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An Experimental Investigation of Machinability of Graphitic Cast Iron Grades; Flake, Compacted and Spheroidal Graphite Iron in Continuous Machining Operations

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Abstract

In this study the machinability of different grades of cast iron has been studied in terms of cutting temperatures, cutting forces, tool life, deformed chip thickness and contact length in different continuous machining operations. The tests performed were: external turning, boring and face turning. Pearlitic Flake Graphite Iron (FGI), Compacted Graphite Iron (CGI) and Spheroidal Graphite Iron (SGI) materials were selected for making the experiments. Later the machinability was also compared with ferritic SGI material. The cutting temperature has been measured with the help of embedded thermocouple inserts. These inserts were having 2 junctions; 0.55 and 1.2 mm away from the cutting edge on the clearance face. It was found that the cutting temperature on the clearance face has not shown any significant difference for different grades of cast irons. However, the tool life and the cutting forces have shown significant differences. The face turning tests were performed in both dry and wet conditions to see the importance of cutting fluids for different grades of cast iron. It has been seen that the CGI and SGI require cutting fluid in a continuous machining operation. Later the wear mechanisms of different grades were also studied for dry and wet conditions in a boring operation. Both CGI and SGI have shown adhesion as a wear mechanism under dry conditions as compared to abrasive wear in wet conditions with a cutting speed of 300 m/min. The results can be input to designing a suitable insert for CGI and SGI and highlight the importance of using cutting fluids while machining CGI and SGI in continuous cutting operations.

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Keywords: Turning; Cast iron; FGI;CGI;SGI; Temperature; Tool Life; Cutting Force; Tool Wear; Dry and Wet machining.

1. Introduction

Cast irons are widely used in the manufacturing processes. In the recent years stronger grades of cast iron like Compacted Graphite (CGI) Iron have been developed. This has been made possible with the advances in computer controlled casting processes [1]. According to the 44th world casting census graphitic cast iron constitute 71 % of total metal casting in the world, followed by 17 % of nonferrous casting and 9 % of steel casting. The same census has reported that the growth rate of Spheroidal Graphite Iron (SGI) has increased as compared to Flake Graphite Iron (FGI) over the last 10 years [2]. Large number of automotive, railways, oil and machine tool components are made from graphitic cast iron. Graphitic cast iron has three grades; FGI, CGI and SGI. These grades differ in terms of the shape of the graphite present in their microstructure. Fig. 1 shows the polished images of different grades of graphitic cast iron. FGI has long thin graphite, CGI has worm like compacted thick and round edged graphite and SGI has spherical shaped graphite. The difference in the shape of the graphite, in combination with the matrix constituents, is also affecting the properties such as hardness, ultimate tensile strength, thermal conductivity, damping, fatigue life etc. The difference in these properties is influencing the machinability of these grades. Fig. 2 shows the deep etched images of FGI, CGI and SGI. It can be seen that the graphite in FGI is having a smooth surface with long and thin flakes, while the graphite in CGI is having thicker and rounded edges. The graphite present in these grades is interconnected at

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some places resulting in higher thermal conductivity compared to the spherical shaped graphite in SGI, where no such interconnection exists. The matrix type of cast irons can be achieved by changing the chemical composition, inoculation and cooling conditions. For a given matrix type, the properties of the cast iron are influenced by the graphite shape. The amount and shape of graphite phase can influence the plastic deformation behaviour of cast iron. A higher amount of graphite lowers the material strength and the sharp flake graphite particles give rise to non-linear deformation behaviour [3]. The common matrix for FGI is pearlite and in the case of CGI and SGI, ferrite grades are also used in manufacturing. For a pearlitic matrix the yield strength is controlled by the interlamellar spacing, pearlite colony size, prior austenite grain size and solid solution strengthening from alloying [4-5].

With the stringent environmental legislations regarding reducing emission rates of engine exhaust, and the need for stronger material to reduce the weight of the final product, has driven the tendency towards using CGI and SGI in manufacturing. In continuous machining operations there is a big difference in tool life observed for CGI and SGI compared to FGI. Due to this, the application of CGI as a material of industrial component is limited. Hence it is important to evaluate the machinability of CGI and SGI as compared to the FGI. Moreover, tool manufacturers have not started putting cutting parameters recommendations for CGI in their catalogues, except for some tools. Hence it has become important to know the machinability of CGI in different operations as compared to FGI.

