669.13-18:621.941.011

Machinability of Nodular Cast Irons*

(Tool Life Tests on Pearlitic Nodular Cast Irons)

By Katsundo HITOMI**, Inyong HAM*** and George L. THUERING****

Tool life tests were conducted on nodular cast iron grades 100-70-03 and 80-60-03 with carbide and ceramic cutting tools. It was found that the cast iron cutting grade carbide was much superior to the steel cutting grade carbide from the standpoint of tool life and metal removal rate. With these carbides, crater wear developed at high speeds as well as flank wear in the entire speed range tested. Ceramic cutting tool had superior cutting performance. Its tool life was greater than that for the cast iron cutting grade carbide at high speeds. The slope of the tool life curve for a ceramic tool was much steeper than that for a carbide tool. Cutting performance for grade 80 nodular cast iron was not always better than that for grade 100 nodular cast iron, though grade 80 is a little softer than grade 100.

1. Introduction

The previous paper, Machinability of Nodular Cast Irons (Tool Forces and Flank Adhesion Phenomenon)⁽¹⁾ reported the results of cutting tests to determine the tool forces required to machine three grades of nodular cast iron (60, 80, and 100) and the cutting performance of several grades of carbide and ceramic cutting tools. Cutting characteristics for grades 80 and 100 were found to be the same as for high-strength gray cast irons with similar Bhn values. When grade 60 was machined with carbide tools, a build-up developed on the flank of the cutting tool and was accompanied by sharp increases in tool forces. This flank build-up occurs in the speed range over a certain cutting speed and flows out between the flank of the tool and the work material in the form of a ribbon.

The effects of cutting conditions, such as feed rate, rake angle, clearance angle, and cutting fluid, on flank adhesion phenomenon were also investigated, and methods were recommended to prevent the development of flank adhesion in practical machining. In addition, the flank build-up was analyzed chemically and metallurgically in an effort to explain its occurrence.

Regarding tool life tests on nodular cast iron,

the 1950 United States Air Force Machinability Report⁽²⁾ states that nodular iron, depending on its strength, has tool life values corresponding to or exceeding those for gray cast iron of considerably less tensile strength, and that the tool life for machining nodular iron is about equal to that for machining cast steels of similar hardness. Hug⁽³⁾ reported the effect of material hardness on the tool life and that increasing the free nodular graphite improves machinability markedly and also larger nose radii of cutting tools, consistent with finish, are desirable.

The purpose of the investigation here reported was to determine the tool life for carbide and ceramic cutting tools when machining pearlitic nodular cast irons, i.e., grades 100 and 80. In addition, the wear of carbide and ceramic tools was investigated.

2. Test equipment and procedure

The tool life tests were conducted in a Lodge and Shipley lathe equipped with a Reeves variable-speed drive.

The tests were run on pearlitic nodular cast irons, grades 100 and 80. The composition, Brinell hardness, and heat-treatment of these grades are given in Table 1. The microstructures of grades 100 and 80 of nodular cast iron are shown in Fig. 1. The microphotographs show the characteristic spheres of carbon, the essentially pearlitic structure of grade 100 and the combined pearlitic and ferritic structure of grade 80. The billets were poured from standard production heats and were subject to standard production heat treatment. Billets were 58 cm long and

* Received 7th August, 1962.

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20 cm in diameter with a cored hole of 9 cm diameter.

All the tests were run with the tool on center, using a clamp-type tool holder and square throw-away carbide and ceramic inserts. The hardness and composition of the carbide and ceramic inserts are

Table 1 Composition, hardness, and heat treatment of nodular cast irons tested

Description	Grade	
	100-70-03	80-60-03
Composition		
Graphitic carbon*	2.66	3.06
Combined carbon*	0.70	0.46
Total carbon*	3.36	3.52
Silicon	2.35	2.23
Manganese	0.84	0.40
Phosphorus	0.058	0.059
Sulfur	0.018	0.022
Copper	0.44	0.08
Nickel	0.05	0.42
Chromium	0.03	0.03
Molybdenum	0.01	0.09
Vanadium	0.01	0.01
Magnesium	0.059	0.033
Brinell hardness		
Range	229~248	204~232
Mean	237	214
Heat treatment	540°C for 2 hr, furnace cooled	885°C for 2 hr, air cooled 540°C for 4 hr, furnace cooled

