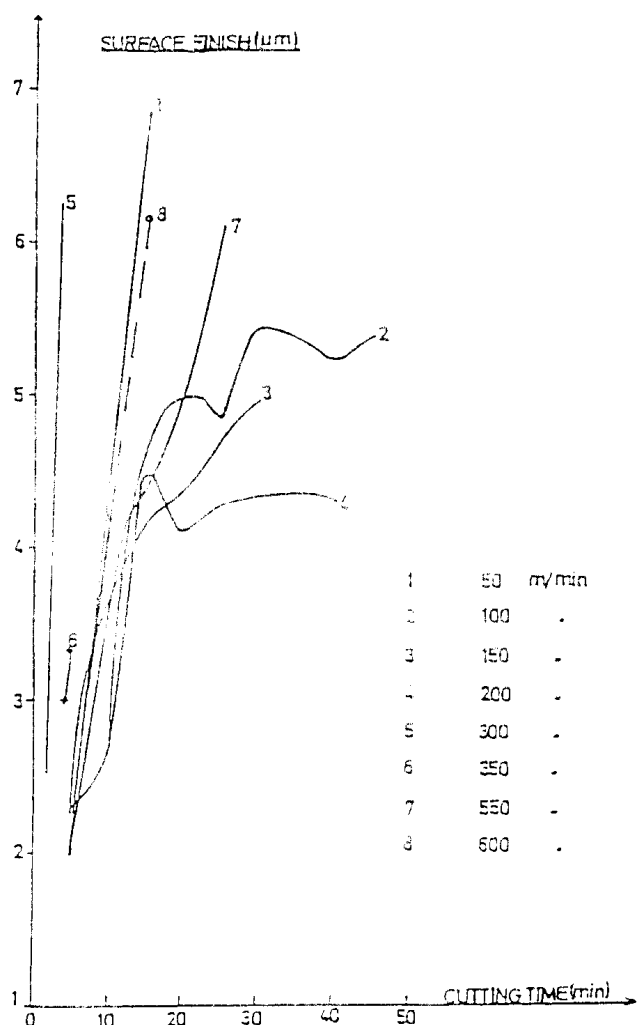
Figure 7. Variations in surface finish of the workpiece vs cutting time at different cutting speeds using sample A.

1	50	m/min
2	100	.
3	150	.
4	200	.
5	300	.
6	350	.
7	550	.
8	600	.

Figure 8. Variations in surface finish of the workpiece vs cutting time at different cutting speeds using sample B.

1	50	m/min
2	100	.
3	150	.
4	200	.
5	250	.
6	300	.
7	350	.
8	400	.
9	450	.
10	500	.
11	550	.
12	600	.

Figures 9 and 10 illustrate the variations in cutting and feed forces against cutting speeds in samples A and B respectively. At a speed of 550 m/min. both the cutting and feed forces are low in both samples A and B which results in a lower power consumption. This is another reason why the cutting speed of 550 m/min. was selected to compare the tool life in samples A and B.

Plots of Taylor's tool-life curves for samples A and B are shown in Figures 11 and 12 respectively. The effect of speed on the tool life can be clearly seen in these figures. The peak tool life at 550 m/min. was 25 min. for sample A and 27 min. for sample B.

Hardness, toughness and fracture strength of a tool are some of the most important mechanical properties which control the tool life. These properties along with the density, grain size, and the Young's modulus of samples A and B are compared with those of pure alumina in Table 2 (data for
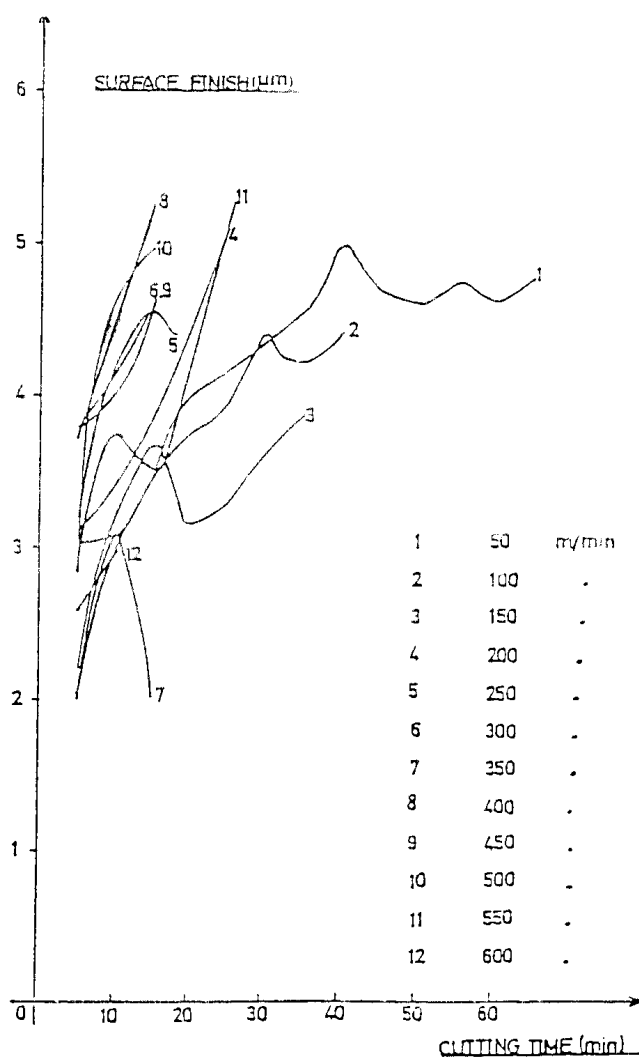
TABLE 2. Mechanical Properties of Samples A, B, and Alumina. *data extracted from Reference 7.

