1973

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John U. E. Shroyer
Lehigh University

Recommended Citation
Shroyer, John U. E., "An evaluation of titanium carbide coated tungsten carbide tools" (1973). *Theses and Dissertations*. 4138.
https://preserve.lehigh.edu/etd/4138

AN EVALUATION OF TITANIUM CARBIDE COATED TUNGSTEN CARBIDE TOOLS

by

John U. E. Shroyer

A Thesis
Presented to the Graduate Committee
of Lehigh University
in Candidacy for the Degree of
Master of Science
in
Department of Industrial Engineering

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

26 April 1973
(Date)

George E. Kane
Professor in Charge

Chairman of Department

ACKNOWLEDGEMENTS

I Express my gratitude to Professor George E. Kane for his guidance and patience during the course of this thesis; and to Mr. Gilbert Zambelli for his much needed assistance during the laboratory exercises. In addition, I thank my parents, D.L. Sutphen, and V.J. Byrd for putting up with me during this time.

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ABSTRACT

Since the introduction of the titanium carbide coated cemented carbide tools in 1969 by no fewer than five manufacturers, several independent studies have acknowledged the superior performance of these tools over the non-coated carbide tools. Since that time the popularity of coated tools has increased. Several manufacturers introduced two TiC coated steel cutting grades which were specifically recommended as a roughing operation grade and a finishing operation grade. Meanwhile several manufacturers of TiC coated carbides did not recognize a difference between roughing and finishing operations by producing only a single coated grade for both roughing and finishing operations.

In this experiment each tool produced by a particular manufacturer was tested at a set of roughing and finishing machining conditions for a turning operation of 4340 heat treated steel to determine if any significant differences in performance existed between the roughing and finishing grades in their respective recommended areas of application. The parameters of performance were conventional flank wear and surface roughness. From this experiment it was concluded that there was very little, if any, significant difference in performance between the two TiC coated grades over

the set of roughing and finishing conditions; and consequently, there is no need for two steel cutting TiC coated grades. The manufacturers of the single-grade steel cutting coated tools were justified in their decision to produce only one grade for both operations. In general, the single-grade coated tools performed significantly better than the multi-grade coated tools. Also, the TiC coated tools were found to perform significantly better than uncoated roughing and finishing tools because of the titanium carbide coating's ability to inhibit the abrasive, thermal, and diffusion mechanisims of tool wear.

INTRODUCTION

One of the most universal and timely dilemmas which confronts the metal removing industry is the need for improved cutting tools. Because of the tremendous advances made in materials, material research technology, and increasing pressures on productivity in the last decade; tool manufacturers are forced to innovate and supply new tooling to meet these needs. One of the tool industry's latest innovations is the titanium carbide (TiC) coated cemented carbide which was introduced in 1969 (1).

Basically the titanium carbide (TiC) coated carbide is no more than a standard cemented carbide grade which is coated on all surfaces with an extremely thin layer of titanium carbide. The thickness of this layer is generally between .0002 and .0004 inches.

By introducing the titanium carbide coated tools, the manufacturers help solve the "hardness-toughness" dichotomy that has plagued tungsten carbide tools since their introduction. This dichotomy is the inverse relationship which exists between the magnitude of hardness and the magnitude of toughness for a particular cutting tool grade. Previous to the coated tools' introduction; if the hardness of the cutting tool was high (good wear resistance), the toughness was low (poor mechanical shock resistance). The converse also followed.

However, if a tough carbide grade is coated with an extremely hard, thin layer of titanium carbide, the resulting cutting tool is one which exhibits the excellent wear resistance properties of TiC and the mechanical shock resistance properties of the tough substrate chosen at both room and elevated temperatures (1,2,3,4).

Manufacturers Performance Claims

In addition to the immediate solution of the hardness-toughness dichotomy, the manufacturers of TiC coated carbides have highly touted the increased performance obtained by using TiC coated inserts on operations previously performed by non-coated tools (5,6,7,8). A brief summary of the claims afforded the coated tools is as follows:

1. increased tool life
2. increased resistance to cratering
3. decreased tool-tip temperatures
4. decreased coefficient of friction
5. decreased flank wear
6. decreased surface finish roughness
7. decreased operating tool forces
8. decreased diffusion wear
9. decreased tool inventory
10. increased productivity

Indeed, the list of improvements attributed to the use of TiC coated inserts over their non-coated relatives is impressive, if not lengthy, and is not without the manufacturers' support in the form of numerous field and laboratory comparisons (2,4,5,6,7,8,9).

Besides the manufacturers' documentation of their superior performing tools, there exists an increasing number of independent institutions whose experimentation and research with TiC coated tools has yielded favorable results (1,3,10,11). The recent research efforts of Nam Suh, (12,13,14), in the area of oxide coatings on tungsten carbide tooling has produced parallel results. Suh, and his associated have determined that various oxides, when deposited on WC tools, increase tool performance because the oxide layer diffuses into the carbide substrate and forms a superior mass diffusion barrier against unwanted elements during steel cutting operations. Also, the oxide layer coated tools reflect lower coefficients of friction at the cutting interfaces than do non-coated tools; therefore, lower cutting forces and temperatures are experienced.

It is quite possible to assume that TiC coatings function in the same manner as the oxide coatings; that is, the increased performance observed may be attributed to TiC's ability to form a diffusion barrier. However, it is not possible to determine exactly how much of the improvement is due to TiC's wear resistant properties, or how much of the improvement is due to TiC's anti-diffusion properties.

The results of all of the research conducted seem to reflect two things; the remarkable physical properties and performance characteristics of TiC which retard the mechanisims of wear, and the importance of a bond of high integrity. Like most present-day manufacturing practices, TiC and TiC bonding techniques are the result of the later-day endeavors discussed below.

History of TiC and TiC Bonding

Titanium carbide and titanium carbide bonding processes are not recent innovations. In 1887, Shimer first identified TiC while conducting experimental work with cast iron (3). Eight years later, in 1895, Moissan produced TiC by reducing TiO_2 in the presence of carbon, and also developed the electric furnace in which this reduction was conducted. Moissan's basic carbon reduction process, although modified, is still the basis of certain operations for preparing TiC (3).

The basic process of applying a coating of TiC is the chemical vapor deposition (CVD) process. This process was demonstrated by the German chemist Moers some 40 years ago. TiC was deposited on a heated filament at 1700°C (3000°F) in an atmosphere of titanium tetrachloride, hydrogen, and toluene. Today, the process is somewhat different; the reaction proceeds at a lower temperature, 1650°F-1950°F, and methane is substituted for toluene. These refinements of Moer's process have resulted in a coating which is a highly dense, zero porosity, layer of pure TiC (3).

Current TiC Coating Processes

The chemical vapor deposition process used today was developed by Metallgesellschaft A.G. of Frankfort/ Main, Germany approximately ten years ago. The process was used to apply TiC coatings to "suitable tool steels and cast iron" (11). The process is as follows:

> "Titanium carbide is formed from the vapor phase reaction of titanium tetrachloride ($TiCl_4$) and gaseous hydrocarbons (CH_4)" (11).
>
> "This reaction occurs in a sealed reaction chamber (retort), at an elevated temperature (1650-1950°F), by passing two separate reaction gases into the coating or reaction chamber. One gas is a dry hydrogen plus titanium tetrachloride. The other gas is a dry hydrogen plus a gaseous hydrocarbon (CH_4). The reaction of these gases with themselves and with the base material to be coated, in accordance with the following equations, produce the TiC coatings:" (11)

$$\underset{\substack{\text{Titanium}\\ \text{Tetrachloride}}}{TiCl_4} + \underset{\text{Methane}}{CH_4} \text{ at } \xrightarrow[\text{Hydrogen}]{(1650\text{-}1950°F)}$$

$$\underset{\substack{\text{Titanium}\\ \text{Carbide}}}{TiC} + \underset{\substack{\text{Hydrochloric}\\ \text{Acid}}}{4\,HCl}\,.$$

Importance of the Titanium Carbide Bond

The integrity of the bond formed by the chemical vapor deposition method is dependent upon the cleanliness of the surfaces to be coated, the preparation of the surfaces to be coated, the purity of the reacting gases, and the integrity of the reaction system. The failure to provide these necessary conditions, in part or whole, will result in a bond which is porous, chemically contaminated, and lacking in hardness and wear resistance (3).

