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The Effect of Interlamellar Distance in Pearlite on CGI Machining

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***Abstract*—**Swedish truck industry is investigating the possibility for implementing the use of Compacted Graphite Iron (CGI) in their heavy duty diesel engines. Compared to the alloyed gray iron used today, CGI has superior mechanical properties but not as good machinability. Another issue that needs to be addressed when implementing CGI is the inhomogeneous microstructure when the cast component has different section thicknesses, as in cylinder blocks. Thinner sections results in finer pearlite, in the material, with higher strength. Therefore an investigation on its influence on machinability was needed. This paper focuses on the effect that interlamellar distance in pearlite has on CGI machinability and material physical properties. The effect of pearlite content and nodularity is also examined. The results showed that interlamellar distance in pearlite did not have as large effect on the material physical properties or machinability as pearlite content. The paper also shows the difficulties of obtaining a homogeneous microstructure in inhomogeneous workpieces.

***Keywords*—**Compacted graphite iron (CGI), machinability, microstructure, milling, interlamellar distance in pearlite.

I. Introduction

INCREASING environmental legislation on engines' emission rates has forced the automotive and heavy truck industry to find new material solutions for their diesel engines. Lower emission rates could be achieved, for instance, by reducing the weight of the engine or by increasing the combustion pressure in the engine. For this reason, the use of ordinary gray cast iron found in many of today conventional diesel engines may have to be replaced, due to the inferior mechanical properties. One of the most interesting candidates to replace gray iron is Compacted Graphite Iron (CGI) which can better withstand the higher combustion pressure, thanks to its superior mechanical properties. Despite this, the use of CGI is limited due to its lower machinability [1].

A. CGI as Engine Material

CGI has twice the strength and 40% higher elastic modulus compared to gray iron [2]. The reason for this is the difference in microstructure, which is usually specified by nodularity and pearlite content but also by coarseness of the pearlite, defined by the interlamellar distance in pearlite. A shorter interlamellar distance gives a stronger material [3].

The CGI component microstructure is also strongly dependent on the cooling- and solidification rate during casting which, in its turn, is controlled by the section thickness. A cylinder block has many different section thicknesses, influencing both the coarseness of the pearlite and the nodularity and thus the material physical properties [4]. Therefore, it is obvious that the microstructure in the cylinder block is inhomogeneous. Heisser simulated the nodularity variations and meant that the nodularity can be between 12% - 70% in one cylinder block, which is very near inspected values. This means that a good simulation tool is required for predicting the nodularity [5].

The higher strength of CGI opens to the possibility of manufacturing components with thinner walls, or alternatively increasing the loads, when changing from alloyed gray cast iron [1]. New concepts in engine design are then possible which could reduce the weight and therefore the emission rates.

B. Challenges in CGI Machining

According to many investigations, shorter tool life is expected when machining CGI compared to gray iron [6], [7]. The greatest difference is seen at high cutting speeds in continuous machining operations, for instance in the boring of the cylinder of engine blocks. For this operation, CBN inserts are often used, where the low feed is compensated by high cutting speed. High cutting speed gives faster tool wear, when machining CGI compared to gray iron, since the wear-attenuating MnS layers are no longer formed [8]. Studies show that machining of CGI is preferably done with carbide cutting tools at low cutting speed [9],[10]. Therefore, when boring the cylinders of the engine block, special attention has to be put on the selection of cutting tools and cutting parameters, if CGI should be implemented as engine material.

Another challenge when machining CGI is the varying microstructure in components with different section thicknesses, as mentioned earlier. This affects the material physical properties and thus its machinability. Thin sections found in walls tend to obtain shorter interlamellar distance and higher nodularity values. This could lead to problems in drilling and milling operations since the tool has to machine "different materials" within the same cutting cycle [11]. As a

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consequence, the tools designed for CGI machining must be capable to withstand these changes in material physical properties.