* Based on analysis of as-cast material (not a chill).

given in Table 2. Tool geometry and insert dimensions were:

Back rake angle	-5 deg
Side rake angle	-5 deg
End relief angle	5 deg
Side relief angle	5 deg
End cutting edge angle	15 deg
Side cutting edge angle	15 deg
Nose radius	0.8 mm

Insert dimensions (square)

12.7×3.2 mm for carbide

12.7×4.8 mm for ceramic

A new cutting edge was used for each test. The inserts were precision ground and were used as obtained from the manufacturer.

Tests were run under the following conditions:

Depth of cut	2.54 mm
Feed	0.127, 0.254, 0.381 mm/rev
Cutting speed, m/min	45 to 185 m/min for carbide 90 to 305 m/min for ceramic

The tool life criterion in this experiment was a flank wear land of 0.381 mm (0.015 in). The wear land was measured with a Bausch and Lomb Tool-makers' microscope, and the cutting was continued until the wear land reached 0.381 mm (0.015 in). Cutting speed was set with a surface speed indicator, and was monitored for change by means of a tachometer mounted on the spindle of the lathe.

All tests were conducted dry.

(a) Grade 100-70-03

(b) Grade 80-60-03

Fig. 1 Typical photographs of pearlitic nodular cast irons tested (×400)

Table 2 Chemical compositions and properties of cutting tools used

Tool*	Density g/cm ³	Hardness Rockwell A	Composition (Percent by weight)							
			W	Co	Ti	Ta	Nb	Ni	Mo	C
Carbide										
C-1	14.9	92.0	86.4	5.74	—	2.0	—	—	—	5.8
C-3	11.1	92.0	65.5	8.75	10.5	2.9	4.6	—	—	7.7
C-8	5.5	93.5	—	—	64.0	—	—	10.0	10.0	16.0
Ceramic O-1	—	92.1	Major ingredient: Aluminum oxide							

* Carbides C-1, C-3, and C-8 are grades K6 (cast iron cutting grade), K3H (steel cutting grade), and 5939 (titanium carbide) of Kennametal, Inc., respectively, and ceramic O-1 is Tungalox of Toshiba Tungalox Co. These symbols are the same as those used in the first report⁽¹⁾

3. Tool life for grade 100-70-03 nodular cast iron

The tool life tests on grade 100 nodular cast iron, which has essentially a pearlitic structure, were run with three grades of carbide, C-1, C-3, and C-8, and one type of ceramic, O-1. The results of tool life tests are given in Figs. 2 and 3 as Taylor tool life curves on bilogarithmic paper, showing the relationship between cutting speed and tool life for a wear land of 0.381 mm (0.015 in). Fig. 2 shows tool life curves for four grades of cutting tool for a depth of cut of 2.54 mm and a feed of 0.254 mm/rev, and Fig. 3 shows tool life curves for the C-1 carbide and the O-1 ceramic for a depth of cut of 2.54 mm and several feeds.

The Taylor tool life equation which shows the relationship between cutting speed V in m/min and tool life T in min corresponding to a wear land of 0.381 mm (0.015 in) is given in the following equation.

$$VT^n = C,$$

where n and C are constants depending on the work material, tool material, cutting conditions, and others. A straight line was fitted and the constants in the above equation were determined by the method of least squares. The empirical formulae corresponding to Figs. 2 and 3 are listed in Table 3. The cutting speed corresponding to a 30 min tool life was calculated from the formula and is given in the table.

Referring to Fig. 2 and Table 3, in the case of carbide, the cast iron cutting grade carbide C-1 is much better than the steel cutting grade carbide C-3, namely, the cutting speed corresponding to a 30 min tool life is 60 m/min for C-1 and 39 m/min for C-3.