In addition to the CVD coating process, three other TiC coating processes exist: flame spray, diffusion, and sintering. Because of the poorer porosity, greater coating thicknesses, and larger TiC grain size of the coating obtained through the use of these processes; they should not be used as coating processes for carbide tooling (3).

The importance of a high integrity bond between the TiC and its carbide substrate cannot be overstated. A contaminated, porous, and/or non-uniform bond inevitably leads to the loss of the advantageous TiC coating, and the subsequent loss of TiC's performance characteristics. The cutting tool's performance will then resemble the performance of the original unprotected substrate carbide (2). That is, crater and flank wear will be increased because the diffusion and abrasion barrier of TiC is lost. Also, the natural lubricity of TiC with its associated low coefficient of friction and anti-welding properties will no longer aid the reduction of built-up-edge and cutting interface temperature problems. The conventional cutting forces encountered during machining will also increase significantly if the coating is breached (4).

Importance of the Substrate

From the preceeding discussion it becomes apparent that the TiC coating, if bonded properly, is the major contributing element to better tool performance. It would seem that the choice of substrate material is of secondary importance. McKee and Brierley (2) agree that the differences in crater and flank wear between uncoated carbide tools is narrowed by the introduction of the TiC coating. However, the areas of ultimate tool wear, deformation, and thermal crack resistance are still governed by the substrate; depending upon the operation and the material being cut. For example, in the machining of grey cast iron or non-ferrous materials a WC-Co type grade would be a probable choice since WC-Co grades exhibit superior abrasion resistance. But, the use of a WC-Co grade for high speed machining of steel could lead to chipping or catastrophic breakage.

One should not expect superior performance from a coated tool if there has been no engineering judgement exercised in the selection of the substrate grade.

Consideration of the nature of the operation, material, and cutting conditions must be made. The coating itself is not going to totally outweigh or significantly alter the inherent performance characteristics of an improperly chosen substrate grade.

A brief glance at the coated tool manufacturers' product catalogues reveals a certain concern for this in that several grades of coated tools are available.

TiC Coated Carbides of Various Cutting Grades

Generally, the TiC coated grades fall into two basic categories: cast iron and steel. Of the five manufacturers of coated inserts reviewed, two manufacture cast iron cutting grades as well as steel cutting grades. The remaining three manufacturers have not, as yet, introduced the cast iron grades; but have steel cutting grades available.

It is quite understandable that it is difficult, if not impossible, for a single carbide grade to perform optimally on both cast iron and higher-speed steel cutting operations. Therefore, the distinction which is recognized by the introduction of both grades is highly justified. There would be little doubt in the consumer's mind that he would prefer the cast iron grade when cutting cast iron. Since there is only one coated cast iron grade available per manufacturer, the consumer has only to decide from whom to purchase the tool.

The process of selecting a coated tool for steel machining operations becomes more than just a question of the lowest bid. Three of the manufacturers of coated tools produce two steel cutting grades. They have referred to these as a "general purpose" grade, and a "finishing purpose" grade. On the other hand, two manufacturers offer a single grade which is labeled as a "general purpose" or a "light to medium roughing and semi-finishing operations" grade.

In essence, the two-grade manufacturers are suggesting that the differences between general and finishing operations are so large that there must be a coated tool grade for each of these operations for optimal performance. Meanwhile, the single grade manufacturers are suggesting that the differences between general and finishing operations are narrowed and virtually eliminated by the use of a TiC coated tool; therefore, a single grade will produce optimal results for both operations.

In addition to the basic confusion of these two ideologies is the lack of any firm guidelines for the use of these steel cutting grades, thus augmenting the difficulty of grade selection. Both single, and multi-grade manufacturers hedge at the limits of useful application. A glance at the multi-grade manufacturers' product literature shows some doubt and overlapping of the areas of application. It is certain that any consumer who is knowledgeable of the product arrays of the coated tool manufacturers will not know whether to buy and stock two TiC coated steel cutting grades, one cutting grade, or some mixture of grades from several manufacturers.

Since the manufacturers are in conflict as to how many coated steel cutting grades are necessary, there is the need to determine if any differences in performance exist within and between the two-grade system, and the single-grade system over a range of roughing and finishing cutting operations. If the manufacturers who support the two-grade system are right, the general purpose tools will outperform the finishing purpose tools for the general cutting cases; and vice-versa. If it is shown that there is little or no difference in performance of the two grades for either roughing or finishing operations, the manufacturers of the single coated grade system will be correct in their decision to manufacture only one coated steel cutting grade.

EXPERIMENTAL DESIGN AND PROCEDURE

Objectives

The objectives of this experiment were to determine if there were any significant differences in performance between:

1) the roughing and finishing TiC coated grades offered by the manufacturers of there grades;
2) the multi-grade manufacturers and the single-grade manufacturers; and
3) the TiC coated carbide tools and the uncoated carbide tools.

The experiment was a fixed factorial experiment comprised of four independent variables and two dependent variables.

The four independent variables were: tools (10 levels, 8 coated with TiC, and 2 uncoated), type of operation (2 levels, roughing and finishing), cutting speed (2 levels) and the duration of cutting (4 levels).

The two dependent variables were conventional flank wear, and surface finish roughness. These variables are considered to be the most common parameters of performance in the metal removing industry, and were considered as such for this experiment. Also, any accompanying abnormalities which occurred to the tool during the experiment were observed, measured, and recorded.

Since the emphasis of this experiment was placed upon discerning any differences in performance between these coated and uncoated tools and manufacturers, the possibility of creating more interdependencies and confusing interactions is limited by chosing a single work material, tool geometry, and machining category.

Discussion of the Independent Variables

Tool Selection-

The tools chosen form three categories:

1) manufacturers who produce two TiC coated steel cutting grades;
2) manufacturers who produce one TiC coated steel cutting grade;
3) and uncoated carbide steel cutting grades.

Three manufacturers produce a roughing and finishing coated grade; therefore, 6 tools belong to the first category. Two manufacturers produce a single coated grade (2 tools), and one uncoated carbide roughing and one uncoated finishing grades were selected as a control group. This gives a total of ten tools. To aid in the reduction of experimental error, all tools were of the one-half inch square indexable throw-away type, all had honed cutting edges, and all had the same tool geometry.

Type of Cutting Operation, Speeds, and Times-

The major objective of this experiment was to determine if the roughing and finishing grades perform best under roughing and finishing operations respectively. Therefore, two combinations of feed and depth of cut were chosen. Each was to reflect typical industrial roughing and finishing parameters. The roughing condition had .020 in./rev. feed and .050 in. depth of cut. The finishing condition had .005 in./rev. feed and .020 in. depth of cut.

A pilot experiment was conducted in order to establish the two levels of speed desired for each operation, and the four intervals of cutting duration. It was decided that the upper limit of speed and time should produce near-failure (.030 in. flank wear, or loss of the cutting edge) on an uncoated tool.

The results of this pilot experiment yielded speeds of 200 and 300 sfpm,and 500 and 800 sfpm for the roughing and finishing operations respectively. The upper limit for the duration of the cuts was 7 minutes, with intermediate intervals at 1, 3, and 5 minutes.

Discussion of Fixed Variables

The machining category was fixed to a simple outer diameter turning of 6" x 54" bar stock on an engine lathe. Other basic machining operations such as milling and shaping would introduce the more complicated thermal fatigue cracking wear phenomena which was not to be evaluated by this experiment.

The work material was fixed to SAE 4340 heat treated steel in the form of 6" diameter by 54" long bar stock, Rockwell C-35-37. This material approaches the "hard" materials category, and would be a sufficient test of the red-hardness properties of the coated and uncoated tools.