C. Aim of Study

CGI is a material family where the mechanical properties span over a large range. The microstructure determines the material physical properties which affects the machinability parameters. It has been seen in an earlier study [11] that it is necessary to investigate the machinability – material microstructure - material physical properties interaction, before any optimization of the material and the cutting process can be done. Previous work has carefully studied the influence of nodularity and pearlite content on machinability and material physical properties [6], [12]. This paper focuses on the influence the interlamellar distance in pearlite has on CGI machinability and on material physical properties, since this has never earlier been studied. Three types of workpieces with different section thicknesses were designed to achieve different interlamellar distance in pearlite. It has also been studied how section thickness affected nodularity and pearlite content.

II. Materials and Machining Experiments

A. Design of Experiments (DoE), Investigated CGI Materials

Three different workpieces were designed (Fig. 1) in order to separate the effect of interlamellar distance in pearlite on machinability and material physical properties from the other microstructural parameters (pearlite and nodularity).

(a) (b) (c)

Fig. 1 Workpieces with different height (80 mm (a), 46 mm (b) and 26 mm (c)). Width is 120 mm and length is 350 mm

The design of the workpieces led to three different cooling- and solidification rates affecting the coarseness of the pearlite. Three different interlamellar distances in pearlite could by this design now be emphasised. It should be mentioned that the aim with the study was to see the effect of interlamellar distance in pearlite, not the one of section thickness. Therefore, the nodularity was kept constant for the three types of workpieces.

The choice of using homogeneous workpieces was supported by previous studies [6], where it was shown that holes and slots in the workpiece results in varying microstructure. The workpieces were pre-milled on the top, bottom and sides, in order to remove the hard cast skin, with different microstructure.

A complete factorial experiment was performed, using the three types of workpieces, to fully investigate the influence of interlamellar distance in pearlite on CGI machinability, CGI material physical properties, nodularity and pearlite content. From now on, the thick workpiece (Fig. 1a) is mention as workpiece A, the middle workpiece (Fig. 1b) as workpiece B and the thin workpiece (Fig. 1c) as workpiece C.

The effect of nodularity and pearlite content on machinability and material physical properties was also studied, so that the effect of interlamellar distance in pearlite could be put into relation to these microstructural properties. Pearlite content was set to three different levels and the nodularity to two levels, resulting in eighteen different CGI materials as illustrated in Table I.

TABLE I
PLANED FACTORIAL VALUES FOR THE CGI MATERIALS

Material	Workpiece	Section thickness[mm]	Nodularity [%]	Pearlite Content [%]
1	A	80	5-10	30-40
2	B	46	5-10	30-40
3	C	26	5-10	30-40
4	A	80	20-25	30-40
5	B	46	20-25	30-40
6	C	26	20-25	30-40
7	A	80	5-10	60-70
8	B	46	5-10	60-70
9	C	26	5-10	60-70
10	A	80	20-25	60-70
11	B	46	20-25	60-70
12	C	26	20-25	60-70
13	A	80	5-10	90-100
14	B	46	5-10	90-100
15	C	26	5-10	90-100
16	A	80	20-25	90-100
17	B	46	20-25	90-100
18	C	26	20-25	90-100

B. Machining Experiments

Machining experiments were performed, in order to evaluate the machinability for the different materials. The tool life experiments of the CGI materials and gray iron reference material were carried out in dry face milling. Each experiment was repeated and the average tool life calculated. A Mazak machining centre (37.7 kW) was equipped with an ISO-50 type cone, at which a mill was mounted (model: R365-063Q22-S15H). The mill was equipped with three coated cemented carbide inserts (R365-1505ZNE-KM K20W), see Fig. 2.

Fig. 2 Magnetic clamping of the workpieces

Cutting speed, v_c, was set to 200 m/min, feed, f_z, to 0.2 mm/tooth, depth of cut, a_p, to 3 mm and width of cut, a_e, was 58 mm. Tool wear was measured at frequent intervals. Tool life end was obtained when any of the following two tool life criterion occurred:

- Maximum flank wear was 0.3 mm for two of the three inserts.
- The average of the maximum flank wear for all inserts was 0.3 mm.