Table 3 Empirical tool life equations for nodular cast iron grade 100

Tool Material	Depth of cut mm	Feed mm/rev	Cutting speed range m/min	Tool life equation	Cutting speed for 30 min tool life m/min
Carbide C-1	2.54	0.127	75~155	$VT^{0.306} = 193$	68
		0.254	50~185	$VT^{0.325} = 180$	60
		0.381	50~125	$VT^{0.335} = 171$	55
Carbide C-3	2.54	0.254	45~185	$VT^{0.361} = 132$	39
Carbide C-8	2.54	0.254	120~185	$VT^{0.343} = 176$	55
Ceramic O-1	2.54	0.127	90~305	$VT^{1.198} = 2170$	37
		0.254	90~305	$VT^{0.817} = 842$	52

Tool life criterion, 0.381 mm (0.015 in) wear land on the tool flank; tool material, carbides C-1 (cast iron cutting grade), C-3 (steel cutting grade), and C-8 (titanium carbide) and ceramic O-1; tool geometry, -5° , -5° , 5° , 5° , 15° , 15° , 0.8 mm; depth of cut, 2.54 mm; feed, 0.254 mm/rev; dry

Fig. 2 Tool life curve for nodular cast iron grade 100 [1]

Tool life criterion, 0.381 mm (0.015 in) wear land on the tool flank; tool material, carbide C-1 (cast iron cutting grade) and ceramic O-1; tool geometry, -5° , -5° , 5° , 5° , 15° , 15° , 0.8 mm; depth of cut, 2.54 mm; feed, 0.127, 0.254 and 0.381 mm/rev; dry

Fig. 3 Tool life curve for nodular cast iron grade 100 [2]

Cutting speed m/min Tool	45.5	52.0	61.0	91.5	122.0	152.5	183.0	244.0	305.0
Carbide C-1	(54.67)	(25.56)	(7.10)	(3.09)	(1.84)	(1.03)	(0.41)	(4.93)	(3.25)
	(20.67)	(8.60)	(2.51)	(1.19)	(0.71)	(0.41)	(0.90)	(6.57)	(3.25)
Carbide C-3	(20.67)	(8.60)	(2.51)	(1.19)	(0.71)	(0.41)	(0.90)	(6.57)	(3.25)
Carbide C-8	(20.67)	(8.60)	(2.51)	(1.19)	(0.71)	(0.41)	(0.90)	(6.57)	(3.25)
Ceramic O-1	(20.67)	(8.60)	(2.51)	(1.19)	(0.71)	(0.41)	(0.90)	(6.57)	(3.25)

Tool material, carbides C-1 (cast iron cutting grade), C-3 (steel cutting grade), and C-8 (titanium carbide) and ceramic O-1; tool geometry, -5° , -5° , 5° , 15° , 15° , 0.8 mm; depth of cut, 2.54 mm; feed, 0.254 mm/rev; dry

Fig. 4 Photographs showing wear of carbide and ceramic cutting tools at the end of tool life for machining nodular cast iron grade 100 [Numbers in parentheses designate tool life (min), i.e., cutting time until wear land on the tool flank reaches 0.381 mm (0.015 in)]

Fig. 4 shows photographs of the tools at the end of tool life. In the low speed range, a built-up edge can be seen on the face and the tool reaches its final stage without any cratering on the face. In the high speed range, however, very little built-up edge exists and the tool reaches its final stage with a large amount of cratering on the face. Crater wear was observed for the steel cutting grade C-3 as well as the cast iron cutting grade C-1. The amount of crater was smaller for C-3 than for C-1 at the same flank wear land of 0.381 mm (0.015 in), but it should be noted that the tool life for C-3 was much shorter than that for C-1. The tool life curve for a titanium carbide C-8, the so-called cermet tool, is very similar to that for carbide C-1, as shown in Fig. 2, but the crater wear was much smaller as shown in Fig. 4.

The O-1 ceramic was consistent in performance and did not show any crater wear, as shown in Fig. 4. The cutting speed corresponding to a tool life of 30 min is 52 m/min. Another ceramic was tested, but under the cutting conditions used in these tests it failed frequently due to cracking and large chipping. Because of the inconsistent performance for this ceramic tool the results are not reported in this paper.

Comparing tool life curves for carbide and ceramic, Fig. 2, the slope of the tool life curve for ceramic is much steeper than that for carbide. The value of the constant n in the tool life equation is 0.3 for carbide and 0.8 for ceramic. It is evident from the curves that the ceramic is superior at high speeds and the carbides are superior at low speeds.