The tool geometry was fixed to SNG 433 with a basic negative geometry of: BRA -5, SRA -5, FCA 5, SCA 5, ECEA 15, SCEA 15, and NR 3-64ths. inches. This geometry ensured these inherently brittle carbide tools of some cutting edge support by having negative rake angles, small clearance angles, and a small end cutting edge angle. Also, there is protection against vibration and chattering because of the small side cutting edge angle and small nose radius.

Discussion of the Dependent Variables

The two dependent variables are conventional flank wear and surface finish roughness.

The flank wear viariable was measured by a toolmaker's microscope for the particular tool, cutting condition, and speed at the end of the first minute of cutting. It was then measured at two minute intervals until the tool either failed or seven minutes of cutting elapsed. Failure was defined as .030 inches of flank wear, or as the loss of the cutting edge by any mechanism of wear. If a tool failed before seven minutes of cutting, a value of .030 in. was assigned to the remaining time intervals to ensure a complete matrix for analysis.

The surface finish roughness was measured by a portable stylus-type surface roughness instrument. A measurement was taken for each flank wear measurement. If tool failure occured prior to seven full minutes of cutting, the roughness measurement was taken at that time and applied to any remaining time intervals to complete the data matrix.

Since there were 10 tools, 2 cutting operations, 2 cutting speeds/operation, 4 time intervals, and 2 replicates, the number of observations of flank wear and surface roughness was 320 (10 x 2 x 2 x 4 x 2=320). The raw data is arranged and presented in Appendix-A.

Experimental Precautions Exercised

1) In order to ensure constant surface speeds with changes in workpiece size, a frequency alternator was coupled to the AC driven lathe. A very accurate hand-held cumulative tachometer was used to measure the actual speed of the revolving workpiece, and the frequency alternator could be adjusted accordingly.

2) When a particular cut was to be terminated, the feed was stopped first, the tool withdrawn, and the rotation of the workpiece stopped, in that order. This helps to guard against any unnecessary chipping and breakage of the tool.

3) When the diameter of the bar stock approximated 3 inches, the bar was removed and replaced with a new

bar from the same heat.

4) When a full longitudinal "pass" on the bar was completed, a "pass" was taken on the bar with a roughing tool in order to generate a homogeneous cutting surface for further cutting.

5) The diameter of the bar was recorded for each replicate for the purposes of explaining some of the variation, if any, between replicates made at different diameters.

6) The built-up-edge deposits, if any, were removed from the tool before the flank wear measurement was taken.

7) The tool holder was recentered, if needed, for each change of the bar stock.

List of Independent Variables

1. Tools:

a. Sandvik G.C. 135	TiC Coated	(Roughing)
b. Sandvik G.C. 125	TiC Coated	(Finishing)
c. G.E. Carboloy "516"	TiC Coated	(Roughing)
d. G.E. Carboloy "514"	TiC Coated	(Finishing)
e. Firth Sterling TC+	TiC Coated	(Roughing)
f. Firth Sterling TC+1	TiC Coated	(Finishing)
g. V.R. Wesson Ti-Bond-1	TiC Coated	(General Purpose)
h. Kennametal KC-75	TiC Coated	(General Purpose)
i. G.E. Carboloy 370	Uncoated	(Roughing)
j. G.E. Carboloy 350	Uncoated	(Finishing)

2. Cutting Conditions:

Roughing Cut-
Depth of Cut = .050 inches (constant)
Feed Rate = .020 inches/revolution (constant)

a. @ 200 surface feet/minute
b. @ 300 surface feet/minute

Finishing Cut-
Depth of Cut = .020 inches (constant)
Feed Rate = .005 inches/revolution (constant)

a. @ 500 surface feet/minute
b. @ 800 surface feet/minute

3. Time Intervals for Measurement:

a. 1 minute
b. 3 minutes
c. 5 minutes
d. 7 minutes

4. Work Material (constant):

SAE 4340 Heat Treated Steel 6" diameter by 54" long Bar Stock Rockwell "C", 35-37

5. Tool Geometry (constant):

SNG 433, -5, -5, +5, +5, +15, +15, 3.

6. Machining Operation (constant):

Turning an Outer Diameter with an Engine Lathe

<u>List of Dependent Variables:</u>

1. Flank Wear

2. Surface Roughness

3. Additional Observed Phenomena(on)

<u>List of Equipment:</u>

1. Le Blond 16" Heavy Duty Engine Lathe

2. Varidyne Frequency Alternator

3. Jagabi Hand-Held Cumulative Tachometer

4. Assorted Micrometers
5. Toolmaker's Microscope
6. Brush Portable Surfindicator
7. Lehigh University CDC 6400 Computer and Facilities

Procedure

1. The experimental conditions and replications are randomized to lesson the chances of obtaining unrepresentative data.
2. The lathe is prepared according to the first, or next cutting condition stipulated by the randomizing.
3. The work material is cut for 1 minute.
4. The flank wear, if any, and the surface roughness are measured. Any other phenomena(on) is observed and measured.
5. The data is recorded.
6. Steps 3.-5. are repeated for the additional three two-minute cutting intervals.
7. Steps 2.-6. are repeated for the remaining 316 observations.

RESULTS

The flank wear and surface roughness data is presented in Appendix-A. For ease of comparison, the data is arranged by tool manufacturer; that is, the roughing grade's and finishing grade's data for that manufacturer appear on the same page. The two single-grade manufacturers and the uncoated roughing and finishing tools are grouped in the same fashion.

Appendix-A also presents two additional measurements. The first of these is the magnitude of thermal discoloration which appeared on the wear land of the tool which was similar in shape and location as the flank wear. The measurement is made along the vertical distance of the flank of the tool with its initial end-point as the flank-face interface.

The other phenomenon appearing in Appendix-A is the "chipping" or "popping" of the TiC coating from the substrate of some tools during the roughing operations. The location of this "popping" is directly under the observed flank wear, but not at the cutting edge, and appears as a thin band which horizontally wraps itself around the nose radius portion of the tools. The measurement taken is the height of this band along the flank. The "popping" is not evident during any of the finishing operations. Because of its infrequent and selective appearance it is not suited for rigorous statistical analysis.

Preliminary Data Analysis

Before any significant and quantitatively supported conclusions can be drawn from this data, it is necessary to test the integrity of the data.

The item which is questionable is the effect of changing workpiece diameter on the replicates. The entire data matrix was subjected to a pilot analysis of variance test using the Lehigh Amalgamated Package for Statistics program (LEAPS) designed by Frank W. Koko, and the Lehigh University Computing Center and its facilities. This test confirmed that the changing diameter had no significant effect on the replicates' flank wear and surface roughness data. The error mean square comprised only 2.5% and 1.6% of the total variation observed for the flank wear and surface roughness observations respectively. Also, the error mean square includes all other experimental sources of error; such as, the consistency of measurement, and the consistency of the work and tool materials. Therefore, no mathematical transformations must be performed on the data.

Data Analysis

Appendix-B contains the analysis of variance tests for the flank wear and surface roughness data. Because the two sets of cutting conditions, roughing and finishing, must be considered as mutually exclusive cutting environments for the purpose of this experiment, it is necessary to have an analysis of variance for each environment. The analysis of variance test used was from the LEAPS package designed by Koko, of Lehigh. The factors which are evaluated by each test are the effects of changes in tool material, cutting speed, cutting time, and their interactions on flank wear and surface roughness.

The criteria for the significance of these effects is the F-Ratio, which is the ratio of the mean square of the particular effect under comparison, and the mean square of the error term. The sign,*, denotes significance at the 95% and/or 99% level of confidence.

Appendix-C contains the correlation matricies for the variables recorded. The flank wear, surface roughness, thermal discoloration, and "chipped" coating measurements were correlated for any general dependencies or relationships which may be present between these variables. The LEAPS package was also used for these tests.