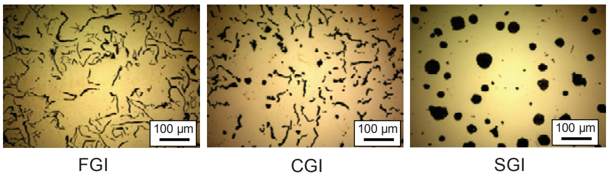

Fig. 1. Polished images of grades of graphitic cast irons; Flake Graphite iron (FGI), Compacted Graphite Iron (CGI) and Spheroidal Graphite Iron (SGI).

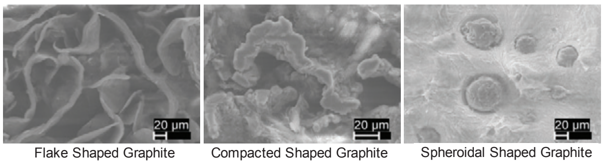

Fig. 2. Deep etched scanned images of grades of graphitic cast irons; Flake shaped Graphite, Compacted shaped Graphite and Spheroidal shaped Graphite.

2. Materials

The properties of the materials used for machinability testing are shown in Table 1. Three pearlitic grades; Flake Graphite Iron (FGI), Compacted Graphite Iron (CGI) and Spheroidal Graphite Iron (SGI-2) were tested and later a ferritic grade of Spheroidal Graphite iron (SGI-5) was also tested for comparison. In the pearlitic grades the material hardness increases with change in graphite shape from flake –compacted – spheroidal. For the ferritic grade of SGI the hardness was 155 HB. Pearlitic CGI and FGI grades selected are widely used as engine block materials in the automotive industry. The cylindrical shaped workpieces used to perform the experiments were having section thicknesses of 60 mm and 25 mm. CGI and FGI workpieces were 60 mm thick and SGI materials were 25 mm thick as shown in Fig. 3. Samples for tensile testing were taken from the centre of the cylindrical section and parallel to the axis of the cylinder, see Fig. 3 (c).

Table 1. Properties of grades of cast iron used for machinability testing.

Mater-ials	Pearl-ite %	Hardness HB(5/750)	Nodular-ity %	Rm	Rp0.2	Elong-ation%
FGI	> 99	175	N.A.	194	182	0.3
CGI	86	210	10	415	310	1.7
SGI-2	76	230	86	-	-	-
SGI-5	22	155	87	-	-	-

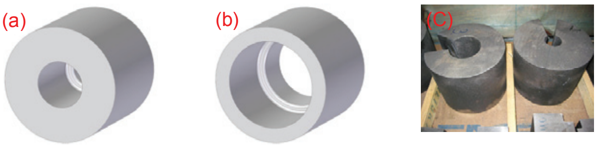

Fig. 3 Workpieces, (a) 60 mm thick CGI and FGI; (b) 25 mm thick SGI; (c) Workpieces showing samples taken from the cylinders

Table 2 shows the chemical composition of the materials used in the machining experiments. Here it can be seen that magnesium (Mg) is the nodularizing element. Both SGI materials have a higher amount of Mg present in their microstructure. SGI-2 has higher wt% of chromium (Cr). It has 0.5 wt% of carbides present in the microstructure. Copper (Cu) is the pearlite promoter. Increase in the quantity of copper can increase the amount of pearlite and the hardness of the material.

Table 2. Chemical composition cast iron grades.