III. Results and Discussion

A. CGI Material Characterization

The CGI material physical properties in different sections are the result of the corresponding microstructure which affects the machinability. Therefore, it is essential to investigate the interaction between material microstructure and material physical properties. Consequently, the CGI materials were characterized, both regarding microstructure and material physical properties. Another purpose of the characterization was to evaluate if the materials complied with the data specified in the DoE model.

1) Nodularity variations within the workpieces

Previous studies [6] have shown that the nodularity can vary with depth into the workpiece. In this investigation, the nodularity was intended to be the same within the same workpiece. It was believed though that it could differ, especially in workpiece A, since it has a slower solidification rate compared to the other workpieces. One CGI material (material 10, Table I) from the DoE was selected and studied more carefully regarding this phenomena. That material was intended to have a nodularity value between 20-25%. The microstructure of the material was investigated in image analysis at different depths. The nodularity as a function of depth can be seen in Fig. 3.

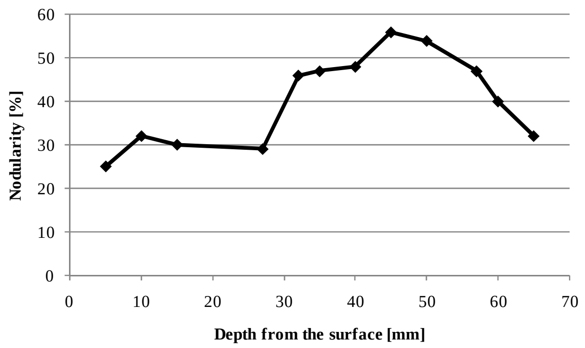

Fig. 3 Nodularity as a function of depth into the material from the surface

As seen in Fig. 3, the nodularity increases towards the middle of the workpiece. This can be explained by the segregation effect. The solidification front pushes the high nodularity forming material towards the part that solidifies last, i.e. the middle of the workpiece.

The large variation in nodularity complicates the evaluation of microstructures effect on machinability. An average value for each material needs to be taken. Therefore, it was decided only to machine the first 30 mm from the surface of workpiece A, which had a more constant nodularity value.

2) Section thickness´ effect on the nodularity and pearlite content

A separate study was made on another workpiece, called OPTIMA Sweden. The aim with this workpiece was not to evaluate the machinability of different CGI materials, but rather to see how the microstructure varied in geometrically complex components. The nodularity in the workpiece was investigated at different positions; see Fig. 4.

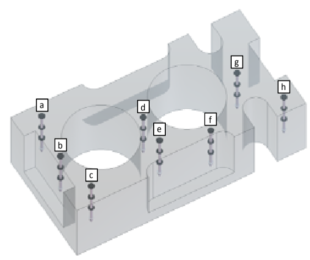

Fig. 4 The OPTIMA Sweden workpiece for microstructure evaluation, (100 x 200 x 400 [mm]). The black rings indicated where the nodularity has been measured

The thinner sections (b and f in Fig. 4 and Fig. 5) tend to result in larger nodularity values at the surface, compared to the thicker sections (e, g and h in Fig. 4 and Fig. 5). This can be explained with faster solidification rate, resulting in higher nodularity values, for given magnesium content. This has also been seen in other studies [4], [13], [14], [15].

The nodularity does not increase towards the middle, as it did in the homogeneous workpiece, see Fig. 3. Instead, it decreases from the surface, especially at thinner sections (b and f in Fig. 4 and Fig. 5). This can be explained by the presence of holes, leading to a more even solidification rate for all sections in the workpiece, compared to the homogeneous workpiece. The larger variation in nodularity, for thin sections, has also been observed in previous studies [15]. No segregation effect could be seen. The pearlite content in the workpiece was rather constant.