Appendix-D shows the results of the Student-T tests for flank wear and surface roughness which were performed by the computer to detect any significant differences between the mean performance of the roughing and finishing coated tools within a particular manufacturer. They were also applied to detect any differences in the performance between the single grade coated tools offered by two manufacturers, and to the two uncoated control group roughing and finishing tools.

These T-tests were conducted at each level of speed, and cutting operation. One set of tests was performed for the overall time periods, and one set of tests was performed for the values at the end of seven minutes of cutting. A 95% level of confidence was chosen as the criterion for a difference to be significant, and the sign, *, indicates significance. The particular Student-T test used was the "BMDX70" program from the <u>BMD Biomedical Computer Programs</u>, published by the University of California Press, Berkeley and Los Angeles, 1968.

Appendix-E shows the results of the Tukey tests (16,17) which were designed to compare the average of one group of means with the average of another group of means. The groupings tested were the multi-grade coated tools verses the single-grade coated tools; and the coated tools verses the uncoated tools. These tests were conducted for the flank wear and surface roughness values obtained for the overall experimental means. All tests for significance are at the 1% level of confidence.

Appendix-F lists the results of the Duncan Multiple Range Tests (15) performed on the mean flank wear and surface roughness observations for all tools. The purpose of this test is to significantly rank all tools in order of their performance. These tests are conducted at the roughing and finishing operation levels, and for the overall experiment. All results are at the 1% level of significance.

DISCUSSION OF RESULTS

Analysis of Variance for the Roughing Operations

Flank Wear-

The analysis of variance for the flank wear (Appendix-B) observed for the roughing operations showed that all factors and their interactions were significant at the 95% level of confidence. The factors significantly affecting the flank wear in order of their magnitude were speed, time, and tools. The mean flank wear was 7.4×10^{-3} inches, and no tools suffered failure.

Speed accounted for 61% of the variance for the flank wear observed, and had a large F-Ratio of 1436.7 . The mean flank wear for all tools increased from 4.88×10^{-3} inches at 200 sfpm to 9.33×10^{-3} inches at 300 sfpm. This difference was due to the complicated combination of increased forces, temperatures, material removal rates, and abrasion rates. All tools reflected this increase in flank wear.

The factor of time significantly increased flank wear for all of the tools; that is, with an increase in time, flank wear also increased. Time accounted for 11.9% of the variation observed. This supports the theory of cumulative flank wear over time.

Although the tools were found to have a significant effect on flank wear, only 3.5% of the variation observed was attributed to them. This suggested that the changes in speed and time were more responsible for changes in flank wear than were the changes in the various tools; thus,this indicates that tool performance was relatively uniform.

Surface Roughness-

The mean surface roughness for these roughing conditions was 235.4μinches. The analysis of variance for the surface roughness at the roughing operation level produced different results than the analysis of the flank wear. The changes in tools and speeds were found to significantly affect the surface roughness. In this case the tool factor was most important, suggesting that surface roughness was more dependent on the particular tool than was flank wear. However, time was not found to be a significant contributor. Also, all interactions which contained the time factor were not significant. This showed that surface roughness was independent of time; and therefore, independent of flank wear since flank wear is dependent upon the time of cut. The correlation matrix in Appendix-C supported this because the correlation coefficient is only .1330 . Hence, it seemed that the portion of the tool which exhibited flank wear was not the portion of the tool which produced surface roughness for the roughing conditions.

Thermal Discoloration-

The thermal discoloration which was observed on the flank portion of the tool was not subjected to the analysis of variance test because it merely accompanies flank wear. This discoloration occurred on both the coated and uncoated tools. The phenomenon of discoloration is the oxidation of the tool's surface due to the extreme localized temperatures encountered at the cutting edge and flank of the tool during machining.

The correlation matrix showed a very positive coefficient, .5718, between this discoloring and flank wear. However, there is almost no correlation between this phenomenon and surface roughness.

Loss of Coating-

The "chipping" or "popping" of the TiC coating from the substrate of some of the coated tools was a phenomenon which was neither strongly correlated with flank wear, .2566, or surface roughness, -.1699. There was no evidence that tools which had lost their coating had experienced greater flank wear. This phenomenon apparently occurs only when some minimum threshold of temperature and mechanical stresses are placed upon the tool. For instance, the higher cutting speed, 300 sfpm, was responsible for the majority, as well as the largest of the observations. This level of speed, coupled with the level of feed, and depth of cut produced "popping"; however, no "popping" was observed for the finishing operations which proceeded at 500 and 800 sfpm. This suggests that the loss of coating may be more dependent on the feed and depth of cut than on speed.

Had the loss of coating been at the cutting edge instead of beneath the lowest portion of the flank wear, the observed flank wear might have increased. Also, had the cutting times been increased, the loss of coating may have continued and the flank wear may have been affected.

Analysis of Variance for the Finishing Operations

Flank Wear-

The analysis of variance for the flank wear (Appendix-B) for the finishing operations showed that all factors and their interactions were significant at the 95% level of confidence. The mean flank wear was $9.1\text{x}10^{-3}$inches, $1.7\text{x}10^{-3}$inches greater than the roughing operations. Paralleling the roughing conditions, the most significant factor was speed, followed by time, and tool type.

Speed accounted for 39.6% of the variation in flank wear, with the mean flank wear increasing from $3.99\text{x}10^{-3}$inches to $9.35\text{x}10^{-3}$inches at 500 and 800 sfpm respectively. No doubt the major contributor to this large increase was the increased temperatures associated with 800 sfpm cutting speed. This was supported by the loss of the red-hardness properties of the uncoated 370 grade, and subsequent smearing of the nose of this tool.

The significant time factor contributed 14.3% of the variation observed and was quite similar to that observed for the roughing conditions.

The tool type factor appears to be more significant on the flank wear observations for these finishing conditions than it was for the roughing conditions.

Surface Roughness-

The mean surface roughness for the finishing operations was 38.1μinches. This was a great improvement over the 235.4μinches for the roughing conditions. The improvement is due to the lighter feed, depth, and higher cutting speeds which ensures a clean shearing action at the tool-work interface and less plastic deformation type shearing.

All major factors were significant at the 95%level, but only one interaction, time-speed was significant. Unlike the roughing observations of surface roughness, the time factor was most significant here. This suggested that the surface roughness was dependent on the flank wear exhibited by the tool since flank wear is dependent on time. The correlation matrix in Appendix-C justified this with a strong positive coefficient of .5613 between flank wear and surface roughness.

Thermal Discoloration-

The thermal discoloration was present on the flank portion of the tool, and the correlation coefficient associated with flank wear was again quite high at .8199. Since the surface roughness and flank wear are positively correlated (.5613), then the thermal discoloration should also be positively correlated with surface roughness. This coefficient was .5161 and agreed with the .5613 surface roughness-flank wear coefficient, but this discoloration is a by-product of temperature and not a cause of surface roughness or flank wear.

Coated Roughing Tools vs. Coated Finishing Tools

Three manufacturers produce a coated roughing grade and a coated finishing grade, and each suggests that the roughing grade performs best under roughing conditions and the finishing grade performs best under finishing conditions.

Appendix-D shows the results of testing the hypothesis that the performance between roughing and finishing coated grades within a manufacturer is different. In order to ensure that a significant difference actually exists, the hypothesis was tested at the 95% level of confidence. The tests were applied to the flank wear and surface roughness data at each level of speed for both operations. If significant differences are present they would be more discernable at the higher speed for each operation. Also, by testing at the seven minute interval, it is possible to concentrate on the total or final flank wear and surface roughness observed. Although tests appear for the mean performance over the entire seven minute intervals, the ability of these tests to detect differences is shrouded by the initial "breaking in" periods of the tool substrates. It was felt that the seven minute interval would minimize these differences in "breaking-in" periods between tools, and reflect a more stabilized, uniform cutting situation with the substrates being in steady equilibrium.