Materials	C	Si	Mn	P	S	Mg	Cu	Cr
FGI	3.40	1.94	0.61	0.02	0.09	-	0.63	0.21
CGI	3.69	2.02	0.36	0.005	0.009	0.011	0.75	0.03
SGI-2	3.63	2.29	0.40	0.033	0.006	0.049	0.394	0.246
SGI-5	3.53	2.36	0.40	0.040	0.007	0.066	0.220	0.050

3. Results and Experimental set-up

3.1. Longitudinal Turning of FGI and CGI

Tool life and cutting forces were measured for all FGI and CGI materials. The machining experiments were performed on a turning centre. Tool life tests were performed with a cutting speed (V_c) = 300 m/min, feed (f) = 0.2 mm/rev and depth of cut (a_p) = 1.5 mm. Flood cooling of soluble oil emulsion having 5 % concentration was used in the tests. The criterion used for tool life was a maximum flank wear (VB_{max}) equals 0.3 mm. The inserts used were type TNMG16 04 08-KM grade 3210. Tests were performed with -6° inclination and -6° rake angle of the tool holder seat. The approach angle (Kr) was 91°. The inserts used had an edge radius deviation of 50±5 µm. The force measurement tests were also performed with the same set-up and the dynamometer used was Kistler type Z15814 with charge amplifier type 5019. The force measurement tests were run in dry condition. Average value for force was taken for analysis. The sampling rate for the measurement was 250 Hz. Fig. 4 shows the experimental set-up for the force measurement.

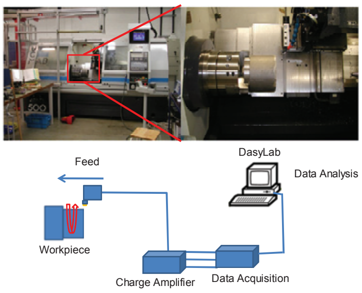

Fig. 4. Set-up used for force measurement.

Fig. 5 shows the tool life measured for FGI and CGI materials. Here it can be seen that the FGI material has almost 10 times the tool life compared to the CGI material in continuous machining operation. The tool life of CGI was taken from the average of 3 different measurements, however for FGI it was measured once. In force measurements, FGI has given almost 100N lower resultant cutting force value as compared to the CGI material as shown in Fig. 6.

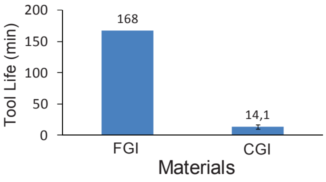

Fig. 5.Tool Life for FGI and CGI.

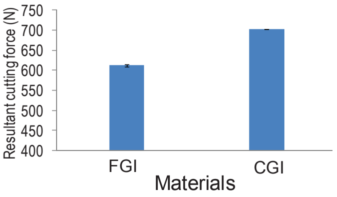

Fig. 6. Resultant force for FGI and CGI.

3.2. Longitudinal Turning of SGI

The insert grade used for machining of SGI-2 and SGI-5 materials was GC3215. The edge radius of the inserts was measured and the inserts with minimum deviation (53±6 µm) of the edge radius were selected for performing the experiments. Tool life tests were performed at cutting speed (V_c) = 250 m/min, feed (f) = 0.3 mm/rev and depth of cut (a_p) = 3.5 mm. Flood cooling with soluble oil emulsion having 8 % concentration was used in the tests. The criterion used for tool life was a flank wear (VB_{max}) of 0.5 mm. The inserts used were CNMA 120412 -KR grade 3215. Tests were performed with -6° inclination and -6° rake angle of the tool holder seat. The approach angle (Kr) was 95°. Fig. 7 shows the tool life results for the SGI materials. Here, it was noticed that the tool life for the ferritic SGI-5 material is almost double the tool life of the pearlitic SGI-2 material.

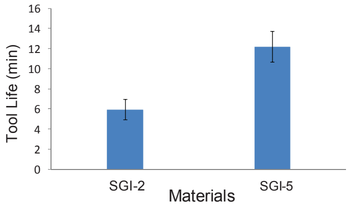

Fig. 7. Tool Life for Pearlitic (SGI-2) and Ferritic (SGI-5) materials.

