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Final Report

A STUDY OF THE MACHINABILITY OF HIGH DENSITY TUNGSTEN AND UNFILTRATED TUNGSTEN

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ABSTRACT

The machining characteristics of almost pure tungsten were studied over ranges of density and carbon content. The results show that it can be cut in lathe turning operations at relatively high rates of metal removal although rates of tool wear are still very high compared to the machining of most other metals. The cutting characteristics of high density tungsten are almost unique in that acceptable conditions of surface finish, size control and rate of tool wear can be achieved only at high speeds and high temperature which requires the use of ceramic cutting tools. It is demonstrated that preheating of the cutting tools to between 1250 and 1400°F increases tool life.

The introduction of copper and silver infiltrated tungsten at a late stage in the study produced a revolutionary change in the nature of the problem. It was found that these materials can be machined with both carbide and ceramic tools almost as readily as ordinary cast iron.

INTRODUCTION

This study of the machining characteristics of almost pure tungsten ultimately resolved itself into three phases. The first two phases dealt with high density tungsten whereby two separate projects were carried out in a search for acceptable machining conditions for this hard, high strength material. The third phase actually began with the introduction of infiltrated tungsten in the later stages of the second study referred to as Phase II. It was quickly discovered that infiltrated tungsten could be machined almost as readily as ordinary cast iron. This development solved the machining problem with tungsten and relegated the earlier experiences and results to a position almost of academic interest only. However, the experience obtained in Phases I and II did bring forth information about some of the unique machining characteristics of tungsten which still remain as minor influences in machining the infiltrated types.

The first study dealt with high density tungsten only at about 95% theoretical density. This investigation revealed that high density tungsten could be turned with satisfactory surface finish and size control only with ceramic or sintered oxide cutting tools. However, it was found that this could be done only at relatively high cutting speeds and high temperatures which were accompanied by two new problems. The first of these was the fact that thermal cracks would appear in the work surface. Furthermore, large chunks of the work material would spall from the machined surface unless the traverse or feed rate was fast enough to minimize local overheating of the machined surface. This then restricted the depth of cut to relatively small values so as to permit higher feed rates. The second difficulty involved catastrophic thermal cracking of the ceramic cutting tools as a result of the high thermal stresses induced at the beginning of a cut. Near the end of the first investigation it was discovered that preheating of ceramic cutting tools with a welding torch could lengthen the useful life of the tools.

Consequently, Phase II or the second investigation was devoted initially to a study of different methods of preheating tools. Attempts at electrical preheating in the tool holder itself were unable to develop sufficient temperature in the limited space available. Attempts at heating the tool in place with an oxy-acetylene torch were successful in minimizing cracking of the ceramic tools but the tool holder was severely weakened or softened and deflected substantially under the cutting load causing a loss of size control and ultimately disastrous loss of rigidity in support of the cutting tool.

Pre-heating of the ceramic tool inserts in a small muffle furnace prior to inserting in the tool holder proved to be a very satisfactory procedure especially when the use of ceramic and chromium carbide supporting pads was introduced to further reduce heat transfer into the tool holder. This reduced the thermal stress gradient from the cutting surface to the under side of the tool insert.

Further attention to the problem of heat transfer plus improvements in tool rigidity and tapered entrance conditions in starting the cut ultimately made it possible to eliminate the preheating of the cutting tools. However, it still remains desirable to combine all of these improvements including furnace preheating in order to provide usable latitude of cutting conditions where pure tungsten must be machined. None of these techniques make it possible to use tungsten carbide tools for this purpose.

Phase III involving the machining characteristics of copper and silver infiltrated tungsten was relatively brief for two reasons. First was the fact that only a small amount of each of these materials was available, secondly and more important was the fact that it became obvious that both could be machined almost as readily as ordinary cast iron. Further, as will be shown later in this report, it can be machined at cutting speeds from three to five times as high as with high density tungsten and at tool wear rates of less than 10% as great even when using tungsten carbide tools. Furthermore, the power requirements are comparable to those of cast iron or from 1/3 to 1/2 that of high density tungsten. In addition, surface finish, size control and chip formation are excellent for both the copper and silver infiltrated forms.

The main body of this report is divided into four major sections with the first section being devoted to a discussion of the overall or general machining characteristics of high density tungsten in particular. Subsequent sections in sequence are devoted to detailed discussions of surface finish, cutting forces and power requirements, and tool wear.

GENERAL MACHINING CHARACTERISTICS

Two general types of studies were carried out. These involved tool wear and cutting forces respectively. In addition careful records were kept of chip formation and surface finish so as to provide an overall picture of significant machining characteristics. Tool wear studies for the infiltrated tungsten materials were carried out in a 22-inch swing Monarch lathe equipped with a steplessly variable speed control. Cutting force tests were carried out with a three component cutting force dynamometer in this same machine and repeated with a two component dynamometer in a 14-inch swing Monarch lathe also equipped with a steplessly variable drive. A listing of all the test materials with their corresponding code numbers and important parameters is summarized in Table I. A complete listing of the chemical composition of these same materials is given in Table XI of the Appendix. Similarly the geometry and dimensions of the cutting tools and tool holders are summarized in Table XII of the Appendix.

TABLE I

TEST MATERIAL*

Code No.	Process	Density, %	Carbon, %
1	Sintered (Variable Density)	95.01	.001
2	Sintered (Variable Density)	88.52	.002
3	Sintered (Variable Density)	77.71	.001
4	Sintered (Variable Carbon)	94.24	.001
5	Sintered (Variable Carbon)	94.51	.004
6	Sintered (Variable Carbon)	93.8	.018
7	Extruded (High Density)	98.00	.002
8	Copper Infiltrated	89.00**	.003
9	Silver Infiltrated	92.00***	.003

*Complete composition is given in Table XI in the Appendix.
**Density before infiltration was 78%.
***Density before infiltration was 81%.

CUTTING FORCES VS. CUTTING SPEED

Figure 1 illustrates the significantly unique machining characteristics of high density tungsten. This figure is a plot of the tangential component of cutting force as it is shown to vary over a wide range of cutting speeds from 20 fpm up to and including 500 fpm. The results shown in Figure 1 were obtained for Material No. 1 of Table I, but they are typical qualitatively of materials 1 through 7 in the table. In other words they are typical of all except the infiltrated tungsten. Along with the cutting forces Figure 1 also shows reproductions or pictures of the machined surface and the chips obtained at representative speeds over the full range.

The solid round dots and solid squares represent actual force data points from the chart records. These in turn determine the solid lines which represent maximum and minimum values achieved by the cutting forces.

The wide range between the minimum and maximum forces measured for carbide tools at speeds from 20 to 150 fpm, reflect a very harsh cutting action which shows up both in the machined surface and in varying degrees of broken chips. This is most pronounced at the lowest speed of 20 fpm at which the cutting action is very much like that of a hard, strong, brittle, alloy cast iron.

There is practically no ductile flow or shear in the formation of the chips. This accounts for the very wide range of fluctuation of the measured cutting forces. In general a brittle fracture or chip formation requires less energy than where some shear distortion takes place in the formation of the chip. This accounts for the very rapid increase in forces as the cutting speed is increased above the minimum of 20 fpm. During this interval the cutting temperature and therefore the temperature of the chip increases with increased cutting speed thus making it possible for some plastic flow to take place in forming the chip. Eventually, the increased temperature reaches a threshold value beyond which the shear strength of the material is substantially reduced thus causing the forces to drop below the maximum achieved at somewhat lower speeds. This in turn is accompanied by a smoother cutting action which results in a narrower range between the minimum and maximum solid lines. The smoother cutting action is reflected also in the surface roughness of the machined surface and in the degree of continuity of the chips. Tests were run on both carbide tools and ceramic tools at the speed of 150 fpm.

It will be noted that the square points representing the ceramic tools at the cutting speed of 150 fpm are substantially lower than the solid round points representing the forces obtained with the carbide tools at the same speed and size of cut. The lower forces for the ceramic tools are due partially to a slightly smaller nose radius on these tools compared with the carbide tools. However, the dominant influence which produced this result is the lower coefficient of friction between the tungsten chips and the ceramic tools. This is evident also in the fact that the chips obtained with the ceramic tools were appreciably thinner and more continuous. The chips illustrated in Figure 1 for a cutting

speed of 150 fpm were obtained with ceramic tools.