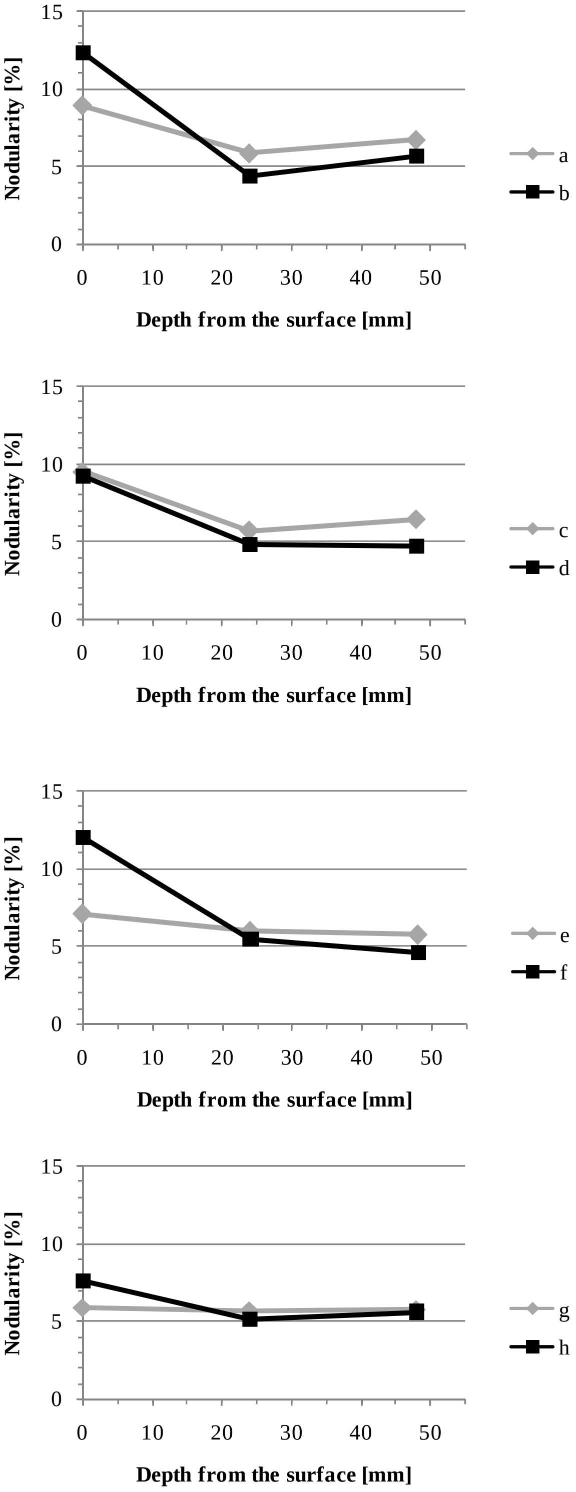

Fig. 5 Nodularity as a function of depth into the workpiece from the surface for different positions on the workpiece (Fig. 4)

3) Microstructure of the CGI materials

The interlamellar distance for the materials from the DoE (Table I) were studied. In Fig. 6, the differences in interlamellar distance in pearlite between the different workpieces are illustrated.

(a)

(b)

(c)