3.3. Cutting Temperature of Cast Iron Grades in Turning

Temperature measurement tests were carried out with Al_2O_3 coated Sandvik Coromant carbide inserts, SPUN 19 04 12, 3015 K15 (P10). The inserts have 0° rake angle and were without chip breaking geometry. The nose radius was 1.2 mm. The selected cutting data were: cutting speeds (V_c) = 52, 100, 211 and 320 m/min; cutting depth (a_p) = 3.5 mm and feed rate (f) = 0.2 mm/rev. The temperature near the cutting edge was measured using thermocouples, placed on the clearance surface and integrated with the insert. The higher depth of cut (a_p = 3.5 mm), as compared to force and tool life tests, was chosen to fully cover the thermocouples (see Fig. 8 for the position of the thermocouples). The thermocouples are manufactured using a thick-film technique and are placed directly on the insert coating (Al_2O_3) which constitutes an electrical insulating layer [6] [7] [8]. The average coating thickness of aluminium oxide was around 15 µm. The gold-platinum conductors were extended down to the bottom side of the insert (Fig. 8 (2)). The electrical voltage was transferred from the conductors by pins mounted in the tool holder on the seat of the insert. These pins were connected to an amplifier, and subsequently data was registered with a computer using Dasy Lab Software. The set-up is shown in Fig. 8. By applying two thermocouples on the clearance surface, see Fig. 8(1), it is possible to measure temperatures on two points very close to the cutting edge. The measuring hot junction points are placed on the clearance face of the cutting tool. The points V1 and V2 have a distance of 0.55 mm and 1.25 mm from the rake face plane of the tool. This gives information about the temperature distribution in the vicinity of the cutting zone. Since the response time for the thermocouples is very short and the accuracy is high, the thermocouples can be used successfully for registering the rapid temperature that changes during a cutting process. The electro motive force (emf) readings were later converted to degree Celsius (°C) by using a standard table [9]. Same insert was used for different materials and the materials were randomized. Average temperature between 15 to 17 seconds of engagement time was used for the readings.

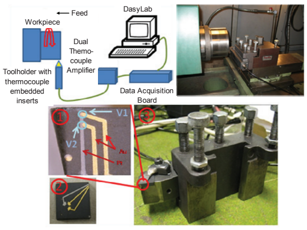
Feed
Workpiece
DasyLab
Dual Themo-couple Amplifier
Toolholder with thermocouple embedded inserts
Data Acquisition Board
①
V1
V2
Au
Pt
②
③

Fig. 8. Temperature measurement set-up, (1) flank face of the insert, (2) bottom view of the insert, (3) toolholder used.

Fig. 9 shows the temperature while machining CGI and FGI, on junctions V1 and V2 located on the insert. FGI has shown less average temperature, from the two measurements taken, as compared to CGI. However, there was no significant difference noticed for measured temperature. An increase in temperature of around 241 °C at junction V1 and 150 °C was observed for both materials by changing the cutting speed from 52 m/min to 320 m/min. Fig. 10 shows the temperature for FGI and SGI materials. Here also, the FGI material has shown less average temperature, however no significant difference of temperature observed for different materials. Ferritic SGI material has shown an increase in temperature of 293 °C with an increase in speed from 52 to 320 m/min at junction V1 and around 175 °C at junction V2.

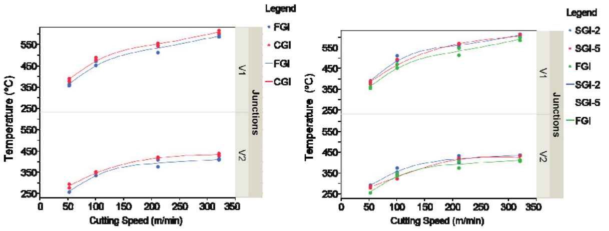

Fig. 9. Temperature for FGI and CGI at hot junctions V1 and V2 at different cutting speeds; . Fig. 10. Temperature for FGI, SGI-2 and SGI-5 materials at hot junctions V1 and V2 at different cutting speeds.

As the heat source on flank face, the tertiary heat zone, is near the cutting edge, the flank temperature decreases while going away from the cutting edge. Assuming a linear gradient, the interpolations of average temperatures measurements at junctions V1 and V2 have shown maximum temperatures of 771, 787, 789 and 786 °C with cutting speed 320 m/min, and temperatures of 462, 469, 405 and 378 °C with cutting speed 52 m/min, for FGI, CGI, SGI-5 and SGI-2 materials, near the cutting edge.