Performance constraints also accompany these comparisons in two areas: tool failure, and acceptable surface roughness. A tool is judged unacceptable in a specific category if it has failed (≥.030 inches flank wear, or loss of cutting edge), or does not produce a surface roughness of ≤ 250μinches and ≤ 63μinches for roughing and finishing operations respectively. These are commonly accepted industrial criterion for performance.

Firth Sterling TC+ vs. TC+1

Firth Sterling's TC+ and TC+1 do significantly differ in performance but not according to their claims.

Roughing Operation Comparison-

At 200 sfpm there was no significant difference in flank wear, however the roughing grade (TC+) produced significantly less surface roughness (189μin. vs. 252μin.).

At 300 sfpm TC+ produced significantly greater flank wear than TC+1 (.0171μin. vs. .0089μin.), but a significantly better surface finish (222.5μin. vs. 315μin.) Although TC+ exhibited greater flank wear its surface roughness was quite acceptable. The finishing grade produced a surface finish which was at an unacceptable level of 315μinches; therefore,it was eliminated and TC+ was upheld as the proper grade for the roughing operations.

Finishing Operation Comparison-

No significant differences were found to exist between TC+ and TC+1 at 500 sfpm. Neither tool failed or produced a surface finish greater than 63μinches.

The results at 800 sfpm also show no significant differences for either performance parameter or tool. Since no significant differences in performance were observed at the finishing level, either tool was acceptable for these operations, but this does not justify the need for two TiC coated grades. Because the roughing grade, TC+, was found superior at the roughing level, and was not found unacceptable or worse than the finishing grade, TC+1, at the finishing level, the need for the additional TC+1 finishing coated grade is not justified at either level, and should be discontinued.

G.E. Carboloy 516 vs. 514

G.E. Carboloy's 516 coated roughing grade and 514 coated finishing grade exhibit significant differences in performance which partly favor the manufacturers claims.

Roughing Operation Comparison-

Appendix-D shows a significant difference in flank wear between 516 and 514 (.004in. vs. .0055 in.) at 200 sfpm. However there was no difference in surface roughness, 235μin. for both tools, and neither tool suffered failure or unacceptable surface roughness.

At 300 sfpm no significant differences are noted; however, the 516 roughing grade had a 262.5μin. surface roughness which exceeded the accepted upper limit of 250μinches. Therefore, the roughing tool does not perform adequately, but the finishing grade 514 is wholly acceptable in terms of flank wear and surface finish.

Finishing Operation Comparison-

The 500 sfpm data does not show significant differences in flank wear and surface roughness for both tools which suggests that either tool could be used for this operation. At the higher speed, 800 sfpm, the 514 finishing grade produced a significantly better surface finish. Since finishing operations concern themselves with the magnitude of the surface roughness obtained, the manufacturer's recommendation for the 514 tool for finishing operations is upheld.

Because the 514 finishing tool gave acceptable and superior performance at the roughing level, and significantly better surface finish at the finishing level, there is no justification for the introduction of the 516 roughing grade.

Sandvik Coromant G.C. 135 vs. G.C. 125

Of the three multi-grade coated tool manufacturers the Sandvik roughing 135 and finishing 125 grades exhibited the least differences in performance.

Roughing Operation Comparison-

At both 200 and 300 sfpm there were no significant differences in performance at the seven minute interval. However, for the overall time t-tests the finishing tool produced significantly better surface finish than the roughing tool, and showed generally less flank wear than the 135 grade.

Finishing Operation Comparison-

For both the 500 and 800 sfpm conditions there were no significant differences at the seven minute testing interval or at the overall testing intervals. The only trend visible was a consistently better performance of the G.C. 125 finishing grade. However, these differences do not justify any preference for a particular tool.

From the results of both the roughing and finishing operations there were no significant differences in performance of these tools. Either tool is an acceptable cutting tool for both operations. The manufacturer's claims for these tools was not justified and consideration should be given to the discarding of one of these steel cutting grades.

V.R. Wesson Ti-Bond-1 vs. Kennametal KC-75

Both of these manufacturers produce a single TiC coated steel cutting grade which they recommend for both roughing and finishing operations. The Student T-tests were applied in this instance to determine which, if either, of the tools performed better at each operation. The results of these tests appear in Appendix-D as well.

Roughing Operation Comparison-

At 200 sfpm the Kennametal KC-75 tool significantly produced less flank wear than the V.R. Wesson Ti-Bond-1 tool. The surface roughness shown was roughly equal for both tools. The 300 sfpm speed data shows significantly less flank wear for Ti-Bond-1 than for the KC-75 tool. Again the surface roughnesses were not different.

These results show that neither tool would be preferred and that each tool performs well under the roughing conditions stipulated.

Finishing Operation Comparison-

The KC-75 tool produced significantly less flank wear than the Ti-Bond-1 tool at 500 sfpm. There was no difference in the surface roughness. At 800 sfpm there was no significant difference in either the flank wear or surface roughness.

It seems that both manufacturers have produced a single coated grade which gives acceptable performance for both roughing and finishing operations; consequently, this shows that there is no need to produce two TiC coated steel cutting grades.

Uncoated G.E. Carboloy 370 vs. 350

Although these tools are not coated with TiC they are labeled as roughing and finishing tools and may also not perform as claimed. These tools are subjected to the same Student T-tests and the results are recorded in Appendix-D.

Roughing Operation Comparison-

Although there was no significant difference in flank wear at 200 sfpm between these grades, the finishing grade (350) produced significantly less surface roughness than the roughing grade (370). Also, the surface roughness produced by the 370 grade was at an unacceptable level of 325μinches. At 300 sfpm the finishing grade again showed less flank wear than the roughing grade, and also a better surface finish.

These differences are the most pronounced of all tools reviewed for the roughing operations, and they are in favor of the finishing grade.

Finishing Operation Comparison-

As was expected, the 350 finishing grade produced significantly less flank wear and surface roughness than the roughing tool at 500 sfpm. Also, the 350 grade showed less wear at 800 sfpm while the 370 roughing tool lost its cutting edge. Most likely, the temperature problems associated with the higher cutting speeds affected the red-hardness properties of the tougher 370 grade.

These findings show the 350 finishing grade to be the better performer for both the roughing and finishing operations. This indicated that the 350 carbide is hard enough to withstand the abrasive and thermal wear, and tough enough to resist breakage and chipping at the roughing operation level. However, the 370 base was not hard enough to withstand the higher speed finishing operations.

Multi-Grade Manufacturers vs. Single-Grade Manufacturers of TiC Coated Tools

Appendix-E shows the results of the Tukey tests which tested for any significant differences at the 1% level of confidence between the average performance of the multi-grade coated tool manufacturers and the single-grade coated tool manufacturers for the entire experiment.

Flank Wear-

The mean flank wear produced by the six tools belonging to the multi-grade manufacturers (Firth Sterling, G.E. Carboloy, and Sandvik Steel) was 6.75×10^{-3} inches. The mean flank wear produced by the single-grade tools from V.R. Wesson and Kennametal Inc. was 5.79×10^{-3} inches. The difference is $.96 \times 10^{-3}$ inches.

By obtaining the standard error of estimate for the flank wear ($.141 \times 10^{-3}$ inches), and securing a studentized range value of 5.25 for 10 means and 160 degrees of freedom at the 1% level of significance, the wholly significant difference is calculated as $.141 \times 5.25 = .741 \times 10^{-3}$ inches.

Since the observed difference of $.96 \times 10^{-3}$ inches is greater than the calculated difference, $.741 \times 10^{-3}$ inches needed for significance, the single-grade tools significantly produce less flank wear than the multi-grade tools.

Surface Roughness-

The average surface roughness produced by the multi-grade tools was 136.4μinches while the average surface roughness produced by the single-grade tools was 122.2μinches. The difference is 14.2μinches.

Since the standard error for the surface roughness was 2.63μinches, the wholly significant difference is 13.8μinches (2.63μinches x 5.25 = 13.8μinches). Comparison of the observed difference and the calculated difference needed for significance shows that the observed difference is greater; therefore, the tools belonging to the single-grade systems do produce a significantly better surface finish than those tools belonging to the multi-grade systems.