The very rough cutting action at speeds below 150 fpm produces very rapid tool wear which is even more pronounced when ceramic tools are used in this speed range. This is due to the rough, brittle action in forming the chips and to the wide range of force pulsations which literally pulverize brittle tool materials like tungsten carbide and the ceramics. The transition from brittle, broken chips to continuous chips at higher temperatures is an almost unique property with high density tungsten. The associated variation in cutting forces has been observed only in one other metal as illustrated in Figure 2.

NOTCH SENSITIVITY IN A SPECIAL STEEL

The data shown in Figure 2 were obtained for a special, high silicon steel which had been developed for missile casings. Values of feeding force for this material are shown plotted over a wide range of cutting speeds up to 612 fpm. The tangential component of cutting force showed the same sharp transitions but the range of variation was not as great as that shown by the feeding force. It will be noted that the cutting forces first decrease with increasing cutting speed until a critical and very narrow range of speeds is reached at which time the force increases to almost three times its minimum value. Further increases in cutting speed drops the forces to levels almost as low as the initial values obtained at the very lowest speeds.

The behavior with this steel is strikingly similar to that observed with high density tungsten. The material property involved might be called notch sensitivity which substantially disappears at a temperature equal to that which prevails at the cutting speed where the pronounced increase in cutting force takes place. It will be noted as in the case of tungsten that chips formed at speeds below the transition value are small and well broken whereas they change over to continuous chips at the transition speed.

This phenomena appears to be caused by a temperature dependent, notch sensitivity which seems to be confirmed by the shape of the cutting force chart records. For example, the chart record shown for a speed of 31 fpm at the left in Figure 2 shows the cutting force increasing for almost 1/4 of the total test interval. The time duration of this increase is far greater than that required to achieve full size of cut. This permits the conclusion that the gradual rise of temperature in the shear zone to an equalibrium value is accompanied by a corresponding rise in the cutting force because the notch sensitivity gradually diminishes within the shear zone.

This is strongly evident in the chart record for 62 fpm shown at the lower left in Figure 2. In this instance the gradual increase in forces was interrupted at intervals by the presence of severe chatter which tends to produce severely segmented and broken chips as shown by the picture of the chips obtained at the speed of 69 fpm. It is further significant that the chips formed at speeds from

103 through 308 fpm were continuous and unsegmented. At 612 fpm segmentation once again appeared in the chip but this is believed to be the result of standing waves either in the workpiece or the cutting tool since it will be noted that the frequency of segmentation was nearly 14 kilocycles compared to the 250 cps frequency of segmentation at the speed of 69 fpm where common chatter was in evidence.

It is believed that an equally sharp transition of cutting force versus cutting speed would be observed for high density tungsten providing all elements of the machine tool and dynamometer system could be correspondingly more rigid.

NOTCH SENSITIVITY VS. CUTTING CONDITIONS

Accepting the hypothesis of notch sensitivity and its relation to temperature enables one to predict the conditions at which high density tungsten can be machined satisfactorily. The color moving picture which was submitted earlier on this project showed clearly that the chips must be at least red hot in order to achieve the smooth cutting conditions associated with close size control and good surface finish. Such a temperature level is achieved only at high cutting speeds in cutting any metal but the speed must be relatively higher in the case of tungsten because of an exceptionally high rate of heat transfer in this material. Therefore one would expect that preheating the tungsten workpiece would make it possible to achieve the necessary shear zone temperature at correspondingly lower cutting speeds. However, one would not expect that preheating of the workpiece would produce an appreciable reduction in the incidence of spalling and thermal cracking of ceramic tools.

EFFECT OF DENSITY AND CARBON CONTENT

The influence of variable density and of different carbon contents are shown respectively in Figures 3 and 4. Figure 3 for example shows a plot of the tangential component of cutting force for three different values of density at a constant size of cut and at a constant cutting speed of 150 fpm. It was at this speed that the transition to equilibrium cutting forces had been substantially achieved in all materials 1 through 7. It will be noted that the forces are lower with lower density but it is also significant that the chips are not as continuous and the machined surface is not as good.

Essentially the same observations can be made for the variable carbon series except that the force variations were somewhat erratic with the possibility of the higher carbon content of 0.018% actually producing some increased friability of this particular composition. Giving weighted consideration to forces, chip formation and surface finish one must conclude that the best machining results for uninfiltrated tungsten is achieved at highest density and lowest carbon content.

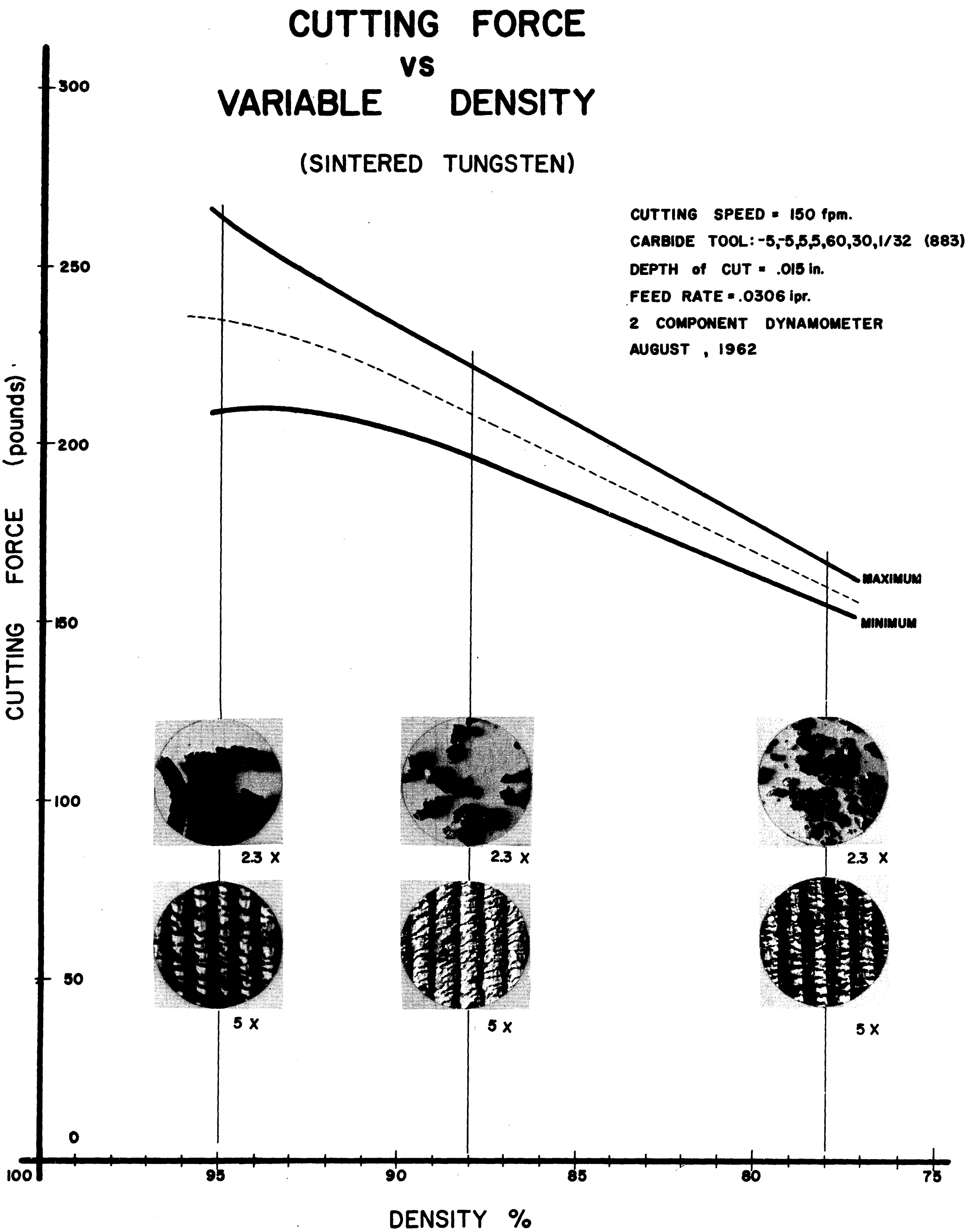

Figure 3. Shows the effect of variable density on tangential cutting force, chip formation and surface finish at constant cutting conditions. All tests made with new tools. Data for 95% density were obtained from a different test specimen than that used for the data in Figure 1.