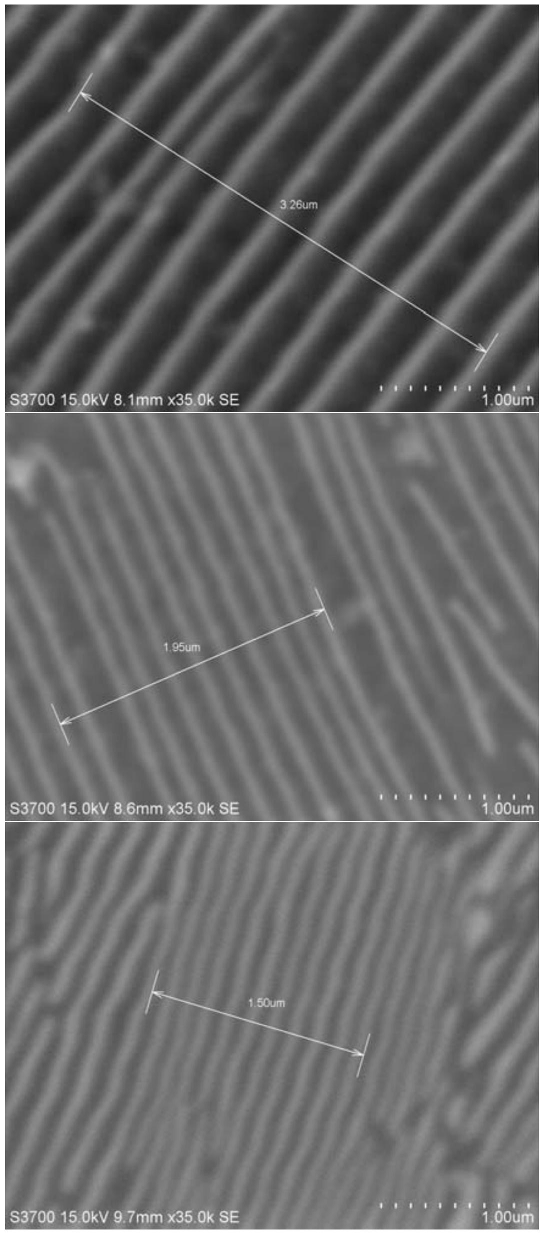

Fig. 6 Example for the difference in interlamellar distance in pearlite for workpiece A (a), workpiece B (b) and workpiece C (c)

As seen in Fig. 6, there is a clear difference in interlamellar distance in pearlite between the three workpieces. The interlamellar distance in pearlite, for all CGI materials can be seen in Fig. 7.

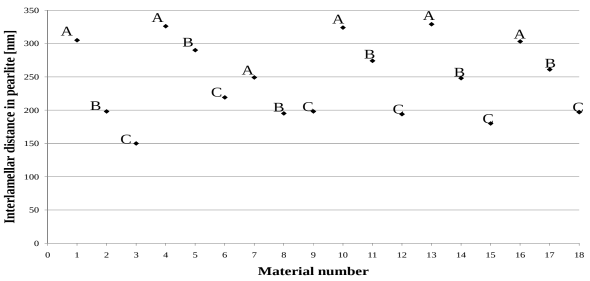

Fig. 7 Interlamellar distance in pearlite for the different CGI materials

Fig. 7 shows that workpiece A, (material: 1, 4, 7, 10, 13, 16), obtained coarser pearlite than the corresponding materials for workpiece B (material: 2, 5, 8, 11, 14, 17), and workpiece C (material: 3, 6, 9, 12, 15, 18). The results from the other microstructural characterization are presented in Table II.

TABLE II
EXPERIMENTAL MATERIAL MICROSTRUCTURE

Material	Work-piece	Section thickness [mm]	Nodularity [%]	Pearlite content [%]	Interlamellar distance in pearlite [nm]
1	A	80	3	23	305
2	B	46	9	21	198
3	C	26	12	23	150
4	A	80	28	23	326
5	B	46	25	23	290
6	C	26	29	23	219
7	A	80	8	80	249
8	B	46	9	86	195
9	C	26	13	80	198
10	A	80	30	80	324
11	B	46	26	85	274
12	C	26	23	89	194
13	A	80	10	96	329
14	B	46	6	95	248
15	C	26	8	97	180
16	A	80	32	89	303
17	B	46	29	95	261
18	C	26	16	97	197

In Table II, the average values are presented. The averages were calculated for each material by weighting higher the positions where the largest amount of material was removed. As seen in Table II, the three distinguished pearlite levels (Table I) were not obtained. The middle pearlite level lied very near the high level, resulting in no possibility to see if there was any non-linear relation between pearlite content and machinability and material physical properties.

Since the nodularity was intended to be kept constant between the three different workpieces, an investigation felt necessary to see if this was achieved. Therefore, the DoE technique was used to see if section thickness only controlled the interlamellar distance in pearlite or if it also affected pearlite content and nodularity, see Fig. 8.