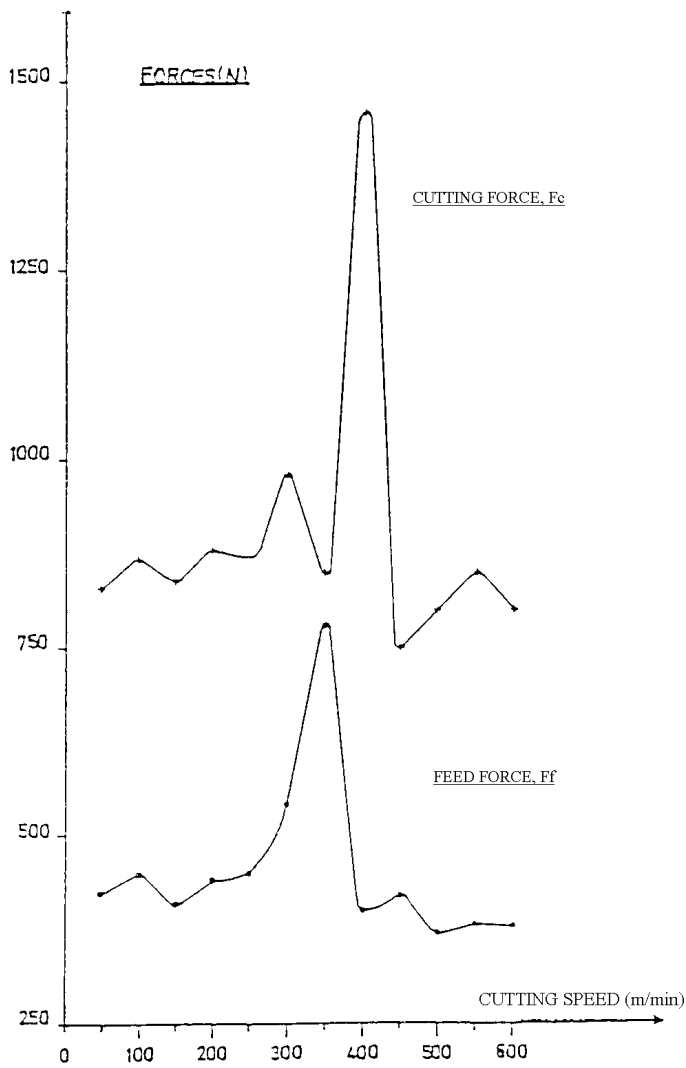|	Sample A	Sample B	*Alumina
Density (g/cm₃)	3.97	4.28	3.85
Grain Size (m)	3	2	1.5
Vickers Hardness (HV 0.5 kg)	2200	2400	1800
Bending strength (MPa)	440	400	400
Young Modulus (GPa)	340	370	360
Fracture Toughness (MPa. m$^{1/2}$)	5.3	4.5	3