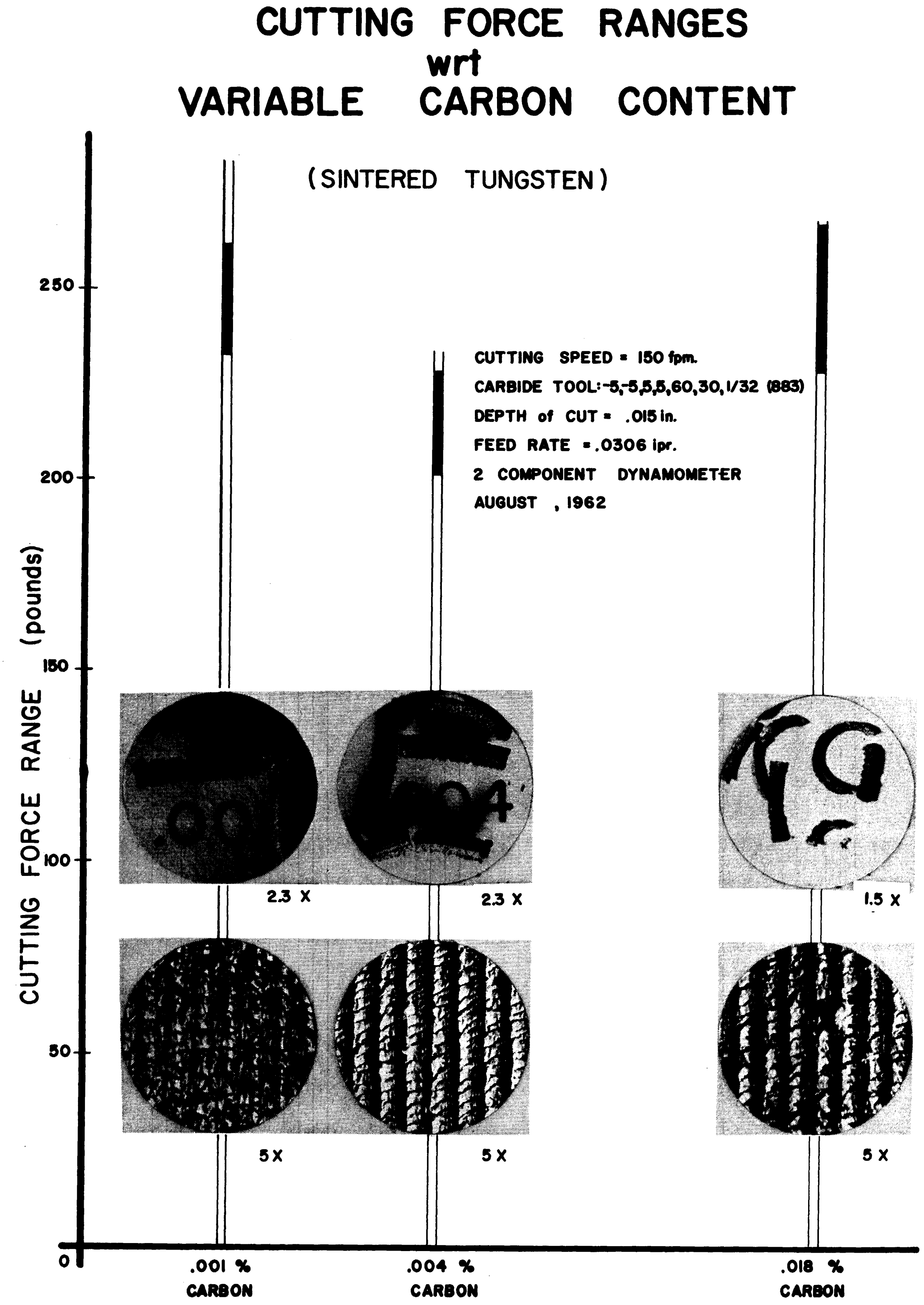

Figure 4. Similar to Figure 3 except that it illustrates the influence of different amounts of carbon at an average density of 94%.

EXTRUDED AND INFILTRATED TUNGSTEN

Figure 5 presents a similar comparison for the extruded tungsten which had the highest density of 98% and for both the copper infiltrated and silver infiltrated tungsten. The light portions of the bars representing cutting force indicate the range of variation between the maximum and the minimum values recorded on the charts. From this one can conclude that the silver infiltrated tungsten provides appreciably smoother operation than the copper infiltrated tungsten which in turn is substantially better than the uninfiltrated, high density tungsten.

It should also be noted in this figure that the chips from both the copper and silver infiltrated tungsten are very well broken in contrast to the substantially continuous chips obtained with the extruded tungsten. This is of course an advantage in chip handling but more importantly it means also that the cutting temperatures were as yet no where near the transition zone where the chips approach becoming continuous. This condition persists even at cutting speeds as high as 1600 fpm.

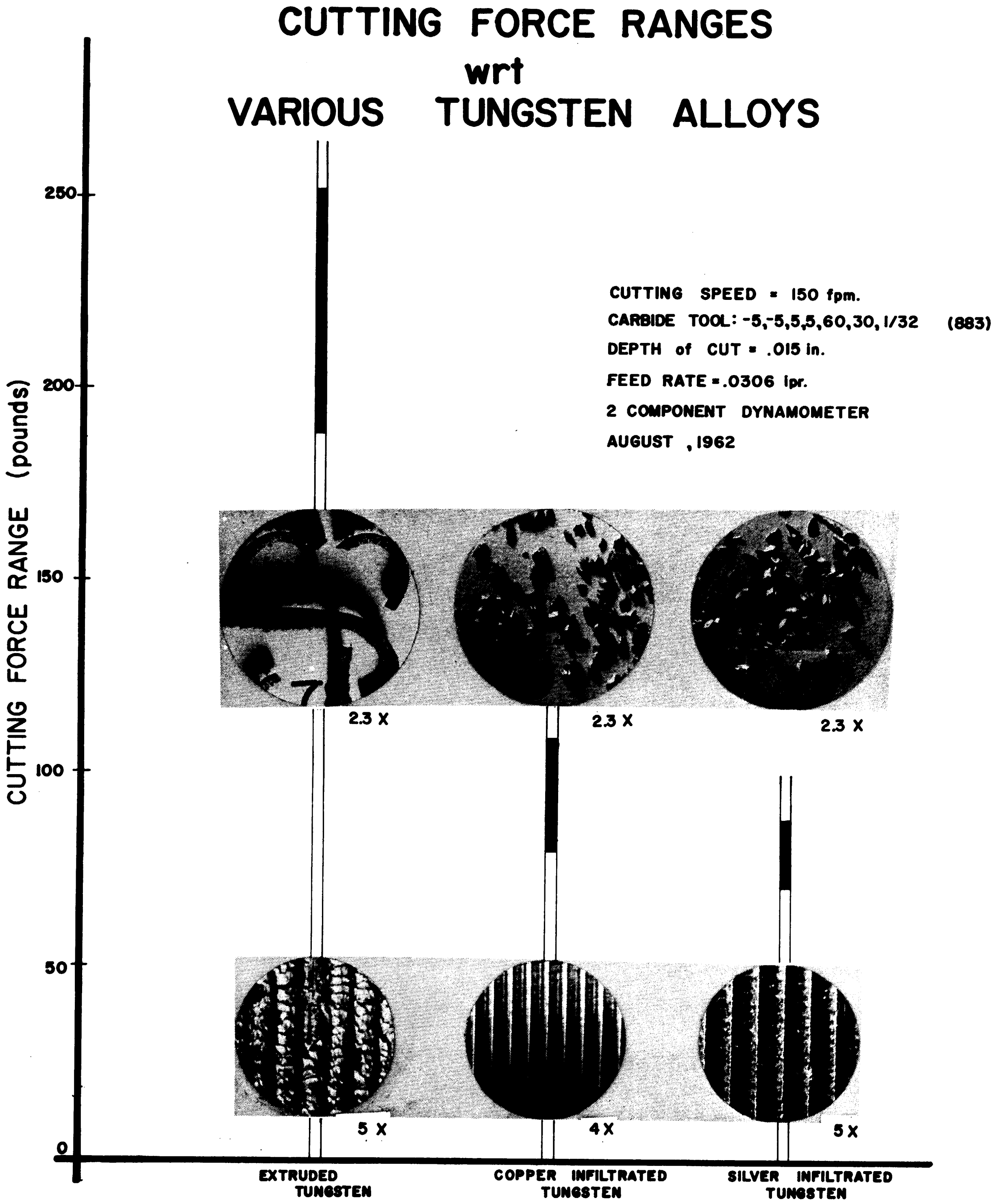

Figure 5. Similar to Figures 3 and 4 except that it compares extruded tungsten which had the highest density (98%) with copper and silver infiltrated tungsten.