The reason(s) for the better performance of single coated grade tools does not lie in the TiC coating's performance characteristics since all of the tools are coated. More likely, the differences occurred because the substrate material chosen for these single-grade tools was a better compromise between the needs of finishing and roughing operations. On the other hand, the manufacturers of the multi-grade tools produced pooere results by believing that such a compromise was not possible, and inadvertently chose substrate materials which they believed were optimal when in fact they were not.

TiC Coated Tools vs. Uncoated Tools

Appendix-E also shows the results of Tukey tests which were applied to the mean performances of the TiC coated tools and the uncoated tools. The calculation of the wholly significant difference statistics is identical to the calculations performed previously. That is, the WSD for flank wear is .741 $\times 10^{-3}$ inches and the WSD for surface roughness is 13.8 μinches.

Flank Wear-

The mean flank wear produced by the eight TiC coated tools was 6.52 $\times 10^{-3}$ inches; while the mean flank wear produced by the two uncoated tools was 9.17 $\times 10^{-3}$

inches. This difference (2.65×10^{-3} inches) is significant at the 1% level of confidence; therefore, TiC coated tools significantly produce less flank wear than tools which are not coated with TiC.

The major contributor to the better performance of the TiC coated tools is the mere presence of this coating. Titanium carbide possesses unusually high resistance to abrasive wear by acting as a shield for the cutting edge and tool substrate. As a coating it replaces the need for an extremely hard substrate with its associated lack of toughness. Also this coating minimizes abrasive wear because it forms a very hard titanium dioxide protective film during its operation at elevated cutting speeds. This oxidized film resists being welded to the cutting material since its adhesion temperature is considerably higher than conventional cobalt alloys. Therefore, the phenomenon of built-up-edge is minimized, and the corresponding minute welds as well. The net effect is lower cutting forces and fewer strain hardenen particles passing over the flank of the tool; thus, less abrasive wear.

Another important function of the titanium carbide coating is to effectively reduce the effects of the thermal environment at the tool-work interface. The mechanical properties of titanium carbide alone guarantee greater hot-hardness and resistance to thermal deformation. In addition, this coating helps to reduce the cause of temperature, friction. With this reduction in friction, the shearing zone friction decreases and less shearing energy is required. Also, the cutting zone temperature decreases, and consequently, so does the temperature at the tool's cutting edge. The fact that no cratering was observed for the TiC coated tools suggests that the TiC coating inhibits the atomic metal diffusion which occurs between the tool-chip interface at higher speeds and temperatures.

Surface Roughness-

The mean surface roughness for the eight TiC coated tools was 132.1µinches, and 155.1µinches for the uncoated tools; a difference of 23.0µinches. This difference is greater than the WSD of 13.8µinches required for significance. This results in the TiC coated tool's better surface finish than the uncoated carbide tools.

Because of the combined effects of a lower coefficient of friction at the tool-work interface, and the reduction of the number of strain-hardened particles (which would have been attributed to a built-up-edge) passing between the tool and newly generated surface; the surface roughness is correspondingly lowered by the use of this TiC coating. Also, the decrease in the energy required at the shearing zone to remove the metal, and a very hard, undulled cutting edge ensures a cleaner mechanical shearing of the work and a better surface finish.

Duncan Ranking of Tool Performance

Appendix-F shows the Duncan statistical rankings of the tools in order of their performance for the overall experiment. It must be noted that some tools are ranked at more than one level. This is due to the statistical peculuarities of multiple grouping. Each "Duncan Tool Grouping" may contain several tools because these tools statistically produced the same wear and surface finish although their absolute values may be quite different.

Because of the lack of any consistent performance of a particular tool or group of tools between operations it is quite difficult to distill any concrete conclusions. However, several trends are evident:

1. There seems to be some positive correlation between the order of performance between flank wear and surface finish; especially for the uncoated tools.
2. The single-grade manufacturers ranked very well in both flank wear and surface roughness when compared to the multi-grade manufacturers and the uncoated tools.
3. The multi-grade tools within a manufacturer generally exhibited the same flank wear, but not the same surface roughness.
4. The uncoated tools produced the greatest flank wear, and the uncoated 370 grade produced the

worst surface finish of all the tools.

The results of the ranking reflect the general disposition of the performances of these tools as discussed previously; therefore this ranking procedure provides good qualitative as well as quantitative monitoring of the results obtained in this experiment.

CONCLUSIONS *

From the preceding discussion and from the results obtained it can be concluded that:

1) For the multi-grade manufacturers the differences in performance between the two TiC coated steel grades are so small that there is no experimental justification for the production of a single grade for roughing and a single grade for finishing; only a single grade is needed for both operations.

2) The single-grade TiC coated tools produced by V.R. Wesson and Kennametal collectively produced significantly less flank wear and surface roughness than the multi-grade TiC coated tools.

3) Tools which are coated with TiC perform significantly better (less flank wear and surface roughness) than uncoated tools because the TiC coating;
    a. increases the wear resistance at the cutting edge,
    b. reduces the friction at the shear zone, tool-work, and tool-chip interfaces,
    c. inhibits the minute welding between the tool-work and tool-chip interfaces, and
    d. increases the resistance to mass diffusion of the work material into the carbide substrate.

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* All conlcusions are significant at at least the 95% level of confidence.

RECOMMENDATIONS FOR FUTURE STUDY

1. A similar experiment could be conducted for a milling operation to determine if the multi-grade TiC coated tools significantly differ in performance for an intermittent cutting environment.

2. Cast iron could be used as the work material for an experiment which would evaluate if any differences in performance exist between TiC coated cast iron grades and steel cutting grades. This experiment could also be conducted for continuous and intermittent cutting operations.

3. The above recommendations could include the use of a thermocouple which could measure the absolute and relative changes in the cutting edge's and substrate's temperature for furthering the understanding of the effects of TiC coating on the various substrate materials.

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APPENDIX-A

RAW DATA*

Roughing Condition for 200 SFPM
Feed = .020 in./rev.
Depth = .050 in.

Sandvik G.C. 135 (Roughing Grade)

	1 min.	3 min.	5 min.	7 min.
Flank Wear $\times 10^{-3}$ in.	3.6	4.0	4.9	6.5
	4.0	4.3	4.8	5.3
Surface μ in. Roughness	260	265	240	240
	255	235	245	250
Thermal $\times 10^{-3}$ in. Discoloration	16.4	19.6	22.1	28.6
	19.0	26.0	29.1	31.7
"Popped" Coating $\times 10^{-3}$ in.	0.0	4.7	4.9	6.5
	0.0	0.0	0.0	0.0

Sandvik G.C. 125 (Finishing Grade)

	1min.	3 min.	5 min.	7 min.
Flank Wear $\times 10^{-3}$ in.	4.2	4.8	5.0	5.6
	4.8	5.0	5.2	5.6
Surface μ in. Roughness	160	175	180	170
	200	210	210	215
Thermal $\times 10^{-3}$ in. Discoloration	20.1	23.0	26.7	28.9
	15.5	17.2	17.8	18.1
"Popped" Coating $\times 10^{-3}$ in.	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	0.0

* Only the data collected for these two tools appears in this Appendix. The remaining data for the eight additional tools is on file with Professor George Kane at Lehigh University.

Roughing Condition for 300 SFPM
Feed = .020 in./rev.
Depth = .050 in.

