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Performance of Laminated Ceramic Composite Cutting Tools

Maurice F. Amateau,[a] Bruce Stutzman,[a] Joseph C. Conway[a] & Joseph Halloran[b]

[a] The Pennsylvania State University, P.O. Box 30, State College, PA 16804, USA
[b] Greenleaf Corporation, Seagertown, PA 16433, USA

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Abstract Laminated ceramic composite cutting tools have been developed which demonstrate improvements in strength, toughness, and thermal shock resistance compared to the conventional non-laminated ceramic composites. Silicon carbide whisker and titanium carbide particulate reinforced ceramic matrix composites have been designed as multilayer structures and fabricated into cutting tool inserts for evaluation in machining tests. Laminated ceramic composite designs exhibited significantly better wear resistances, as well as improved mechanical strength and toughness. Successful designs were achieved by minimizing residual core tensile stress and interlaminar stress while maximizing the compressive residual stress on the contact surfaces. These designs minimized flank wear and chipping.

1 INTRODUCTION

Cutting tool materials must have high hardness and stiffness to resist deformation under the high cutting forces exerted in machining operations. They must also possess high wear resistance to maintain sharp cutting edges and permit high machining accuracy over extended periods of time. Long cutting tool life also requires high tensile and compressive strength, fatigue resistance, high temperature strength, chemical inertness, high fracture toughness, impact resistance and high thermal shock resistance.

Ceramics possess many, but not all, of the desirable properties required for cutting tools and have some of the characteristics necessary to counteract the principal wear mechanisms. The principal advantages of ceramic cutting tools are hardness, stiffness, high temperature strength, and chemical stability at elevated temperatures. Chemical stability is particularly important in minimizing rake face crater wear. Minimizing reactive type wear permits higher cutting speeds, which lowers cutting forces, thus minimizing work piece distortion. High temperature strength of ceramics also retains tool hardness and minimizes abrasive wear during extended cutting operations.

The main limitations of ceramics for cutting tools is their low tensile strength, fracture toughness, impact resistance and thermal shock resistance. These property limitations make ceramic cutting tools prone to premature failure by chipping, cracking or edge failure. Various methods may be employed to increase the impact resistance and fracture toughness of ceramics; however, whisker toughening is particularly effective.[1,2] The low toughness and the thermal shock resistance of monolithic ceramics can be significantly improved by the incorporation of discontinuous reinforcements such as silicon carbide whiskers. Whiskers improve the toughness and strength of the ceramics through crack bridging,[3] whisker pullout, crack deflection, microcracking and transformation toughening.[4]

The toughness and strength can also be improved through the use of thermoelastically tailored surface residual compressive stresses. Surface residual compressive stresses can be incorporated into ceramic laminates upon cooling by introducing low coefficient of thermal expansion layers to the surface of the material. The residual surface compressive stresses resist surface tensile stresses typically generated through bending. The compressive stresses can also serve to effectively blunt or close cracks in the material.[5,6]

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Whisker-reinforced ceramics also exhibit improved wear resistance compared to unreinforced ceramics. The tribological characteristics of monolithic ceramics can be improved through the addition of wear resistant surface layers such as Si_3N_4, SiAlON, or TiC.[7] In the current art of manufacturing whisker-reinforced ceramic cutting tools, the matrix ceramic and the whiskers are pre-blended and hot pressed to form the densified tool insert body. This method provides very little control over the distribution and orientation of the whisker reinforcements in the final tool body. Another significant limitation to the current method of manufacturing of whisker-reinforced ceramic cutting tools is the cost of the silicon carbide whiskers. Whiskers cost 10 times that of the common matrix materials; hence, material designs and manufacturing methods suitable for cost effective cutting tools, are required. Manufacturing method and material designs for ceramic cutting tools, that make efficient use of the minimum amount of reinforcing whiskers to minimize cost, are the ultimate goals of this research.