SURFACE FINISH

The significant cutting characteristics referred to in the previous section are illustrated and clarified further in pictures of the machined surfaces. These are included in Figures 6, 7, and 8.

STARTING CONDITIONS

Figure 6 shows pictures of surfaces obtained at the beginning of a cut at cutting speeds of 150, 200, 275, and 350 fpm, respectively. Figure 7 shows pictures of the surfaces obtained during the same cuts at later times after temperature had achieved equilibrium. It will be noted that the best finish is obtained at the highest speed of 350 fpm but even then only after equilibrium temperature has been achieved. The cut surface is badly torn at all four speeds at the beginning of the cut. This is accompanied by varying degrees of rough cutting which increases the danger of sudden spalling of the friable tool materials. Thus one would expect that both preheating of the workpiece and the cutting tool would hasten the achievement of equilibrium temperature in the shear zone and thereby increase tool life as influenced by this property.

THERMAL CRACKS

Cracks will be noted in Figure 7 in the pictures for the surfaces produced at 150 and 275 fpm. Similar cracks also occurred at 200 fpm. These are thermal cracks resulting from the fact that the tool did not move rapidly enough along the longitudinal axis of the workpiece as it was being turned in the lathe. The cracks are the origin of the spalling referred to earlier in the report as being common at low traverse or feed rates. This is another reason for restricting cutting conditions to shallow depth of cut, high feed rates in ipr and high cutting speeds in fpm.

EFFECT OF SIZE OF CUT

Figure 8 shows similar pictures obtained for equilibrium cutting conditions at a constant speed of 275 fpm constant depth of cut of 0.020 inch and feed rates ranging from 0.005 to 0.026 ipr. It is evident from these pictures that high speed alone does not assure a high enough temperature in the shear zone to produce smooth cutting conditions and a smooth surface. The smaller feed rates present almost as much surface area per unit length of chip as do the heavier feed rates. This causes heat to be transferred faster from the shear zone resulting in lower shear zone temperatures, rougher cutting and poorer finish. One concludes from this that the choice of cutting speed, feed rate, depth of cut and tool shape should be such as to retain a sufficiently high temperature in the shear zone. For example, a lighter feed rate must be accompanied by an increase in speed to cope with the higher rate of heat transfer from the surfaces of the chip.

FORCES AND POWER REQUIREMENTS

Cutting forces were measured both with a three-component dynamometer and a two-component dynamometer and in some cases with both tungsten carbide tools and ceramic tools.

EFFECT OF SIZE OF CUT

Figure 9 summarizes the cutting force components obtained for turning material No. 1, high density tungsten, at a constant cutting speed of 275 fpm with ceramic tools over ranges of both feed rate and depth of cut. It is particularly significant that the radial component of cutting force is almost as large as the tangential component in most cases. On the other hand, the feeding force is appreciably less as is common in cutting most other metals. The relatively high level of the radial force component emphasizes the need for exceptional rigidity in the machining of tungsten as in the case of some titanium alloys which also exhibit this same characteristic. The results plotted in Figure 9 are summarized in equation form in Table II.

COMPARISON OF MATERIALS AT CONSTANT SIZE OF CUT

Three components of cutting force were obtained for all seven of the uninfiltrated tungsten materials while turning with tungsten carbide tools at speeds ranging from 20 to 150 fpm at a constant size of cut. These are summarized in Tables III, IV, and V respectively for the tangential, radial and feeding components. The values recorded in these tables represent maximum values obtained from the records.

INFILTRATED TUNGSTEN

Similar three component force information is given in Table VI for both the copper and silver infiltrated tungsten for a broader range of speeds and including both carbide and ceramic tools. This information in turn is plotted for each component in Figures 10, 11, and 12 thus permitting a comparison between the silver and copper on the one hand and with the results for high density tungsten as plotted in Figure 1 on the other hand.

Attention is called to shapes of the curves for radial force as shown in Figure 11. It will be noted that a maximum occurs for the copper infiltrated material at a cutting speed of about 150 fpm. It is believed that this maximum arises from the same basic causes which produced a maximum at about 40 fpm for high density tungsten as shown in Figure 1. The same characteristic appears

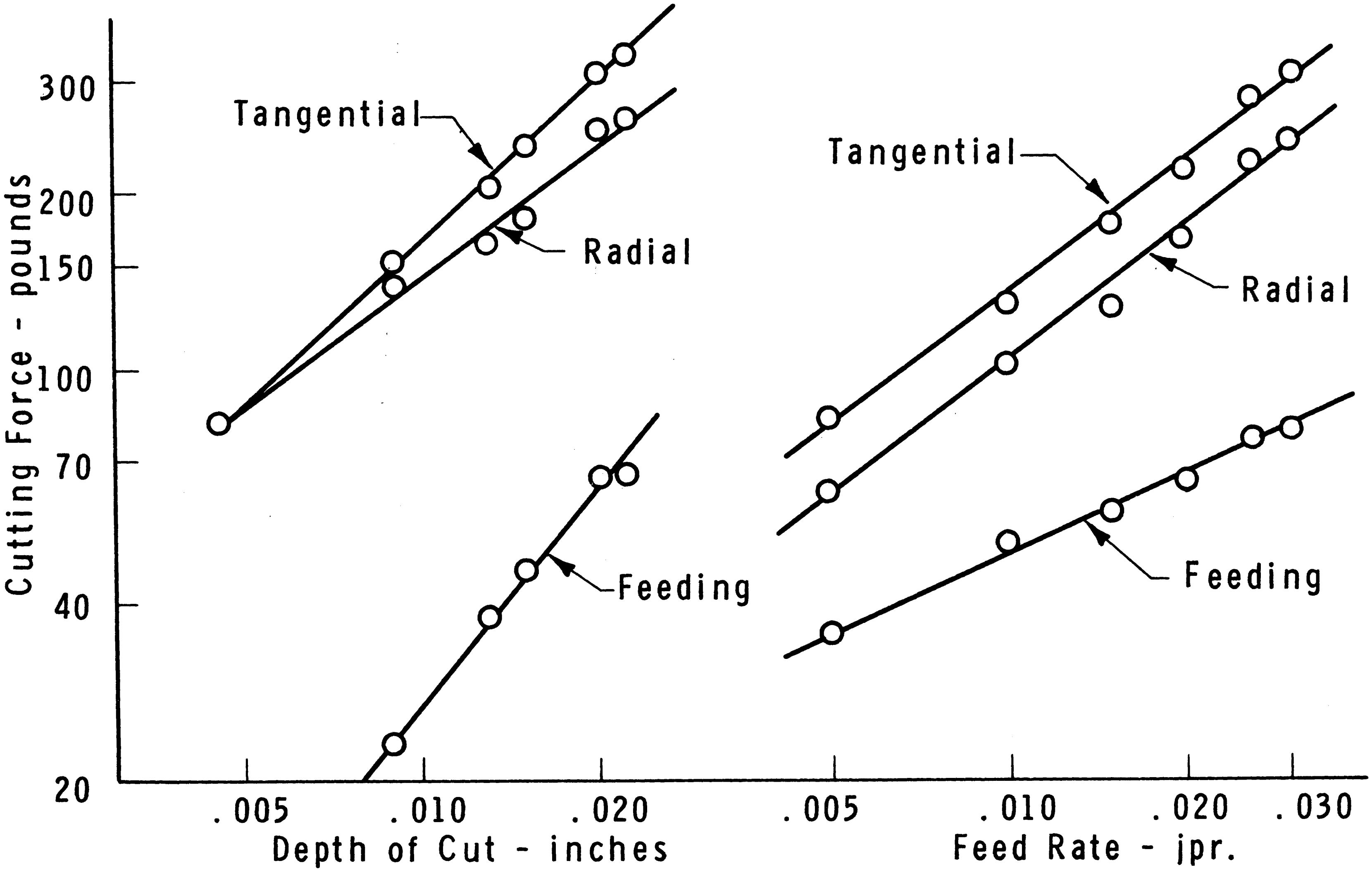

Figure 9. Influence of size of cut on 3-components of cutting force when turning sintered, high density tungsten with ceramic tools. Cutting speed was constant at 275 fpm. Feed rate was held constant at 0.030 ipr for variable depth series. Depth of cut was constant at 0.020 inch for variable feed series.