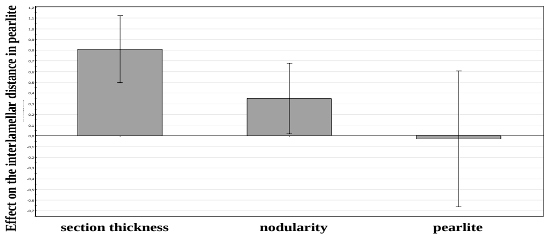

Fig. 8 The effect of section thickness, nodularity and pearlite on the interlamellar distance in pearlite of the CGI materials

As seen in Fig. 8, there is a strong relationship between section thickness the interlamellar distance in pearlite. The nodularity and pearlite content was therefore not affected by the different section thicknesses.

4) Material physical properties

Repeated tensile- and hardness tests were performed on all CGI materials and the reference material to map the material physical properties. The test specimens were prepared from different positions in the workpieces. The positions were carefully selected and they give together significant values for the material physical properties, see Table III.

TABLE III
MATERIAL PHYSICAL PROPERTIES

Material	Work-piece	Ultimate tensile strength [MPa]	Yield strength [MPa]	Elongation to fracture [%]	Hardness [HBW]
1	A	278	220	4.8	133
2	B	291	226	5.1	136
3	C	301	230	5.9	133
4	A	320	244	5.3	138
5	B	319	244	5.1	142
6	C	320	245	4.4	143
7	A	384	281	2.5	198
8	B	417	302	2.4	215
9	C	410	300	2.3	197
10	A	463	312	3.2	201
11	B	471	330	2.4	224
12	C	500	354	2.3	224
13	A	419	313	1.7	219
14	B	434	334	1.6	236
15	C	420	316	1.9	226
16	A	501	335	3.1	217
17	B	505	353	2.6	231
18	C	510	372	2.0	238

As a comparison, the ultimate tensile strength for an alloyed gray iron reference material was 222 MPa and the elongation to fracture value was 1.3%. Almost all CGI materials are stronger than the reference material, as seen in Table III.

The DoE technique was used to see how strong effect the interlamellar distance in pearlite had on the ultimate tensile strength. The results are presented in Fig. 9.

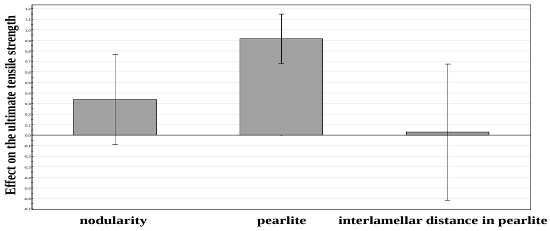

Fig. 9 The effect of interlamellar distance in pearlite, nodularity and pearlite on the ultimate tensile strength of CGI materials

The interlamellar distance has a minor effect on the ultimate tensile strength. Pearlite content is the predominant microstructural parameter affecting the ultimate tensile strength. The results could have been different if workpiece A was thinner than 26 mm. Then the interlamellar distance in pearlite would have been smaller, resulting in a stronger material, as shown by Mampaey [16]. He investigated the influence of eutectoid transformation in gray cast iron, achieved by different cooling rates. A difference in tensile strength up to 50 MPa could be seen. The higher strength in the fast cooled specimens was caused by shorter interlamellar distance in the pearlite.

As the pearlite content is the microstructural parameter that has the strongest effect on ultimate tensile strength it is the most important microstructural parameter to take into consideration if a high strength cylinder block is desired.

In Fig. 10, the ultimate tensile strength for the different CGI materials is therefore shown as a function of the pearlite content. Increasing the pearlite content gives a stronger material.

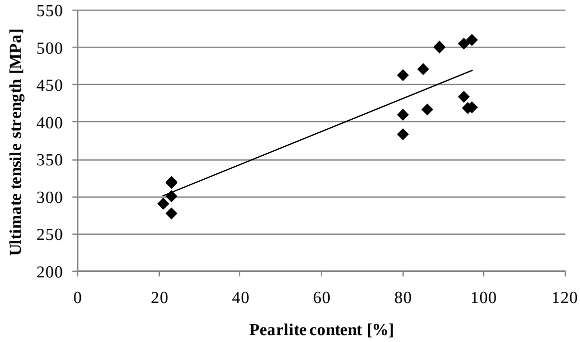

Fig. 10 UTS as a function of pearlite content for the CGI materials

This can be explained with the fact that stronger materials are promoted by a more pearlitic microstructure. Larger pearlite values do on the other hand strongly decrease the elongation to fracture value. The elongation to fracture can also be raised by increasing the nodularity, but not at the same extent as by decreasing the pearlite content.