2 MATERIALS

Composites were fabricated using either Al_2O_3 or Si_3N_4 as the matrix with TiC particulate, TiN particulate, or SiC whisker reinforcements. A list of these materials and their designation is given in Table 1. The composition amounts given in this table are in volume percent. The alumina powers, grade RC-HPBM containing 0·05% MgO, with a particle size of 34 μm were obtained from Malakoff Industries Inc. The SiC whiskers were obtained from Advanced Composite Materials Corporation, Greenville S.C.

3 LAMINATE DESIGN

Modified classical plate laminate theory was used to thermoelastically tailor the laminate design to optimize the residual stresses, toughness and the tribological performance. Thermoelastic properties of lamina materials used for laminate properties calculations were obtained from manufacturer supplied data when available. For composites where such data were not available the lamina properties were calculated from constituent data using the Halpin–Tsai method.[8,9] A summary of lamina properties is given in Table 2.

The designs used in this study are considered hybrid composites by conventional laminate terminology since they use multiple compositions within a single laminate. Some of the designs used pure alumina surface layers to provide chemically inert material on the rake face, while other designs used titanium carbide and silicon carbide reinforcement alumina on this surface. The individual layers in all designs were arranged symmetrically with respect to the mid-plane to eliminate in-plane and out-of-plane coupling of stresses and deflections. Laminate designs have been selected to avoid large tensile stresses within the lamina and large differences in stresses between lamina to minimize delamination. All designs except GX-06 and GX-08 use compressive stresses on the outer surfaces.

Table 1. Materials used in this program

Composition	Designation	Source
30SiCw–70 Al_2O_3	WG-300	Greenleaf Corporation
26TiCp–79Al_2O_3	HC-2	NTK Corporation
17TiNp–83Si_3N_4	RD-3905	Greenleaf Corporation
17TiNp–83Si_3N_4	SX-5	NTK Corporation
TiCp–Al_2O_3 5 layer laminate #1	GX-06	Penn State University
TiCp–Al_2O_3 5 layer laminate #2	GX-08	Penn State University
TiCp–Al_2O_3 3 layer laminate	GX-20	Penn State University
SiCw–Al_2O_3 7 layer laminate	DX-14	Penn State University
SiCw–Al_2O_3 5 layer laminate	DX-13	Penn State University

Table 2. Lamina properties used to calculate laminate properties

Material	Elastic modulus (GPa)	Poisson's ratio	Shear modulus (GPa)	Coefficient of thermal expansion (10^{-6}/°C)
Alumina	390	0·23	159	7·92
5SiCw/95Alumina	392	0·23	160	7·72
10SiCw/90Alumina	395	0·22	161	7·54
20SiCw/80Alumina	400	0·22	165	7·16
26TiC/74Alumina	395	0·22	162	8·10

Table 3. Residual stresses in hybrid laminate designs

Design	Composition	Thickness (mm)	Stress *x* (MPa)	Stress *y* (MPa)
GX-06	Al_2O_3	0·64	306	306
	26TiCp–Al_2O_3	3·49	–110	–110
	Al_2O_3	0·64	306	306
GX-08	Al_2O_3	0·25	365	365
	26TiCp–Al_2O_3	4·25	–44	–44
	Al_2O_3	0·25	365	365
GX-20	26TiCp–Al_2O_3	0·25	–365	–365
	Al_2O_3	4·25	44	44
	26TiCp–Al_2O_3	0·25	–365	–365
DX-13	10SiCw–Al_2O_3	0·05	–135	–81
	20SiCw–Al_2O_3	0·30	–364	–335
	5SiCw–Al_2O_3	4·03	54	48
	20SiCw–Al_2O_3	0·30	–364	–335
	10SiCw–Al_2O_3	0·05	–135	–81
DX-14	10SiCw–Al_2O_3	0·13	–34	–12
	20SiCw–Al_2O_3	0·19	–262	–267
	10SiCw–Al_2O_3	0·19	–34	–12
	5SiCw–Al_2O_3	3·75	127	117
	10SiCw–Al_2O_3	0·19	–34	–12
	20SiCw–Al_2O_3	0·19	–262	–267
	10SiCw–Al_2O_3	0·13	–34	–12