TABLE II

SUMMARY OF CUTTING FORCE EQUATIONS*

Force Component	Equation**
Tangential	$F_t = 166{,}000f^{.76}d^{.92}$
Radial	$F_t = 62{,}000f^{.75}d^{.75}$
Feeding	$F_t = 49{,}000f^{.46}d^{1.23}$

*Data obtained with 3-component dynamometer while turning with ceramic tools at a constant speed of 275 fpm.

**Force is in lb: d = depth of cut in in.; f = feed rate in ipr.

TABLE III

SUMMARY OF TANGENTIAL FORCES*

(Obtained with three-component dynamometer)

Material No.	Cutting Speed, fpm						
	20	40	60	80	100	125	150
1	310	380	325	275	275	285	255
2	263	288	363	325	306	306	363
3	156	200	220	231	200	244	250
4	318	350	325	294	313	287	300
5	238	206	262	256	288	312	307
6	350	313	288	350	350	375	350
7	325	337	343	300	294	420	375

*Forces in pounds for a turning cut with carbide tools at a depth of cut of 0.015 in. and a feed rate of 0.030 ipr.

TABLE IV

SUMMARY OF RADIAL FORCES*

(Obtained with three-component dynamometer)

Material No.	Cutting Speed, fpm						
	20	40	60	80	100	125	150
1	210	280	225	200	130	120	130
2	140	190	245	240	240	270	235
3	95	133	157	165	145	185	210
4	245	225	280	265	310	280	325
5	215	180	260	260	320	375	400
6	240	240	230	295	340	375	400
7	225	265	285	250	265	412	412

*Forces in pounds for a turning cut with carbide tools at a depth of cut of 0.015 in. and a feed rate of 0.030 ipr.

TABLE V

SUMMARY OF FEEDING FORCES*

(Obtained with three-component dynamometer)

Material No.	Cutting Speed, fpm						
	20	40	60	80	100	125	150
1	65	80	65	55	60	60	65
2	50	55	70	63	60	68	51
3	35	43	50	49	43	51	54
4	61	60	64	60	68	58	50
5	33	33	60	58	65	70	70
6	65	60	50	65	63	70	55
7	44	54	63	55	55	70	45

*Forces in pounds for a turning cut with carbide tools at a depth of cut of 0.015 in. and a feed rate of 0.030 ipr.

TABLE VI

THREE COMPONENTS OF CUTTING FORCE* FOR INFILTRATED TUNGSTEN

Material	Force Component	Carbide Tools							Ceramic Tools			
		Cutting Speed, fpm							Cutting Speed, fpm			
		20	40	60	80	100	125	150	150	250	350	500
Copper Infiltrated	Tangential	110	106	115	115	109	115	115	120	120	118	120
	Feeding	12	11	12	14	14	15	15	16	14	14	12
	Radial	54	50	53	64	63	70	71	68	65	58	51
Silver Infiltrated	Tangential	83	81	75	83	80	80	80	87	93	94	98
	Feeding	11	10	10	11	10	11	12	10	12	11	11
	Radial	40	40	38	40	39	43	48	43	48	48	47

*Data obtained for turning at constant depth and feed rate of 0.015 in. and 0.030 ipr respectively. Forces are given in pounds.

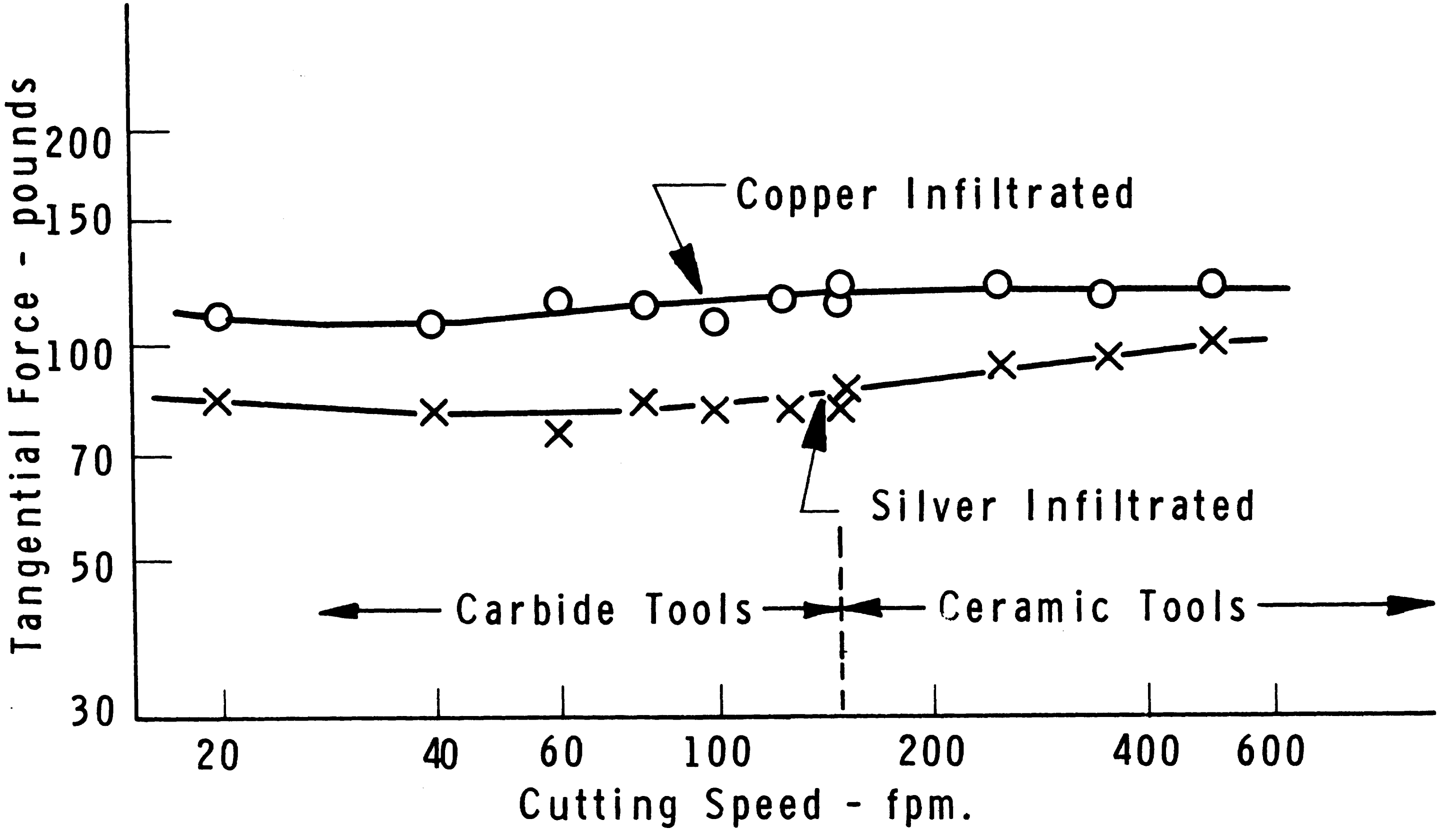

Figure 10. Comparison of tangential cutting forces for copper and silver infiltrated tungsten. Tool holder = KSDR-16; 1/2 inch square x 1/8 inch thick inserts. Carbide = Carboloy 883; ceramic = Carboloy 0-30 Depth of cut = 0.015 inch; feed = 0.030 ipr. 3-component dynamometer.