3.4. Boring Tests

For boring tests the boring bar used was, Sandvik Coromant, of the type A40T-STFCR 16, with inserts of type TCMT 16 T3 08-KM GC 3210. The cutting parameters selected for performing the experiments were cutting speed (V_c) = 300 m/min; cutting depth (a_p) = 1.5 mm and feed rate (f) = 0.3 mm/rev. The tests were performed in both dry and wet conditions for CGI to compare the wear mechanism in both conditions. The setup is shown in Fig. 11

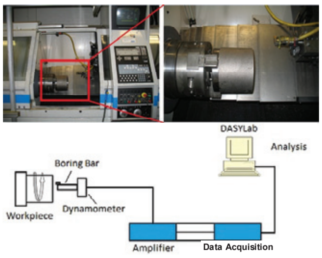

Fig. 11. Set-up for boring tests.

Fig. 12 shows that the lowest average tool life in boring was shown by SGI-5 material at around 5 minutes, followed by CGI at 8.2 min. FGI has not shown any wear even after 20 min. of machining. The tools were used till catastrophic failure for CGI and SGI-5. It was found that the wear mechanism for CGI and SGI-5 was adhesive but for FGI abrasive wear was the dominant wear mechanism in dry machining conditions with the used parameters. Fig. 13 shows the adhesion of workpiece material mainly ferrite on the rake face of the insert. However, no such adhesion was seen on the insert used for machining of FGI. In wet conditions, the abrasive wear was noticed to be the dominant wear mechanism for CGI and SGI at a cutting speed of 300 m/min. The major difference between tool life of FGI and CGI is because of the formation of protective MnS layer on cutting tool while machining FGI [10] [11]. Fig. 14 shows the resultant force values of FGI, CGI and SGI-5. Here the lowest resultant force was measured for FGI. CGI and SGI-5 have not shown any significant difference in the measured force.

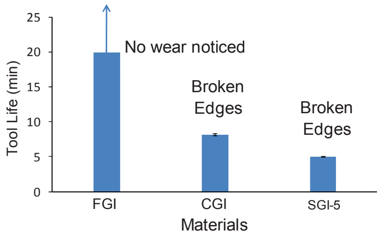

Fig. 12. Tool life for FGI, CGI and SGI-5 in dry condtions.

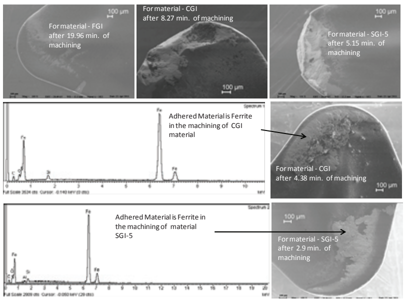
For material - FGI after 19.96 min. of machining
100 µm
For material - CGI after 8.27 min. of machining
100 µm
For material - SGI-5 after 5.15 min. of machining
100 µm
Adhered Material is Ferrite in the machining of CGI material
For material - CGI after 4.38 min. of machining
100 µm
Adhered Material is Ferrite in the machining of material SGI-5
For material - SGI-5 after 2.9 min. of machining
100 µm
Fe

Fig. 13. Inserts for FGI, CGI and SGI-5 in dry condtions.

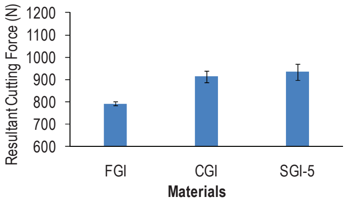

Fig. 14. Resultant force for FGI, CGI and SGI-5 under dry conditions in boring.

3.5. Face Turning Tests

Fig. 15 shows the experimental setup for the face turning tests. The inserts used were uncoated standard cemented carbides (TCMW16T304-H13A) having 0.4 mm nose radius, 0° rake angle and 91° approach angle. The selection of uncoated inserts was to minimize the effect of coating lubrication for coated inserts. The machining trials were performed at a feed of 0.2 mm/rev and a depth of cut of 1.5 mm. The cutting speed used for the experiments was 100 m/min and 200 m/min. A dynamometer Kistler type 9257 A was used for force measurement. For every test run a new edge of the triangular insert was used in order to minimize the effect of tool wear. The data was collected with a sampling frequency of 1000 Hz with a low–pass filter at 50 Hz. Resultant force was taken for the analyses. The tests were performed both in dry and wet conditions.