The laminate configurations and their residual stress distributions are given in Table 3. The designs were restricted to odd-number plies between three and seven. The center ply constituted 60–90% of the total thickness. Designs designated GX-06, GX-08 and GX-20 contain TiC particulate-reinforced alumina (Greenleaf Corp. grade GEM 2), while designs designated DX-13 and DX-14 contain SiC whisker-reinforced alumina. Designs GX-06 and GX-08 have pure alumina outer surfaces to minimize erosion by eliminating carbides from the rake face contact surface. This design, however, results in a residual tensile stress in the outer alumina layer. Design GX-20 produces compressive stresses in the outer layer but exposes the carbide containing material to erosion wear. Designs DX-13 and DX-14 were selected to minimize the carbide content of the outer surface while still resulting in surface compressive residual stresses.

4 SPECIMEN FABRICATION

The outer surface layers of the laminated ceramic structures were fabricated by tape casting. Individual tapes of 0·102–0·152 mm thick and up to 76 mm wide were deposited continuously onto a carrier tape under a spreading blade (Doctor Blade) from which they were separated after drying. The tapes were cast from a formulated slurry comprised of ceramic powder, organic polymer,[10] and solvent. The composition of the slurry provided the required rheological properties for casting, as well as flexibility for handling and shaping of the dried tape. As much as 20 vol% of the unfired laminate was composed of organic additives that must be removed by thermal decomposition or oxidation prior to high temperature densification. The high temperature densification step was performed by hot pressing at 1750°C.

Table 4. Slurry formulations for tape cast surface layers

Composition	Solid volume fraction	Binder volume fraction	Toluene volume fraction
Al_2O_3	0·220	0·609	0·171
5SiC/Al_2O_3	0·219	0·594	0·187
10SiC/Al_2O_3	0·211	0·583	0·206
20SiC/Al_2O_3	0·200	0·554	0·246
30SiC/Al_2O_3	0·171	0·521	0·307
26TiC/Al_2O_3	0·210	0·619	0·171

The processing techniques normally used for producing multilayer laminated ceramic composites were modified in these studies to simplify manufacturing and decrease production time. The previous techniques used tape cast materials to form the entire specimen. This procedure was time consuming due to the time needed for tape casting, cutting and laminating many plies. Long periods were also required to burn out the organic matter prior to hot pressing. Tape casting is still used to form the thin outer layers; however, direct dry powder filling was used to form the thick core. This processing change reduced the number of tape cast layers that needed to be cut and laminated from eighty to twenty. This also allowed the intermediate binder burnout step to be eliminated, since the small amount of binder contained in the outer layers can be burned out during the hot pressing cycle. This process was used to produce nine ceramic tiles 50·8 mm × 50·8 mm × 4·76 mm, designated as DX-13, DX-14, GX-06, GX-08, and CX-20, with a maximum thickness variation of 0·254 mm.

Tape casting slurry mixtures for Al_2O_3, SiC_w/Al_2O_3, and TiC/Al_2O_3 were optimized to provide the proper rheological properties necessary for tape casting while producing a high quality, easily handled tape 0·127 mm thick with excellent uniformity. Slurry formulations are given in Table 4.

5 TESTING AND CHARACTERIZATION

In order to verify the residual stress calculations and the processing techniques, one of the specimens, designated as DX-14, was machined into 4 test bars 4·76 mm × 6·35 mm × 50·8 mm for material property characterization. The four test bars were ground and the edges chamfered to 0·762 mm. The corners were finished to 0·0635 mm radius to minimize the stress concentrations. The remaining plate was machined into cutting tool specimens 12·7 mm × 12·7 mm × 4·76 mm. The density of the DX-14 specimens was measured using Archimedes' principle with water as the liquid medium. The measured value of 3·88 g/cc was within 2% of the expected density for fully solid material. A four-point bend test with a major span of 31·7 mm, minor span of 15·875 mm, and loading rate of 0·51 in/min was used to measure the modulus of rupture (MOR) of the DX-14 material. The elastic modulus of this material was measured using a dynamic resonance technique. The elastic moduli and MOR values for an average of four tests were 380 GPa and 577 MPa, respectively.