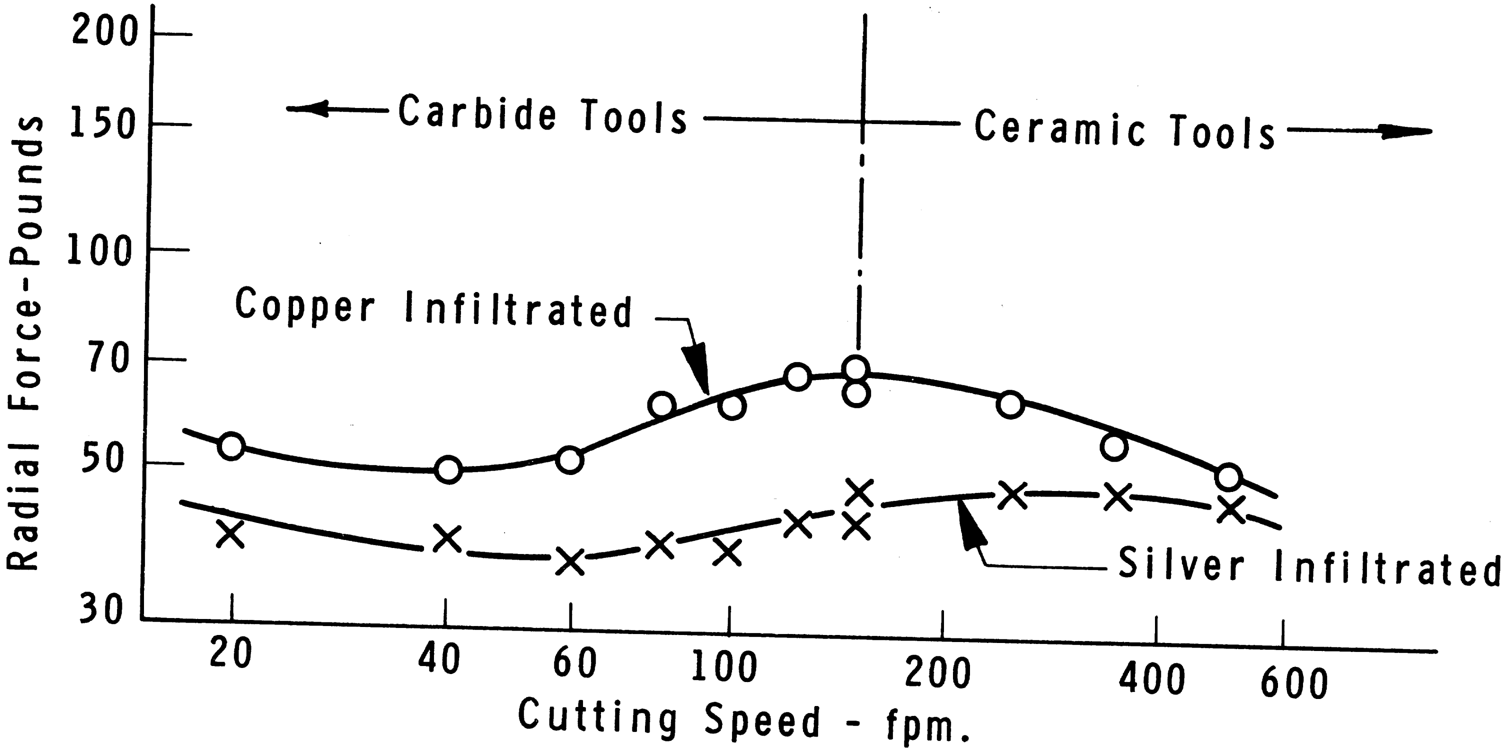

Figure 11. Comparison of radial cutting forces for copper and silver infiltrated tungsten. Cutting conditions same as for Figure 10.

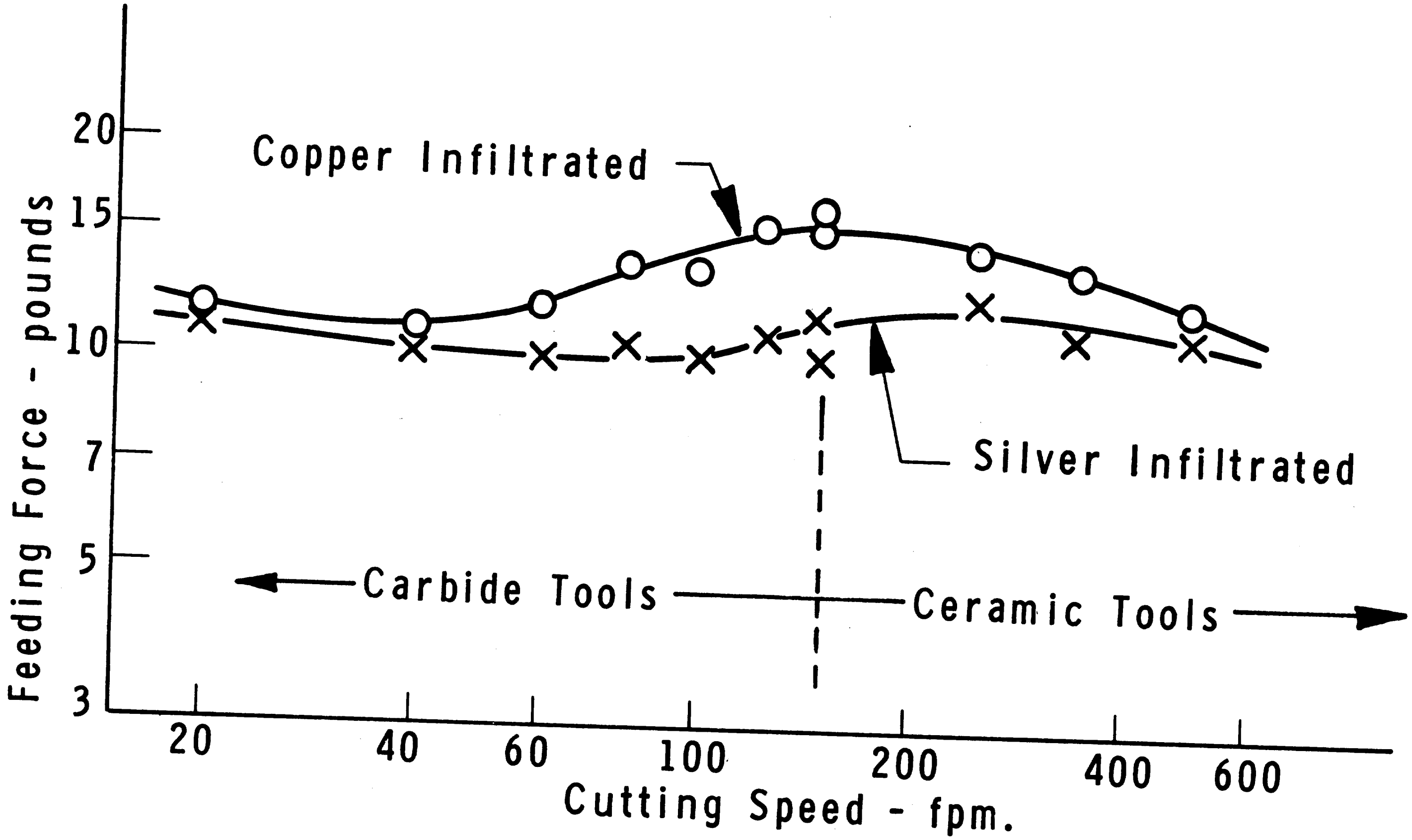

Figure 12. Comparison of feeding forces for turning copper and silver infiltrated tungsten. Cutting conditions same as for Figure 10.

with the silver infiltrated material but with the maximum occurring somewhere around 300 fpm. Thus it appears feasible for the forces from both the copper and infiltrated tungsten materials to drop still further with increases in cutting speed ranging up to perhaps 2000 to 3000 fpm. The same shape characteristics of the force curves are evident in all three components although it is obviously least in the case of the tangential component as plotted in Figure 10.

TWO-COMPONENT MEASUREMENTS

Summaries of the average cutting forces as measured in a two component dynamometer are given in Tables VII and VIII for all nine types of tungsten material as cut with both carbide and ceramic tools. These results show the same qualitative behavior as those obtained with the three-component dynamometer.

POWER REQUIREMENTS

Power requirements at three different conditions are summarized for one size of cut in Table IX. The steady-state values listed in the last column represent the requirements at satisfactory cutting conditions which means smooth cuts at high speeds. The peak values reported in the next to the last column are typical of the maximum forces encountered at speeds below 140 fpm. Those in the second column identified as "initial values," refer to the lowest values of forces which occurred in the range of 20 fpm cutting speed.