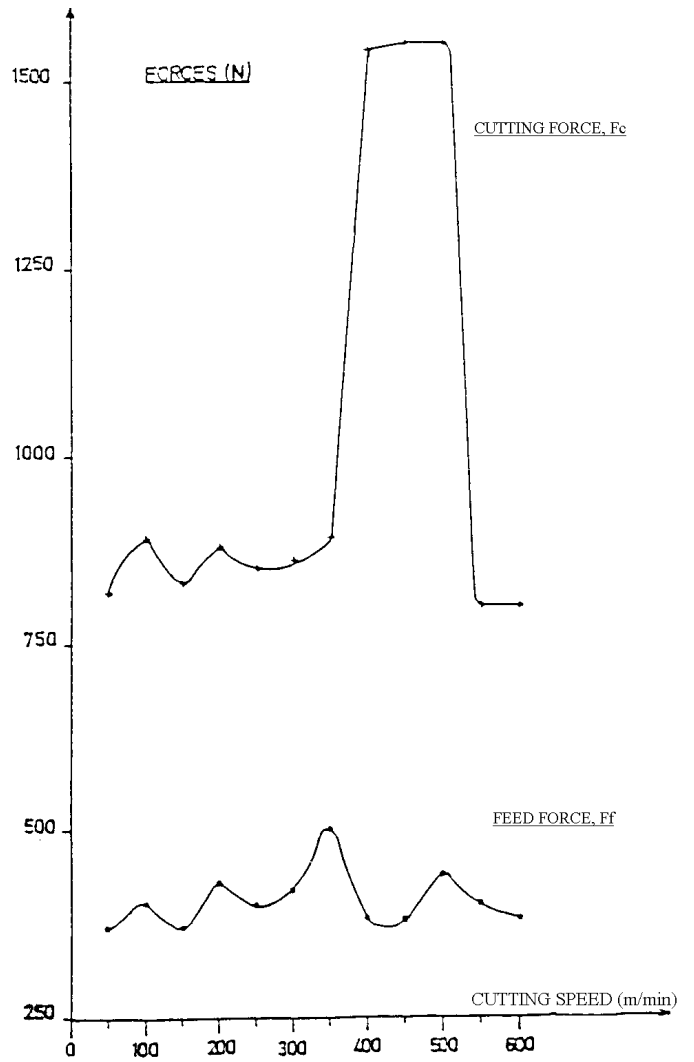**Figure 9.** Variations in cutting and feed forces vs cutting speed for sample A.

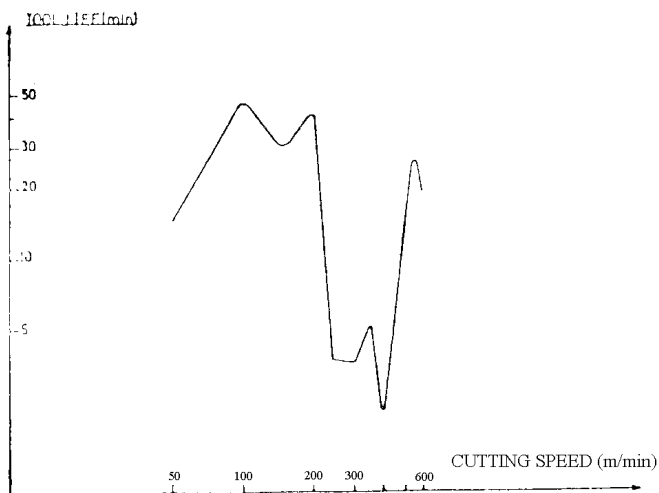**Figure 10.** Variations in cutting and feed forces vs cutting speed for sample B.

Figure 11. Taylor's tool-life curve for sample A.
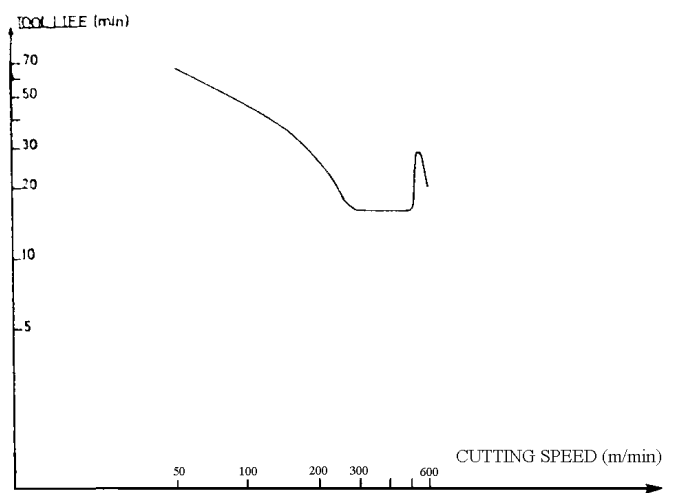

Figure 12. Taylor's tool-life curve for sample B.

pure alumina have been extracted from[7]. The addition of ZrO_2 or TiC increases significantly both the fracture toughness and hardness of the pure alumina. However, the relative comparison of hardness and fracture toughness in tool A and B showed that hardness is higher in sample B and fracture toughness is higher in sample A. Therefore in spite of higher fracture-toughness values in both samples A and B, in comparison with pure alumina, the higher hardness value in sample B appears to play a greater role in tool life.

CONCLUSION

The addition of 10 vol.% ZrO_2 or 20 vol.% TiC to alumina proved to be beneficial in increasing the mechanical properties of the alumina-based ceramic tools, thus improving the tool performance in cutting a grey cast iron of grade 14. The superior performance of tools A and B in comparison to pure alumina can be related to higher fracture-toughness values in these samples which can prevent premature tool failures under machining shop conditions. Sample A showed even better fracture toughness than sample B. However, the higher hardness and wear resistance in sample B proved to be more effective in increasing the

tool life. The results of this investigation favour the use of the 20 vol% TiC-doped alumina to that of 10 vol% ZrO_2 in cutting a grey cast iron of grade 14.

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