Sandvik G.C. 135 (Roughing Grade)

	1 min.	3 min.	5 min.	7 min.
Flank Wear	5.2	9.4	12.9	16.9
x10^{-3}in.	6.4	10.1	12.5	16.1
Surface μin.	230	230	225	230
Roughness	250	260	245	230
Thermal x10^{-3}in.	17.0	18.5	22.1	30.1
Discoloration	14.2	18.8	26.7	34.7
"Popped"	0.0	0.0	0.0	0.0
Coating x10^{-3}in.	0.0	0.0	0.0	0.0

Sandvik G.C. 125 (Finishing Grade)

	1 min.	3 min.	5 min.	7 min.
Flank Wear	7.9	9.7	11.4	13.2
x10^{-3}in.	8.1	10.6	12.0	15.3
Surface μin.	210	210	215	235
Roughness	185	185	190	200
Thermal x10^{-3}in.	18.4	22.9	28.5	33.6
Discoloration	15.7	24.6	28.8	30.3
"Popped"	0.0	0.0	0.0	7.8
Coating x10^{-3}in.	12.0	13.6	16.8	17.2

Finishing Condition for 500 SFPM
Feed = .005 in./rev.
Depth = 1020 in.

Sandvik G.C. 135 (Roughing Grade)

	1 min.	3 min.	5 min.	7 min.
Flank Wear x10^{-3} in.	2.8	3.3	3.9	4.0
	3.2	3.6	3.9	4.6
Surface Roughness μin.	40	41	41	38
	22	38	40	44
Thermal Discoloration x10^{-3}in.	10.8	11.7	12.2	12.5
	10.1	11.9	13.4	14.6
"Popped" Coating x10^{-3}in.	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	0.0

Sandvik G.C. 125 (Finishing Grade)

	1 min.	3 min.	5 min.	7 min.
Flank Wear x10^{-3} in.	2.3	3.1	3.8	4.3
	2.6	3.0	3.4	3.8
Surface Roughness μin.	27	29	31	34
	38	38	41	42
Thermal Discoloration x10^{-3}in.	10.1	10.9	11.8	12.9
	9.8	11.1	12.2	13.2
"Popped" Coating x10^{-3}in.	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	0.0

Finishing Condition for 800 SFPM
Feed= .005 in./rev.
Depth = .020 in.

Sandvik G.C. 135 (Roughing Grade)

	1 min.	3 min.	5 min.	7 min.
Flank Wear	5.3	11.6	13.3	16.5
x10^{-3}in.	4.6	7.4	10.5	13.0
Surface μin.	37	42	45	50
Roughness	36	34	42	50
Thermal x10^{-3}in.	14.0	15.2	18.7	23.2
Discoloration	12.7	15.2	17.4	20.1
"Popped"	0.0	0.0	0.0	0.0
Coating x10^{-3}in.	0.0	0.0	0.0	0.0

Sandvik G.C. 125 (Finishing Grade)

	1 min.	3 min.	5 min.	7 min.
Flank Wear	4.8	14.5	16.0	16.8
x10^{-3}in.	5.0	10.3	12.0	15.1
Surface μin.	31	40	43	43
Roughness	32	36	42	58
Thermal x10^{-3}in.	0.0	16.8	19.4	20.1
Discoloration	0.0	13.6	17.6	19.0
"Popped"	0.0	0.0	0.0	0.0
Coating x10^{-3}in.	0.0	0.0	0.0	0.0

APPENDIX-B

Analysis of Variance of Flank Wear for Roughing Cuts:

Source	Sum of Squares	Degrees of Freedom	Mean Square
A (Tool)	271.29	9	30.14
B (Speed)	1020.10	1	1020.10
C (Time)	385.19	3	128.39
AB	166.83	9	18.53
AC	43.95	27	1.63
BC	100.31	3	33.43
ABC	26.77	27	.99
R(ABC)	37.62	80	.47

Source	F-Ratio	F-Ratio at 95%	F-Ratio at 99%	Significant at 95%	Significant at 99%
A(Tool)	64.10	2.04	2.72	*	*
B (Speed)	2169.27	4.00	7.08	*	*
C (Time)	273.05	2.76	4.13	*	*
AB	39.42	2.04	2.72	*	*
AC	3.46	1.70	2.12	*	*
BC	71.11	2.76	4.13	*	*
ABC	2.11	1.70	2.12	*	

Analysis of Variance of Surface Roughness for Roughing:

Source	Sum of Squares	Degrees of Freedom	Mean Square
A (Tool)	177651.0	9	19739.00
B (Speed)	6760.0	1	6760.0
C (Time)	458.1	3	152.70
AB	25821.2	9	2869.03
AC	4885.6	27	180.95
BC	31.3	3	10.41
ABC	3387.5	27	125.46
R(ABC)	28975.0	80	362.19

Source	F-Ratio	F-Ratio at 95%	F-Ratio at 99%	Significant at 95%	at 99%
A (Tool)	54.50	2.04	2.72	*	*
B (Speed)	18.66	4.00	7.08	*	*
C (Time)	.42	2.76	4.13		
AB	7.92	2.04	2.72	*	*
AC	.50	1.70	2.12		
BC	.03	2.76	4.13		
ABC	.35	1.70	2.12		

Analysis of Variance for Flank Wear for Finishing Cuts:

Source	Sum of Squares	Degrees of Freedom	Mean Square
A (Tool)	563.69	9	62.63
B (Speed)	1149.18	1	1149.18
C (Time)	919.80	3	306.60
AB	168.23	9	18.69
AC	364.09	27	13.49
BC	348.12	3	116.04
ABC	210.70	27	7.80
R(ABC)	63.99	80	.80

Source	F-Ratio	F-Ratio at 95%	F-Ratio at 99%	Significant at 95%	at 99%
A (Tool)	78.30	2.04	2.72	*	*
B (Speed)	1436.7	4.00	7.08	*	*
C (Time)	383.31	2.76	4.13	*	*
AB	23.37	2.04	2.72	*	*
AC	16.86	1.70	2.12	*	*
BC	145.07	2.76	4.13	*	*
ABC	9.76	1.70	2.12	*	*

Analysis of Variance of Surface Roughness for Finishing:

Source	Sum of Squares	Degrees of Freedom	Mean Square
A (Tool)	3152.23	9	350.25
B (Speed)	1305.31	1	1305.31
C (Time)	4783.82	3	1594.61
AB	848.01	9	94.22
AC	2062.62	27	76.39
BC	950.31	3	316.77
ABC	863.62	27	31.99
R(ABC)	6164.50	80	77.06

Source	F-Ratio	F-Ratio at 95%	F-Ratio at 99%	Significant at 95%	at 99%
A (Tool)	4.55	2.04	2.72	*	*
B (Speed)	16.94	4.00	7.08	*	*
C (Time)	20.69	2.76	4.13	*	*
AB	1.22	2.04	2.72		
AC	.99	1.70	2.12		
BC	4.11	2.76	4.13	*	
ABC	.42	1.70	2.12		

APPENDIX-C

Correlation Matricies

Overall Experiment-

Flank Wear	Flank Wear	Thermal Disc.	Popped Coating	Surface Roughness
Thermal Disc.	.6597	1.0000		
Popped Coating	.1687	.2370	1.0000	
Surface Roughness	.1382	.5642	.2070	1.0000

Roughing Conditions-

Flank Wear	Flank Wear	Thermal Disc.	Popped Coating	Surface Roughness
Thermal Disc.	.5718	1.0000		
Popped Coating	.2566	.2147	1.0000	
Surface Roughness	.1330	.0127	-.1699	1.0000

Finishing Conditions- *

Flank Wear	Flank Wear	Thermal Disc.	Popped Coating	Surface Roughness
Thermal Disc.	.8199	1.0000		
Popped Coating	.0000	.0000	.0000	
Surface Roughness	.5613	.5161	.0000	1.0000

* No "popping" of the coating was observed for any of the tools for either finishing condition speed.