A chemical analysis was performed on the CGI materials, see Table IV. The chemical analysis did not show anything extraordinary. Cr, Mo and Ti concentrations should not result in the formation of larger carbide particles.

B. Machining Experiments

1) Tool life

The tool life for each CGI material was tested in face milling. The tests were repeated and tool life for each material established. For two of the CGI materials, tool life could not be established. The tool wear, when machining those CGI materials, did not exceed 0.2 mm after more than 140 minutes machining, and it was therefore stopped. The results are shown in Table V.

TABLE IV
MATERIAL CHEMICAL ANALYSIS

Material	C [%]	Si [%]	Mn [%]	P [%]	S [%]	Cr [%]	Ni [%]	Mo [%]	Cu [%]	Sn [%]	Ti [%]	Al [%]	Mg [%]
1	3.79	1.95	0.40	<0.005	0.008	0.03	0.03	<0.01	0.30	0.006	0.005	0.003	0.008
2	3.67	1.96	0.37	<0.005	0.009	0.03	0.03	<0.01	0.29	0.005	0.005	0.003	0.010
3	3.55	1.96	0.36	<0.005	0.008	0.03	0.03	<0.01	0.28	0.005	0.004	0.003	0.008
4	3.70	1.95	0.40	<0.005	0.008	0.03	0.03	<0.01	0.30	0.005	0.005	0.003	0.015
5	3.71	2.02	0.38	<0.005	0.008	0.03	0.03	<0.01	0.29	0.005	0.005	0.003	0.017
6	3.70	2.00	0.38	<0.005	0.007	0.03	0.03	<0.01	0.28	0.005	0.004	0.003	0.016
7	3.79	1.93	0.40	<0.005	0.008	0.03	0.03	<0.01	0.76	0.031	0.005	0.003	0.009
8	3.69	2.02	0.36	<0.005	0.009	0.03	0.03	<0.01	0.75	0.030	0.005	0.003	0.011
9	3.75	1.97	0.37	<0.005	0.007	0.03	0.03	<0.01	0.75	0.033	0.005	0.003	0.009
10	3.75	1.98	0.41	<0.005	0.007	0.03	0.03	<0.01	0.78	0.031	0.005	0.003	0.017
11	3.69	1.99	0.39	<0.005	0.008	0.03	0.03	<0.01	0.93	0.061	0.005	0.003	0.016
12	3.65	1.96	0.37	<0.005	0.006	0.03	0.03	<0.01	0.79	0.035	0.004	0.003	0.017
13	3.84	1.92	0.40	<0.005	0.008	0.03	0.03	<0.01	0.93	0.067	0.005	0.002	0.010
14	3.62	1.99	0.37	<0.005	0.008	0.03	0.03	<0.01	0.95	0.074	0.005	0.003	0.009
15	3.61	2.01	0.36	<0.005	0.006	0.03	0.03	<0.01	0.91	0.072	0.005	0.003	0.008
16	3.79	1.99	0.39	<0.005	0.008	0.03	0.03	<0.01	0.93	0.061	0.005	0.003	0.016
17	3.62	2.08	0.37	<0.005	0.006	0.03	0.03	<0.01	0.79	0.035	0.004	0.003	0.017
18	3.65	2.04	0.37	<0.005	0.006	0.03	0.03	<0.01	0.95	0.075	0.005	0.003	0.016

TABLE V
AVERAGE TOOL LIFE FOR THE CGI MATERIALS

Material	Workpiece	Tool life [minutes]
1	A	108.2
2	B	>140
3	C	97.5
4	A	43.5
5	B	99.2
6	C	>180
7	A	54.2
8	B	73.5
9	C	75.0
10	A	35.3
11	B	35.5
12	C	37.3
13	A	33.7
14	B	31.2
15	C	44.7
16	A	37.0
17	B	26.6
18	C	25.8

The tool life of the CGI materials is spread over a large time interval. It was found that the tool life for Material 4 was somewhat deviant, it was unexpectedly short. Therefore, the material was more carefully investigated, regarding carbide particles, which significantly could affect the tool life. The material did contain carbides, at some places, but the tendency was not greater than for the other materials of the same sort, for example material 1 and 10. Since the machining results from material 4 deviated significantly from the others, these were excluded from the tool life analysis.