The steady-state values for the uninfiltrated tungsten range from 1.0 to a little more than 1.25 hp/in.^{3}/min. This is only slightly higher than what normally would be required by a medium carbon alloy steel. Consequently, exceptionally high power requirements is not a unique property in the machining of high density tungsten. On the other hand the infiltrated tungstens designated in the table as materials 8 and 9 show very little variation in the power requirements as between the three columns. More importantly the average power requirements for both copper and silver infiltrated tungsten is approximately 1/2 hp /in.^{3}/min which is of the same order of magnitude as that required for cast iron and brass.

TABLE VII

SUMMARY OF TANGENTIAL FORCES*
(Obtained with two-component dynamometer)

Material No.	Carbide Tools Cutting Speed, fpm							Ceramic Tools Cutting Speed, fpm			
	20	40	60	80	100	125	150	150	250	350	500
1	206	197	255	304	234	230	234	224	214	215	215
2	190	240	281	284	350	260	208	192	188	194	-
3	81	103	110	140	147	160	160	215	180	175	175
4	327	331	281	262	250	250	260	219	231	231	190
5	340	305	230	243	243	220	215	197	233	240	-
6	-	340	260	247	266	255	247	210	225	208	200
7	281	295	295	270	246	265	239	264	201	215	206
8	92	100	106	110	112	105	105	103	100	100	87
9	96	87	92	87	87	82	80	65	70	72	70

*Average forces in pounds for a turning cut at a depth of 0.015 inch and a feed rate of 0.030 ipr.

TABLE VIII

SUMMARY OF FEEDING FORCES*
(Obtained with two-component dynamometer)

Material No.	Carbide Tools Cutting Speed, fpm							Ceramic Tools Cutting Speed, fpm			
	20	40	60	80	100	125	150	150	250	350	500
1	32.5	35	47.5	43	43	45.5	46	55	52.5	45	45
2	50	60	70	75	67.5	52	-	-	22	35	-
3	20	25	25	34	36	36	40	48	40	34	19
4	31	65	54	52	58	67	77	80	68	53	55
5	55	65	52	56	55	53	47	60	53	70	-
6	62	72.5	65	60	70	80	55	48	45	41	22.5
7	52	60	63	52.5	43	57	48	53	43	43	38
8	14	14	13	15	15	16	15	22	15	15	19
9	15	12.5	15	12	12	13	13	13	8	9	13

*Forces in pounds for a turning cut at a depth of 0.015 inch and a feed rate of 0.030 ipr.

TABLE IX

TYPICAL POWER REQUIREMENTS[a]

Material No.	Initial[b]	Peak[c]	Steady-State[d]
1	1.101	1.414	1.222
2	1.212	1.651	1.045
3	0.523	1.046	0.975
4	1.812	1.910	1.250
5	1.868	1.868	1.268
6	1.980	2.125	1.156
7	1.541	1.634	1.129
8	0.531	0.616	0.551
9	0.523	0.523	0.396

(a) Values tabulated are unit horsepower-HPu which is the power required to cut the metal at a rate of 1 in.^{3}/min. They were calculated for a feed of 0.030 ipr and a depth of 0.015 inch.

(b) Typical of lowest requirements at low speed.

(c) Typical of maximum over entire speed range.

(d) Typical of good cutting conditions with ceramic tools used at high speeds.

TOOL WEAR

Tool wear studies were made only on materials No. 1, 8, and 9; the latter two being the copper and silver infiltrated materials respectively.

FOR HIGH DENSITY

It was possible to obtain reliable tool wear information only with the Carboloy 0-30 ceramic tools in the machining of high density tungsten. Even then numerous tests had to be carried out because of the aforementioned difficulties surrounding early spalling of the cutting tools. Some earlier tests reported in one of the progress reports were represented by the equation $VT^{.125}=215$. Further tests were run at these same conditions and are plotted along with the earlier results in Figure 13.

The two parallel lines in this figure represent the upper and lower limits of expectancy as obtained for a cut at 0.030 ipr feed rate and 0.030 in. depth of cut. The tool life was established as that time at which the width of the land worn on the flank of the tool reached 0.040 in. It can be seen that the lines representing these limits are steeper than previously reported. The lower one which represents the minimum performance is represented by the equation $VT^{.2} = 190$. A similar equation relating the area (A) to the cutting speed (V) is $VA^{.25} = 540$ where the area (A) is expressed in square inches and the cutting speed (V) in fpm.

FOR INFILTRATED TUNGSTEN

Limited volume of the infiltrated tungsten materials did not permit obtaining a full cutting speed tool life curve of the type shown in Figure 13. Instead, progressive measurements were made of the width of the wear land at a cutting speed of 1600 fpm while turning at a depth of cut of 0.015 in. and a feed rate of 0.005 ipr. The results are shown plotted in Figure 14.

It is evident that the wear rates for both materials are less than 10% that of the high density tungsten even though the speed is more than 8 times as great as that which gave 10 times the wear rate with the high density material. It would appear that the silver infiltrated material has a slight advantage over the copper infiltrated material with regard to rate of wear.

Roughness measurements were made of the surfaces produced by the tool wear tests on the infiltrated tungsten materials and these are combined in Table X with some obtained for surfaces machined in the force tests. It will be noted

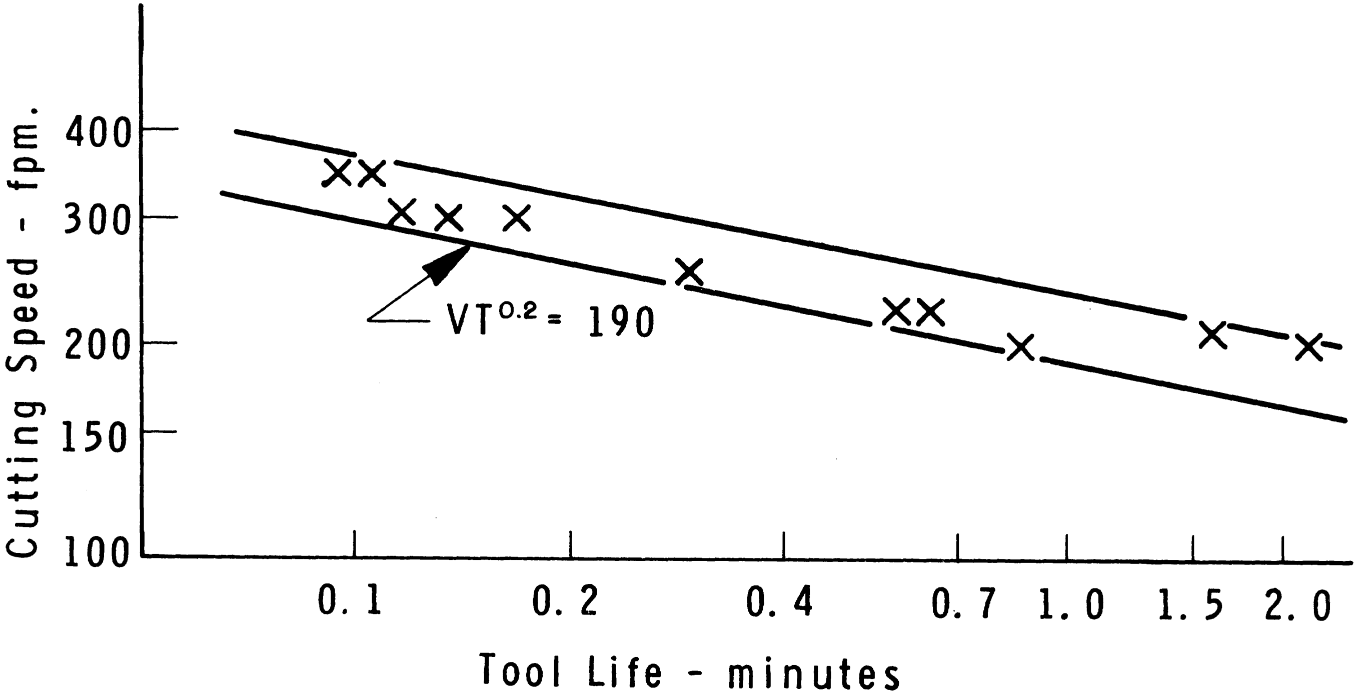

Figure 13. Tool life line for high density (95%) tungsten turned with Carboloy O-30 ceramic tools at a depth of 0.030 inch and a feed rate of 0.030 ipr. Tools were preheated in a muffle-furnace to 1250°F. Tool life is defined as elapsed cutting time required to produce a wear land 0.040 inch wide on the flank of the tool.