The elastic modulus results are within 2% of the rule-of-mixtures (ROM) calculations. The strength of the DX-14 laminate is about 8% greater than would be expected for monolithic silicon carbide whisker-reinforced alumina. Density measurements on the DX-14 material indicate at least 98% of theoretical density was obtained during fabrication of this specimen. This indicates that the hot pressing parameters are sufficient for complete densification The agreement between elastic modulus measurements and ROM predictions indicates that good bonding between fiber reinforcement and matrix was achieved.

6 WEAR PERFORMANCE TESTS

The ceramic tiles were cut into cutting tool specimens 12·7 mm × 12·7 mm × 4·76 mm and tested for cutting performance by measuring nose and either notch or flank wear rate versus cutting time. The insert style of the cutting tools used was Greenleaf Corporation Style SNGN-433. The cutting tool specimens were tested against either Inconel 718 superalloy or 4340 steel in lathing operation using a negative rake angle configuration. The negative rake angle configuration was chosen because it is the most aggressive of all cutting configurations. The performance of the laminated ceramics was compared to the performance of other typical ceramic cutting tools. The testing parameters for the standard tool life tests are given in Table 5.

Table 5. Testing parameters for the standard tool life tests

Material	Allvac 718 superalloy	AISI 4340 steel
Hardness (Rc)	42	28/32
Coolant	Yes	No
Feed (mm/rev.)	0·15	0·25
Speed (m/min)	213	457
Depth of cut (mm)	1·0	1·9

6.1 Cutting tests against 718 superalloy

Four cutting tool materials were evaluated against 718 nickel based superalloy: two grades of TiN reinforced Si_3N_4 (SX-5 and RD-3905), one grade of conventional SiC whisker-reinforced alumina (WG300) and one grade of laminated SiC whisker reinforced alumina (DX-14). Four separate cutting operations were performed on a 718 superalloy billet. The first operation removed approximately 4 mm of material from a 159 mm diameter billet. The second cutting operation removed 2·0 mm of material from the remaining 152 mm diameter billet using unused tools of the same composition as in the first cutting operation. The third cutting operation removed 6 mm from the 141 mm diameter billet with a new WG-300 cutting tool. The last cutting operation removed 2·0 mm from a 133 mm diameter billet using new SX-5, DX-14 and RD-3905 cutting tools. Flank wear in the nose region and in the depth-of-cut region were measured and are referred to as nose and notch wear, respectively. The average wear rates measured after the first cutting operation are given in Table 6.

Table 6. Wear rates for cutting tool materials against 718 nickel based superalloy

Tool material	Average wear rate for nose wear (mm/min)	Average wear rate for notch wear (mm/min)
RDC-3905	0·178	0·051
SX-5	0·117	0·127
DX-14	0·053	0·127
WG-300	0·046	0·300

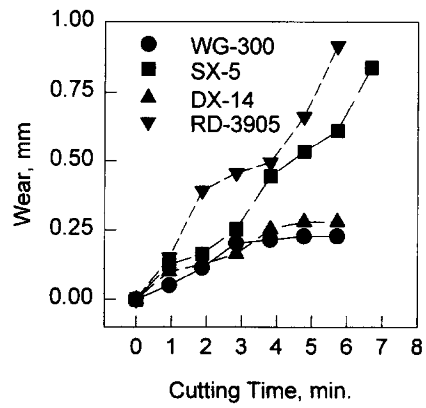

Fig. 1. Nose wear of ceramic composite cutting tools against 718 nickel based superalloy.