Fig. 3 shows the effect of feed rate on the tool life for carbide C-1 and the ceramic for depth of cut of 2.54 mm and three different feeds of 0.127,

0.254, and 0.381 mm/rev. The ceramic did not stand up well at a feed rate of 0.381 mm, and a curve is not shown for this feed. In the case of the carbide the tool life decreases with an increase in feed rate. However, with the ceramic, due to the differences in the slopes of the tool life curves the tool life for a feed of 0.127 mm/rev is higher than that of 0.254 mm/rev at high speeds, whereas it is lower at low speeds. The value of n for a feed of 0.127 mm/rev is 1.2 and for a feed of 0.254 mm/rev it is 0.8.

It is a noteworthy fact that a constant n expressing the slope of tool life curve for ceramic tool increases with a decrease in feed rate, and is sometimes greater than 1.

Fig. 5 shows the influence of cutting speed on the amount of metal removed for a 0.381 mm (0.015 in) wear land when machining grade 100 with carbides C-1 and C-3 and the ceramic O-1 for a depth of cut of 2.54 mm and a feed of 0.254 mm/rev. The amount of metal removed U in cm^3 is calculated from the following equations:

$$U = dfVT,$$

where d is depth of cut in mm, f is feed rate in mm/rev, V is cutting speed in m/min, and T is tool life at a wear land of 0.381 mm (0.015 in) in min. It is evident from Fig. 5 that the C-1 carbide is preferable at low speeds, less than 65 m/min, and the O-1 ceramic is preferable at speeds exceeding 65 m/min.

4. Tool life for grade 80-60-03 nodular cast iron

Similar tool life tests were conducted on nodular cast iron grade 80, which has essentially the combined pearlitic and ferritic structure, with two grades of carbide C-1 (the cast iron cutting grade) and C-3 (the steel cutting grade) and O-1 ceramic.

The results are given in Figs. 6 and 7 as tool life

Tool life criterion, 0.381 mm (0.015 in) wear land on the tool flank; tool material, carbides C-1 (cast iron cutting grade) and C-3 (steel cutting grade) and ceramic O-1; tool geometry, -5° , -5° , 5° , 15° , 15° , 0.8 mm; depth of cut, 2.54 mm; feed, 0.254 mm/rev; dry

Fig. 5 Relationship between cutting speed and metal removed until the end of tool life for nodular cast iron grade 100

Tool life criterion, 0.381 mm (0.015 in) wear land on the tool flank; tool material, carbides C-1 (cast iron cutting grade) and C-3 (steel cutting grade) and ceramic O-1; tool geometry, -5° , -5° , 5° , 15° , 15° , 0.8 mm; depth of cut, 2.54 mm; feed, 0.254 mm/rev; dry

Fig. 6 Tool life curve for nodular cast iron grade 80 [1]

curves and the empirical formulae are given in Table 4.

Fig. 6 shows the tool life curves for carbides C-1 and C-3 and the ceramic O-1 for a depth of cut of

Tool life criterion, 0.381 mm (0.015 in) wear land on the tool flank; tool material, carbide C-1 (cast iron cutting grade) and ceramic O-1; tool geometry, -5° , -5° , 5° , 5° , 15° , 15° , 0.8 mm; depth of cut, 2.54 mm; feed, 0.127, 0.254, and 0.381 mm/rev; dry

Fig. 7 Tool life curve for nodular cast iron grade 80 [2]

Table 4 Empirical tool life equations for nodular cast iron grade 80

Tool material	Depth of cut mm	Feed mm/rev	Cutting speed range m/min	Tool life equation	Cutting speed for 30 min tool life m/min
Carbide C-1	2.54	0.127	75~185	$VT^{0.322}=213$	71
		0.254	60~185	$VT^{0.352}=208$	63
		0.381	60~155	$VT^{0.343}=195$	61
Carbide C-3	2.54	0.254	35~185	$VT^{0.411}=137$	34
Ceramic O-1	2.54	0.127	90~305	$VT^{1.613}=9851$	41
		0.254	90~305	$VT^{0.776}=693$	50

2.54 mm and a feed of 0.254 mm/rev. Comparing tool life data for various tool materials, the same trend as for grade 100 was observed. The cast iron cutting grade carbide C-1 is much better than the steel cutting grade carbide C-3 from the standpoint of tool life. The cutting speed corresponding to a 30 min tool life is 63 m/min for C-1 and 34 m/min for C-3. The photographs showing cutting tools at the end of tool life are given in Fig. 8. At high speeds crater wear developed for both cast iron and steel cutting grades as for grade 100.