An alloyed gray iron was machined and used as a reference material. The experiments were repeated and a tool life of 122 min was established. The ultimate tensile strength of the alloyed gray iron reference material was 222 MPa, compared to the weakest CGI material that had 278 MPa.

The DoE technique was used to see how strong effect the interlamellar distance in pearlite had on the tool life. The results are presented in Fig. 11.

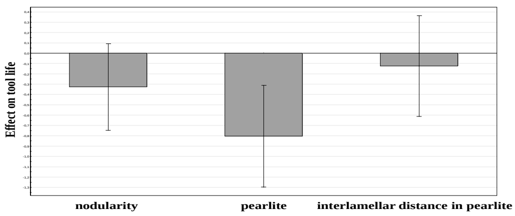

Fig. 11 The effect of interlamellar distance in pearlite, nodularity and pearlite on the tool life

The results showed that the interlamellar distance in pearlite did not have as strong effect on CGI tool life as the pearlite or the nodularity. That pearlite is the most important microstructural parameter affecting CGI tool life has also been seen in previous studies [6].

2) Tool wear behaviour

The wear of the inserts, when machining the low pearlitic CGI materials (material 1 to material 6) compared to the high pearlitic CGI materials (material 7 to material 18) were significantly different, see Fig. 12.

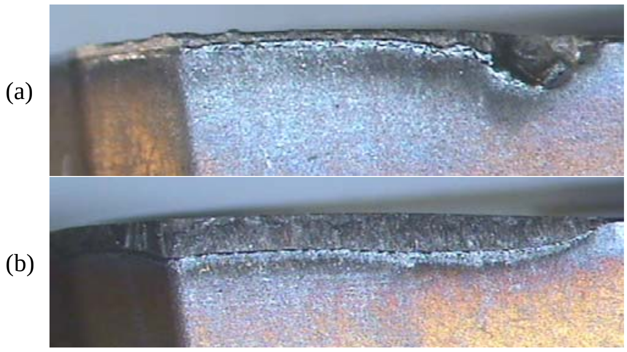

Fig. 12 Typical wear of the cemented coated carbide insert when milling (a) low pearlitic CGI, (b) high pearlitic CGI

The wear was more concentrated and a tendency to notch wear could be seen when machining the low pearlitic materials (Fig. 12a). This was not observed for the high pearlitic CGI materials (Fig. 12b) where even abrasive wear was the predominant wear mechanism. The interlamellar distance in pearlite did not seem to affect the wear behavior. Wear development of the inserts were also affected by the difference in pearlite content. The high pearlitic CGI material had a more, predictive tool life, with a rather steady wear progress of the inserts, while it for the low pearlitic materials suddenly increased rapidly.

IV. CONCLUSION

From this study the following conclusions can be drawn:

- Interlamellar distance in pearlite does not seem to affect tool life or material physical properties as strong as nodularity and pearlite content.
- High pearlite content gives a more even tool wear behaviour.
- It is evident that it is hard to obtain a constant microstructure through the whole component, when casting CGI.
- The presence of holes in workpieces leads to different solidification- and cooling rates, resulting in large variations in microstructure.

The interlamellar distance in pearlite in the CGI materials, did not seem to have any larger effect on either machinability or the material physical properties. It is although a possibility that its influence could have been larger with thinner workpieces.

When designing a CGI material suited as engine material, the pearlite content is an important microstructural parameter to take into consideration. It is a delicate situation where the increase of material strength results in loss of machinability. The approach must therefore be to look from both points of view; material-machining and machining-material.

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