APPENDIX-D

Student T-Tests for Flank Wear

"T" values needed for 95% significance (*):

1.76 for means calculated over seven minutes (A)
2.92 for means calculated at seven minutes (B)

Firth Sterling TC+ and TC+1

Roughing Conditions				Finishing Conditions			
200 sfpm		300 sfpm		500 sfpm		800 sfpm	
A	B	A	B	A	B	A	B
.98	.70	4.37*	9.91*	1.11	2.85	.35	.67

G.E. Carboloy 516 and 514

Roughing Conditions				Finishing Conditions			
200 sfpm		300 sfpm		500 sfpm		800 sfpm	
A	B	A	B	A	B	A	B
4.67*	4.53*	1.69	1.42	1.16	1.34	1.04	.64

Sandvik G.C. 135 and G.C. 125

Roughing Conditions				Finishing Conditions			
200 sfpm		300 sfpm		500 sfpm		800 sfpm	
A	B	A	B	A	B	A	B
.84	.79	.09	2.00	1.22	.64	.69	.62

V.R. Wesson Ti-Bond-1 and Kennametal KC-75

Roughing Conditions				Finishing Conditions			
200 sfpm		300 sfpm		500 sfpm		800 sfpm	
A	B	A	B	A	B	A	B
2.07*	3.28*	1.04	5.97*	2.42*	12.02*	1.88*	2.68

G.E. Carboloy 370 and 350

Roughing Conditions				Finishing Conditions			
200 sfpm		300 sfpm		500 sfpm		800 sfpm	
A	B	A	B	A	B	A	B
.02	.54	3.27*	5.79*	2.06*	22.63*	.48	23.86*

Student T-Tests for Surface Roughness

"T" values needed for 95% significance (*):

1.76 for means calculated over seven minutes (A)
2.92 for means calculated at seven minutes (B)

Firth Sterling TC+ and TC+1

Roughing Conditions				Finishing Conditions			
200 sfpm		300 sfpm		500 sfpm		800 sfpm	
A	B	A	B	A	B	A	B
9.60*	7.07*	8.56*	4.01*	1.53	1.94	1.95*	1.18

G.E. Carboloy 516 and 514

Roughing Conditions				Finishing Conditions			
200 sfpm		300 sfpm		500 sfpm		800 sfpm	
A	B	A	B	A	B	A	B
1.16	0.00	1.22	1.89	5.11*	2.89	2.88*	4.92*

Sandvik G.C. 135 and G.C. 125

Roughing Conditions				Finishing Conditions			
200 sfpm		300 sfpm		500 sfpm		800 sfpm	
A	B	A	B	A	B	A	B
7.01*	2.28	4.47*	.71	1.02	.60	.37	.07

V.R. Wesson Ti-Bond-1 and Kennametal KC-75

Roughing Conditions				Finishing Conditions			
200 sfpm		300 sfpm		500 sfpm		800 sfpm	
A	B	A	B	A	B	A	B
1.86*	.63	11.39*	.69	.70	1.30	.03	.56

G.E. Carboloy 370 and 350

Roughing Conditions				Finishing Conditions			
200 sfpm		300 sfpm		500 sfpm		800 sfpm	
A	B	A	B	A	B	A	B
22.3*	10.3*	3.70*	1.23	1.13	3.49*	1.07	.40

APPEDNIX-E

Tukey Grouped Means Tests For

Multi-Grade Coated Tools vs. Single-Grade Coated Tools*

Flank Wear-

Multi-Grade Mean Flank Wear = 6.75×10^{-3}in.

Single-Grade Mean Flank Wear = 5.79×10^{-3}in.

The Mean Difference is = $.96 \times 10^{-3}$in.

The Wholly Significant Difference = $.741 \times 10^{-3}$in.

WSD= Standard Error of Estimate x Studentized Range (q_k)
WSD= $.141 \times 10^{-3}$in. x 5.25

Since; $.96 \times 10^{-3}$in. is greater than $.741 \times 10^{-3}$in. there is a significant difference between Multi and Single Grades.

Surface Roughness-

Multi-Grade Mean Surface Roughness = 136.4μin.

Single- Grade Mean Surface Roughness = 122.2μin.

The Mean Difference is = 14.2μin.

The Wholly Significant Difference = 13.8μin.

WSD= Standard Error of Estimate x Studentized Range (q_k)
WSD= 2.63μin. x 5.25

Since; 14.2μin. is greater than 13.8μin. there is a significant difference between Multi and Single Grades.

* These tests are at the 1% level of confidence.

Tukey Grouped Means Tests For
Titanium Carbide Coated Tools vs. Uncoated Carbide Tools*

Flank Wear-

TiC Coated Tools Mean Flank Wear = 6.52×10^{-3} in.

Uncoated Tools Mean Flank Wear = 9.17×10^{-3} in.

The Mean Difference = 2.65×10^{-3} in.

The Wholly Significant Difference = $.741 \times 10^{-3}$ in.

WSD = Standard Error of Estimate x Studentized Range (q_k)
WSD = $.141 \times 10^{-3}$ in. x 5.25

Since; 2.65×10^{-3} in. is greater than $.741 \times 10^{-3}$ in . there is a significant difference between coated and uncoated tools.

Surface Roughness-

TiC Coated Tools Mean Surface Roughness = 132.1 μin.

Uncoated Tools Mean Surface Roughness = 155.1 μin.

The Mean Difference = 23.0 μin.

The Wholly Significant Difference = 13.8 μin.

WSD = Standard Error of Estimate x Studentized Range (q_k)
WSD = 2.63 μin. x 5.25

Since; 23.0 μin. is greater than 13.8 μin. there is a significant difference between coated and uncoated tools.

* These tests are at the 1% level of confidence.

APPENDIX-F

Duncan Multiple Range Rankings for Flank Wear*

Tool	Mean
G.E. Carboloy 516 (R)	5.19 x10^{-3}in.
V.R. Wesson Ti-Bond-1(G)	5.35 "
G.E. Carboloy 514 (F)	5.79 "
Kennametal KC-75 (G)	6.23 "
Firth Sterling TC+1 (F)	6.39 "
Sandvik G.C. 135 (R)	7.45 "
Sandvik G.C. 125 (F)	7.78 "
Firth Sterling TC+ (R)	7.90 "
G.E. Carboloy 350 (F)	8.02 "
G.E. Carboloy 370 (R)	10.30 "

(R)- Roughing Grade

(F)- Finishing Grade

(G)- General Purpose Grade

Duncan Ranking

1. G.E. 516 (R)
   Ti-Bond-1 (G)
2. Ti-Bond-1 (G)
   G.E. 514 (F)
3. G.E. 514 (F)
   KC-75 (G)
4. KC-75 (G)
   TC+1 (F)
5. G.C. 135 (R)
   G.C. 125 (F)
   TC+ (R)
6. G.C. 125 (F)
   TC+ (R)
   G.E. 350 (F)
7. G.E. 370 (R)

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* These rankings are significant at the 1% level of significance.

Duncan Multiple Range Rankings for Surface Roughness*

Tool	Mean	Duncan Ranking
Firth Sterling TC+ (R)	116.9μin.	1. TC+ (R)
Sandvik G.C. 125 (F)	117.3μin.	G.C. 125 (F)
V.R. Wesson Ti-Bond-1(G)	120.5μin.	Ti-Bond-1 (G)
Kennametal KC-75 (G)	124.7μin.	KC-75 (G)
G.E. Carboloy 514 (F)	134.7μin.	2. G.E. 514 (F)
G.E. Carboloy 350 (F)	136.4μin.	G.E. 350 (F)
Sandvik G.C. 135 (R)	141.6μin.	G.C. 135 (R)
G.E. Carboloy 516 (R)	142.6μin.	G.E. 516 (R)
Firth Sterling TC+1 (F)	159.0μin.	3. TC+1 (F)
G.E. Carboloy 370 (R)	173.8μin.	4. G.E. 370 (R)

(R)- Roughing Grade

(F)- Finishing Grade

(G)- General Purpose Grade

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* These rankings are significant at the 1% level of significance.

VITA

John U.E. Shroyer was born in Danville, Pennsylvania on October 30th., 1948 to John and Margaret. He graduated from Shamokin Area High School in 1966; then attended Lehigh University where he earned his Bachelor of Science Degree with honors in Industrial Engineering in 1970. He is presently self-employed as a free-lance photographer.