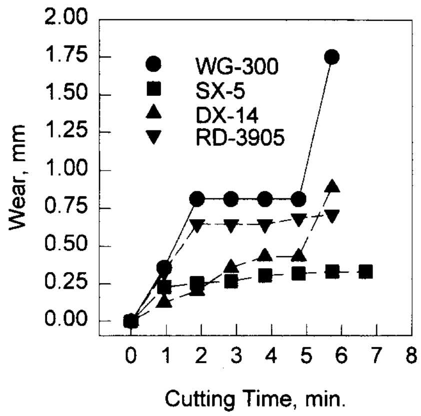

Fig. 2. Notch wear of ceramic composite cutting tools against 718 nickel based superalloy.

Figures 1 and 2 compare the nose and notch wear, respectively, for monolithic materials, WG-300, SX-5 and RD-3905, with the laminated ceramic design DX-14 during the first cutting operation. Both TiN reinforced Si_3N_4 compositions, SX-5 and RD3905, exhibited significantly greater wear than either the monolithic SiC whisker-reinforced alumina, WG-300, or the laminated SiC whisker/alumina hybrid design, DX-14, for up to 5·7 minutes of cutting. The DX-14 specimen experienced chipping at 6·7 minutes of cutting. The notched wear of these materials during this operation (Fig. 2) did not follow the same order of wear resistance as did the nose wear. In this case, the SX-5 material had the best wear performance while the WG-300 had the poorest. Both WG-300 and DX-14 chipped after 4·7 minutes of cutting.

The chipping in the depth-of-cut notch region is clearly seen in Fig. 3. The chipping on the rake face near the nose region of the cutting tool can also be seen in this figure. The nose wear for the SiC whisker composites WG-300 and DX-14 are all low compared to the TiN reinforced Si_3N_4 materials (SX-5 and RD3905) for all subsequent cutting operations.

Fig. 3. SEM photograph of laminated SiC/alumina (DX-14) cutting tool showing large chip near the depth-of-cut region.

6.2 Cutting tests against 4340 steel

One commercially available conventional TiC–alumina cutting tool and various TiC–alumina laminated designs and one SiC whisker/alumina design were tested against 4340 steel. In these tests, each of the eight corners of the cutting tool were subjected to increasing cutting times. Figure 4 shows a comparison of nose wear for the conventional and laminated TiC/alumina composite and a laminated SiC whisker/alumina cutting tool material. The nose wear data for these tests appear to fall into three groups. The TiC/alumina composite laminate designs GX-06 and GX-08 have the highest wear rates, while the design GX-20 has the lowest wear rate. The former two designs use alumina on the outer surface which results in a residual tensile stress in that layer. The latter design uses TiCp–alumina as the outer layer and results in a substantial residual compressive stress. The conventional TiCp–alumina cutting tool material has a wear rate between these two designs.

The results of these tests indicate that the cutting performance of ceramic cutting tools is influenced by the state of residual stress in the material. A typical wear surface is shown for laminate design GX-20 in Fig. 5. Both the wear land in the nose area and in the flank area are similar. Errosive wear is seen to extend from the depth-of-cut notch to the nose area on the rake face. A laminated SiC–alumina design (DX-13) cutting tool was also tested against 4340 steel. The wear surface for this cutting tool is shown in Fig. 6. The low flank and nose wear for this tool design is

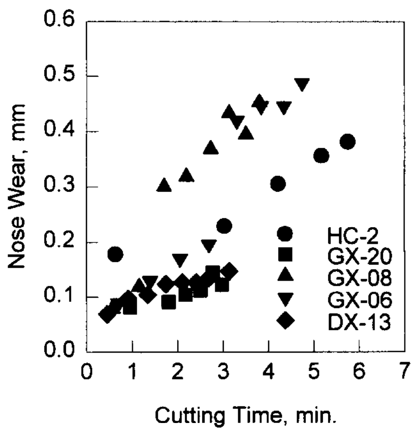

Fig. 4. Nose wear of various laminated ceramic composites against 4340 steel.