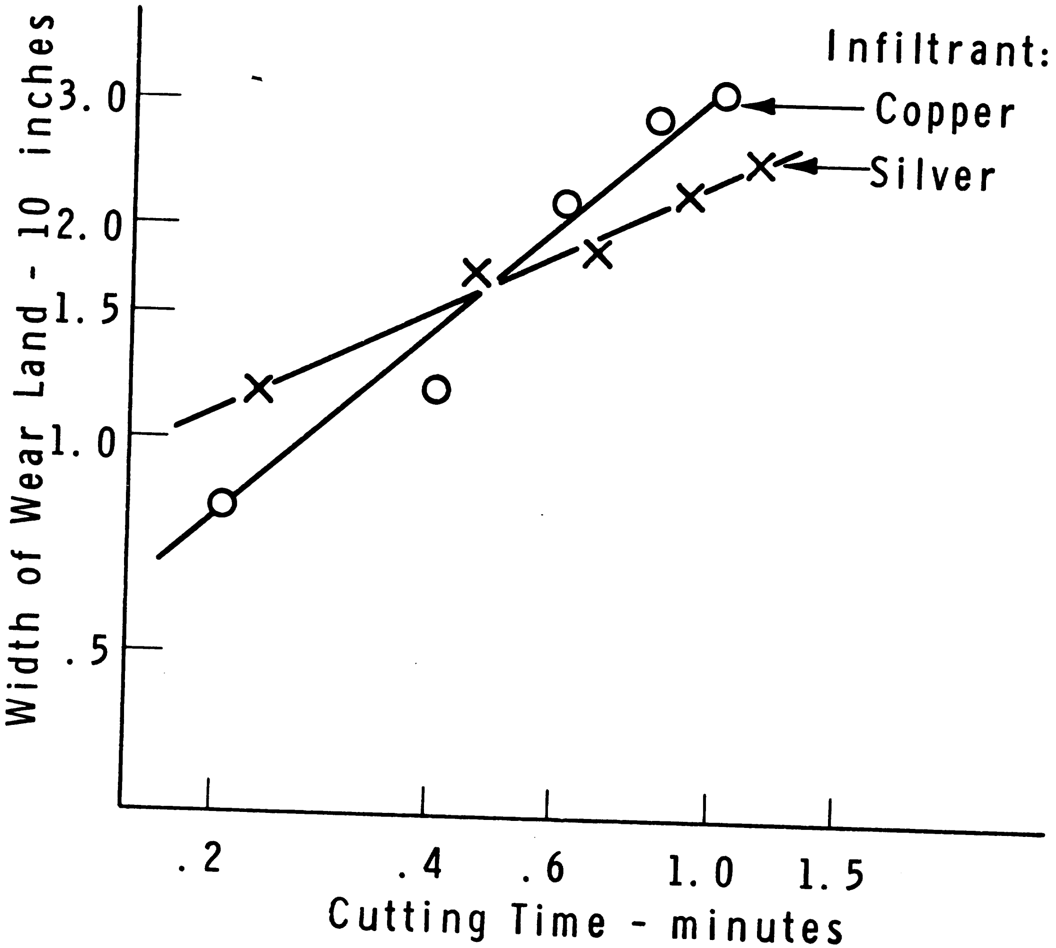

Figure 14. Wear of carbide tools at a constant cutting speed of 1600 fpm. Depth of cut = 0.015 inch and feed = 0.005 ipr. Carboloy Grade 883, 1/2 inch square x 1/8 inch thick inserts. Tool signature = -5,-5,5,5,45,45,1/32.

TABLE X

ROUGHNESS OF TURNED SURFACES ON INFILTRATED TUNGSTEN

Cutting Speed, pm	Feed, ipr	Depth, in.	Tool Material	Roughness-Microinches, rms			
				Copper		Silver	
				Cutting Direction	Feeding Direction	Cutting Direction	Feeding Direction
150	.030	.015	carbide	13-17	130-160	13-17	160-240
350	.30	.015	ceramic	*40-55	80-120	*50-70	90-190
500	.30	.015	ceramic	*60-80	120-180	*50-70	130-190
1600	.005	.015	carbide	6-8	35-40	7-8	45-55

*High values caused by burr formation at crest of feed marks.

significantly that the surface roughness in the cutting direction is very low on both materials at the highest cutting speed. The range of 13 to 17 microinches in the cutting direction at the lowest cutting speed is also very good. The higher values shown for the ceramic tools were due to a slight chatter which in turn created burrs at the crest of the feed marks. This does not accurately reflect the very good surfaces which can be obtained with these materials. The higher values reported in the feeding direction are typical of the minimum values that would be expected on any metal at the feed rates which were used.

CONCLUSIONS

With regard to the high density or uninfiltrated tungsten one may conclude the following:

1. The material is basically notch sensitive and as such exerts a unique influence on the cutting characteristics.

2. It is essential to cut at temperatures high enough to overcome or at least to mimimize notch sensitivity.

3. Sufficiently high temperatures in the shear zone can be attained through proper combinations of

   a. preheating the workpiece,
   b. preheating the cutting tool,
   c. high speeds and heavy feed rates,
   d. use of ceramic tools,
   e. the use of ceramic or chrome carbide tool supports or other means to inhibit heat transfer from the tool insert into the tool holder.

4. Preheating of the tool appears to be accomplished most satisfactorily outside of the tool holder in a small muffle furnace.

5. Machine, tool holder and work clamping should be as rigid as possible.

6. Tapering or beveling the workpiece at the point of tool entry to provide for gradual increase in size of cut would be helpful.

7. Carbide tools are completely unsatisfactory.

With regard to infiltrated tungsten

1. Both tungsten carbide and ceramic tools can be used at very high speeds.

2. Difficulty in machining is not appreciably greater than that experienced with ordinary cast iron.

3. Commercial tooling and practices for cast iron can be expected to be satisfactory for both copper and silver infiltrated tungsten.

APPENDIX

TABLE XI

COMPOSITION OF WORK MATERIALS

Code No.	Process	Density, %	Carbon %	Al	Ca	Si	Fe	Cr	Ni	Cu	Mo	Mn	Mg	Sn
1	Sintered (Variable Density)	95.01	.001	.001	.001	.001	.001	.001	.001	.001	.004	.001	.001	.001
2	Sintered (Variable Density)	88.52	.002	.001	.001	.001	.002	.001	.001	.001	.006	.001	.001	.001
3	Sintered (Variable Density)	77.71	.001	.001	.001	.001	.004	.001	.001	.001	.006	.001	.001	.001
4	Sintered (Variable Carbon)	94.24	.001	.001	.001	.001	.003	.001	.001	.001	.003	.001	.001	.001
5	Sintered (Variable Carbon)	94.51	.004	.001	.001	.001	.001	.001	.001	.001	.005	.001	.001	.001
6	Sintered (Variable Carbon)	93.8	.018	.001	.001	.001	.001	.001	.001	.001	.003	.001	.001	.001
7	Extruded (High Density)	98.00	.002	.001	.001	.001	.002	.001	.001	.001	.001	.001	.001	.001
8	Copper Infiltrated	89.00*	.003	.001	---	.001	.02	.02	.02	---	.01	---	---	---
9	Silver Infiltrated	92.00**	.003	.001	---	.001	.02	.02	.02	---	.01	---	---	---

*Density before infiltration was 78%.

**Density before infiltration was 81%.

TABLE XII

SUMMARY OF TOOL SPECIFICATIONS

Insert Material	Specifications For Two-Component Dynamometer Used in 14-Inch Lathe*	 For Three-Component Dynamometer Used in 22-Inch Lathe**
Carboloy 883 Carbide	TBT - 163U3 A triangular tool 15/16 inch on a side with a 3/64 inch nose radius; 1/8 inch thick.	SQT - 163 - P2 A square tool 1/2 inch on a side with a precision ground 1/33 inch nose radius; 1/8 inch thick.
Carboloy 0.30 Ceramic	TBT - 163 - P2 A triangular tool 15/16 inch on a side with a precision ground 1/32 inch nose radius; 1/8 inch thick.	SQT - 163 - P4 A square tool 1/2 inch on a side with a precision ground 1/16 inch nose radius; 1/8 inch thick.

Tool Signature

*For 14-inch Lathe - triangular
Signature: -5,-5,5,5,60,30,R

**For 22-inch Lathe - square KSDR-16
Signature: -5,5,5,45,45,R