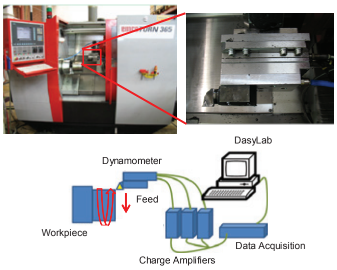
DasyLab
Dynamometer
Feed
Workpiece
Data Acquisition
Charge Amplifiers

Fig. 15. Set-up for face turning tests.

The force measurement results in Fig. 16 show that there is a decrease in the force value with the use of cutting fluids for all materials at cutting speeds of 100 m/min and 200 m/min. Maximum force was measured for pearlitic SGI followed by ferritic SGI and CGI. The lowest force was shown by the FGI material. Deformed chip thickness measurements were also performed on the chips collected after machining of the different grades. The results of deformed chip thickness were highly unreliable, as a large variation in the thickness was observed because of the segmented and discontinuous nature of the chips.

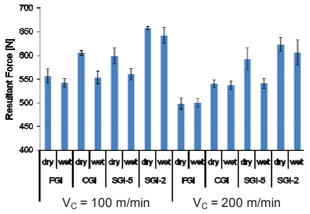

Fig. 16. Resultant force for FGI, CGI and SGI-5 and SGI-2 in face turning operation.

Contact length measurements were also performed and have shown a general trend of decreasing contact length with the use of cutting fluids. However, no significant difference of contact length was noticed for the different grades of cast iron, while machining with uncoated inserts and the selected parameters.

4. Discussion and Conclusions

Various tests operations with different grades of inserts were performed to evaluate the machinability of different grades of cast iron. The following conclusions and observations can be made out of these tests.

- Temperature on the flank face has not shown any significant difference while machining different grades of graphitic cast iron. Hence this temperature measurement method cannot be used for the machinability variation testing of different grades of cast iron.
- Increase in temperature of 293 °C was noticed with an increase in cutting speed from 52 to 320 m/min on the clearance face near the cutting edge.
- A tool life difference of 11 times was noticed between pearlitic CGI and FGI at a cutting speed of 300 m/min for coated carbides with grade 3210.
- Cutting fluid can increase the tool life and decrease the cutting forces for the machining of graphitic cast irons with carbides inserts. Also at a cutting speed above 200 m/min, the use of cutting fluid for CGI and SGI is desired when machining with coated carbide tools in a continuous machining operation. It is not recommended to machine CGI and SGI in dry conditions above a cutting speed of 200 m/min because of adhesion of the workpiece material on the tool, whereas FGI could be machined dry in a continuous machining operation.
- Within the graphitic cast iron grades, hardness and type of matrix can give an indication of the machinability. But, if all parameters are considered, the shape of graphite is the main machinability influencing factor. As it has been seen for ferritic SGI-5, the tool life was less than for pearlitic CGI in dry machining conditions, although it has a lower hardness. However, ferritic CGI and ferritic SGI would have better machinability than pearlitic CGI and SGI.
- The wear mechanisms is for all grades abrasive wear under wet machining conditions up to the cutting speed of 300 m/min with coated carbides. However, in dry machining CGI and SGI have shown an adhesive wear mechanism influencing the rake face of the tool with the adherence of the workpiece material at a cutting speed of 300 m/min. The wear in CGI and SGI was uniform and easy to follow on the flank side, whereas FGI has shown first a notch wear followed by uneven abrasive wear on the flank face.
- Chips produced for all grades of cast irons were segmented and discontinuous. Chip ‘breakability’ in machining is not a problem in any of these graphitic grades of cast iron.
- As no significant difference of contact length was observed for different grades of cast iron and the force value measured is lower for FGI compared to CGI and SGI, the stress load on the tool is higher when machining CGI and SGI.

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