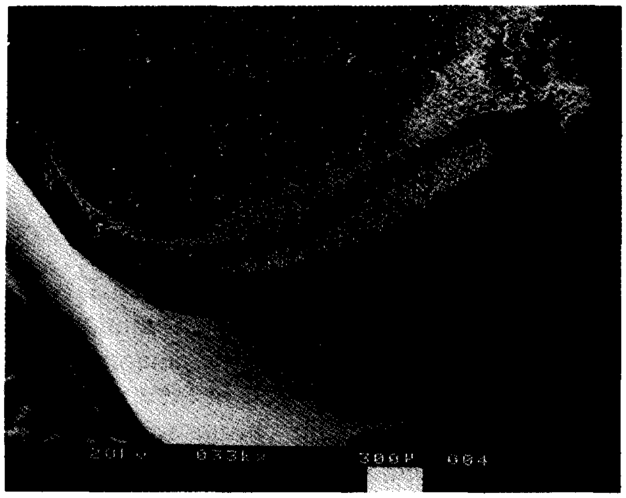

Fig. 5. Wear surface of laminated TiCp–alumina cutting tool (GX-20).

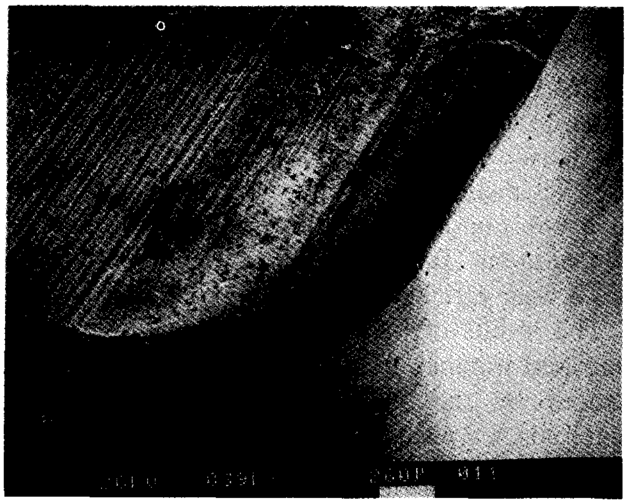

Fig. 6. Wear surface of laminated SiCw–alumina cutting tool (DX-13).

quite obvious in this figure. However, there appears to be cracking in the bottom of the crater wear scar on the rake face. These cracks are confined to the surface layer and are terminated before they reach the region of residual tensile tress.

7 DISCUSSION AND CONCLUSIONS

The objective of these experiments was to determine if thermoelastic and wear properties could be optimized by laminate design to improve cutting tool performance. The tool wear in actual cutting operations is a complex phenomenon, which, among other things, depends upon the homogeneity of the metal being cut and the distribution of flaws in the cutting tool. For these reasons, standard cutting tool tests normally produce large amounts of scatter. Nevertheless, the results of the tests performed in this work provide a reasonable indication of the effect of laminate tailoring.

The design concept is to avoid large differences in residual stress between layers while still providing reasonable compressive stresses in the outer layer (i.e. the rake face surface). This may require a large number of different layer compositions as demonstrated in the design DX-14. The residual stress criteria, however, may be in conflict with the need to minimize wear and erosion resistance; hence, some designs that contained tensile stresses in their outer layer were evaluated (e.g. GX-06 and GX-08).

The results of this study showed that both composition and residual stress patterns affected the cutting tool performance. The SiCw–alumina cutting tool compositions exhibited greater resistance to nose wear than TiCp–alumina compositions for cutting nickel based superalloy 718. The conventional SiCw–alumina composition, however, is not as resistant to notch wear as the TiNp–Si_3N_4 tool materials. Low notch wear was, however, retained for the laminated version of the SiCw–alumina cutting tool. The lamination process which produces surface compressive stresses results in ceramic cutting tool materials with improved wear performance compared to laminated designs which produce surface tensile stresses. The laminated design with surface compositions similar to the composition showed superior wear performance compared to the conventional tool material design.

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