The ceramic cutting tool showed better tool life than the carbides as for grade 100. This is very pronounced at high speeds, due to the steep slope of the tool life curve. Since the wear at the end of tool life for the ceramic tool was almost the same as that for machining grade 100 nodular cast iron, the photographs are not shown in Fig. 8.

From the above, the cast iron cutting grade carbide C-1 and the ceramic O-1 are recommended for machining nodular cast iron grade 80 as well as grade 100.

Fig. 7 shows the effect of feed rate on the tool life for the cast iron cutting grade carbide C-1 and the ceramic for a depth of cut of 2.54 mm and three different feeds of 0.127, 0.254, and 0.381 mm/rev. As on grade 100, the tool life decreases with an

Tool material, carbides C-1 (cast iron cutting grade) and C-3 (steel cutting grade); tool geometry, -5° , -5° , 5° , 5° , 15° , 15° , 0.8 mm; depth of cut, 2.54 mm; feed, 0.254 mm/rev; dry

Fig. 8 Photographs showing wear of carbide cutting tools at the end of tool life for machining nodular cast iron grade 80 [Numbers in parentheses designate tool life (min), i.e., cutting time until wear land on the tool flank reaches 0.381 mm (0.015 in)]

increase in feed rate. The slopes of the tool life curves are similar for different feeds in the case of carbide C-1, but the slope is larger for small feed than for high feed in the case of the ceramic. The slope constants are 0.3 for C-1 and 1.6 at 0.127 mm/rev and 0.8 at 0.254 mm/rev for the ceramic. A steep slope of the tool life curve for ceramic, compared with that for carbide, is a characteristic of ceramic tool. This tendency is significant for small feeds. Therefore, superior cutting performance of ceramic tool is limited to high speeds.

Fig. 9 shows the amount of metal removed for a 0.381 mm (0.015 in) wear land when machining grade 80 with two carbides C-1 and C-3 and ceramic O-1 for a feed of 0.254 mm/rev. This is similar to Fig. 5 for grade 100, and the conclusions are the same, that is, the cast iron cutting grade carbide C-1 is economical to use at speeds lower than 77 m/min and the ceramic is preferred at speeds higher than 77 m/min.

5. Comparison of tool life for grade 100 and grade 80

Fig. 10 shows comparison of tool life curves for grades 100 and 80 of nodular cast iron with the cast iron cutting grade carbide C-1, the steel cutting grade carbide C-3, and the ceramic O-1 for a depth of cut of 2.54 mm and feed of 0.254 mm/rev for carbides and 0.127 and 0.254 mm/rev for ceramic.

In the case of carbides, the slopes of the tool life curves for grades 80 and 100 are almost the same. With the cast iron cutting grade carbide C-1, grade 80 nodular cast iron shows a greater tool life than grade 100; that is, comparing the cutting speed for a 30 min tool life, 60 m/min for grade 100 and

63 m/min for grade 80. On the other hand, with the steel cutting grade carbide C-3, grade 80 shows larger values of tool life than grade 100 at high speeds above 100 m/min, while smaller at low speeds below that. Cutting speed for a 30 min tool life is 39 m/min for grade 100 and 34 m/min for grade 80. Actually high speeds above 100 m/min are not practical because of a very short tool life. Therefore, it is concluded that grade 100 shows better tool life than grade 80 in practical use when using the steel cutting grade carbide C-3.

Referring to Table 1, Brinell hardness number is 237 for grade 100 nodular cast iron and 214 for grade 80 nodular cast iron. Hence, grade 100 is a little harder than grade 80. Tool life tests indicate that in the case of the cast iron cutting grade C-1, soft grade 80 shows a longer tool life than hard grade 100. This relation between the trends of hardness of work materials and of tool life is reasonable. In the case of the steel cutting grade carbide C-3, however, soft grade 80 shows a shorter tool life than hard grade 100 in the practical speed range. This indicates that hardness is not the only factor influencing the tool life.

In the case of ceramic O-1, the tool life is much longer for grade 80 than for grade 100 for a feed of 0.127 mm/rev, but a little shorter for a feed of 0.254 mm/rev, though data points are scattered. The slopes of the tool life curves for grades 100 and 80 for a feed of 0.254 mm/rev are almost the same, and the cutting speed for a 30 min tool life is 52 m/min for grade 100 and 50 m/min for grade 80. The slope of the tool life curve for ceramic is much steeper than that for carbide. This tendency is remarkable for a smaller feed. Therefore, the ceramic is superior at high speeds to the carbide, as mentioned previously. It is difficult to explain the reversal of tool life curves for grade 80 and grade 100

Fig. 9 Relationship between cutting speed and metal removed until the end of tool life for nodular cast iron grade 80

Fig. 10 Comparison of tool life curves for grades 80 and 100 of nodular cast iron

at feeds of 0.127 and 0.254 mm/rev. In all cases the flank wear was the same and there was no evidence of chipping.

6. Conclusions

Tool life tests performed on pearlitic nodular cast irons with carbide and ceramic tools led to the following conclusions:

(1) The cast iron cutting grade carbide C-1 is much superior to the steel cutting grade carbide C-3 from the standpoint of tool life when machining pearlitic nodular cast irons. Titanium carbide (the so-called cermet tool) C-8 shows almost the same cutting performance as the cast iron cutting grade carbide C-1. With these carbide tools, the crater wear develops at high speeds as well as the uniform flank wear in the entire speed range tested.

(2) Ceramic O-1 has superior cutting performance when machining pearlitic nodular cast irons. Its tool life is greater than that for the cast iron cutting grade carbide C-1 at high speeds. Consequently,

the cast iron cutting grade carbide C-1 is economical to use at low speeds and ceramic O-1 is preferred at high speeds. The critical cutting speed is around 65 m/min for grade 100 nodular cast iron and 80 m/min for grade 80 nodular cast iron.

(3) Nodular cast iron grade 100 is a little harder than grade 80, but tool life for grade 100 is not always shorter than that for grade 80.

(4) Decreasing the feed increases the tool life. This tendency is slight for carbide tool, but it is conspicuous for ceramic tool.

(5) The slope of the tool life curve for ceramic tool is steeper than that for carbide tool. This tendency is remarkable when a feed rate is small. It was sometimes observed that a constant expressing the slope of the tool life curve exceeds 1.

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Machinability of Nodular Cast Irons*

(Tool Life and Variation in Tool Forces with Flank Wear)

By Katsundo HITOMI**, Inyong HAM*** and George L. THUERING****

Tool life tests were conducted on ferritic nodular cast iron (grade 60) with carbide and ceramic cutting tools, and the results were compared with those for pearlitic nodular cast iron (grades 80 and 100). It was found that the ribbon type flank build-up or smear protects the flank of carbide tool from flank wear. The tool life for ferritic nodular cast iron was much longer than that for pearlitic nodular cast iron. The cast iron cutting grade carbide showed better tool life than the steel cutting grade carbide when machining nodular cast irons. The tool life for ceramic tool was longer than that for carbides, especially at high speeds because of the steep slope of the tool life curve for the ceramic tool. The wear processes of carbide and ceramic tools were investigated together with the variation in tool forces due to flank wear.

1. Introduction

The previous paper, Machinability of Nodular Cast Irons (Tool Forces and Flank Adhesion Phenom-

enon)⁽¹⁾, reported the results of cutting tests to determine the tool forces required to machine three grades of nodular cast iron (60, 80, and 100) and the cutting performance of several grades of carbide and ceramic cutting tools. Flank adhesion phenomenon observed when machining grade 60 (ferritic) nodular cast iron with carbide tools was investigated in relation to cutting conditions, and methods were recommended to prevent the development of flank

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