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# Machinability of Malleable Iron Powder Materials vs Ductile Iron and Powder Forged FC-0205 Materials

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**Abstract**

Malleable iron powder, MIP, is an iron-graphite composite powder in which carbon is dispersed as graphite nodules in a ferritic matrix. This material achieves almost 100% densification through liquid phase sintering. However, because of the large shrinkage occurring during sintering, it is difficult to hold tight dimensional tolerances. Therefore, a machining operation could be necessary to meet the application requirements or accommodate features that cannot be molded during compaction.

A study was carried out to compare the machinability of test pieces made with these new materials and those made with powder forged FC-0205 with 0.3% MnS and ductile iron castings. Results showed that ferritic malleable iron powder parts machined similarly to DI 65-45-12 and pearlitic malleable iron powder parts machined similarly to DI 80-55-06 and powder forged FC-0205 with 0.3% MnS.

**Keywords:** Malleable Iron Powder, Machinability, High Density.

**Introduction**

Increasing final density is the most efficient way to improve the static and dynamic properties of PM parts. Among others, supersolidus liquid phase sintering (SLPS) is a process that makes possible to reach full density during the sintering operation. To be successful, this process requires prealloyed powders that, when heated to an intermediate temperature between the solidus and liquidus, nucleate a liquid within each particle [1]. Fe-2C-1Si system is well suited for SLPS because the carbon is fully prealloyed and makes the sintering possible at temperatures around 1160°C. Recently, a new malleable iron powder (MIP) grade has been developed to produce PM parts reaching sintered density of 7.50 g/cm³ through SLPS mechanism [2,3]. MIP is produced by water atomization of a Fe-2C-1Si melt which is then heat treated to malleabilize the material and to produce a ferritic structure in which carbon is distributed as graphite nodules. The mix of this powder with lubricant is called MIP-A. With the proper sintering profile, a pearlitic structure with a mixture of round and flaky graphite particles surrounded by a ferritic layer can be achieved [3]. Although the presence of graphite flakes is not detrimental to the static properties, it has a negative effect on fatigue strength when the number of flakes longer than 100 µm per $mm^2$ "nb flakes/mm² >100 µm" exceeds four. Thus, it is preferable to have graphite nodules instead of flakes. This can be done by decreasing the sintering temperature of MIP, which prevents the total dissolution of carbon in the austenite. Therefore, a fraction of carbon is maintained in the ferrous matrix at the sintering temperature, and can act as nucleation sites for the precipitation of graphite nodules upon cooling. It has been shown that the addition of 0.2 wt% phosphorus to the MIP powder, MIP-B, as $Fe_3P$ can reduce the sintering temperature down to 1120°C and produce a larger number of graphite nodules both inside grains and in grain boundaries in the sintered structure [4]. The microstructure of MIP-B is also pearlitic but with graphite nodules. However, when the post-sintering cooling rate is not fast enough, a ferrite ring could be present around graphite particles in both MIP materials which should be preferably avoided to improve the mechanical properties. A normalization treatment can also be performed on the sintered MIP parts in order to transform ferrite to pearlite and to refine the pearlitic grains. MIP materials have shown to have comparable mechanical properties to those of ductile iron castings with the exception of elongation [4]. Since a dimensional change of about -4% is seen with MIP materials due to the shrinkage upon sintering, machining operations could be necessary to meet the application requirements or accommodate features that cannot be molded during compaction. Because of the presence of free graphite, parts made with MIP grades should exhibit good machining performances [4]. The objective of this paper is to present the results of the machining performances of MIP-A and MIP-B compared to those of two grades of ductile iron castings, ASTM A536 DI 65-45-12 and DI 80-55-06, and a powder forged FC-0205 material with 0.3% MnS.

**Experimental procedure**

The chemical and physical properties of the MIP base powder are presented in Table 1. Table 2 presents the mix composition of MIP-A and MIP-B mixes. MIP-A and MIP-B were sintered at the average temperature of their sintering window (10 min at 1162°C for MIP-A and 30 min at 1121°C for MIP-B). The complete sintering profiles for both materials were presented in a previous paper [4]. MIP-A was evaluated both as-sintered with a ferritic structure and as-normalized, while MIP-B was evaluated only after normalization. The normalization treatment was performed on MIP-A and MIP-B parts by heating for 45 minutes at 900°C and cooling immediately in air. The machinability of ferritic MIP-A, normalized MIP-A and MIP-B materials in face turning operation was evaluated and compared to that of DI 65-45-12, DI 80-55-06 and powder forged FC-0205 with 0.3% MnS. Face turning tests were performed using a Boehringer NG200 two-spindle turning center. Rings of 50.8 mm OD, 25.4 mm ID and 22.86 mm thickness were pressed out of MIP-A and MIP-B and used as test samples. Rings with the same dimensions were machined from ductile iron castings and FC-0205 PF with 0.3% MnS. Two regimes of cutting operation were tested. One semi-roughing operation that involved two cutting speeds (183 and 274 m/min), one feed rate (0.254 mm/rev), and one depth of cut (DOC) (1.52 mm). The second was a finishing operation which involved one cutting speed (137 m/min), one feed rate (0.102 mm/rev), and one depth of cut (1.02 mm). Two types of tool holders were used: DCKN and DCLN having 15° and –5° lead angles respectively (Fig. 1). The same insert shape and grade was used on both holders (CNMG 120408-M5 grade VP5515, in carbide). Cutting forces were monitored during face turning tests. Forces were measured with a three-component 9121- type Kistler Dynamometer. Fig. 2 shows the directions of the measured X, Y and Z cutting forces. Samples were characterized using mainly tangential forces but feed forces were also considered. A total of 36 tests were performed which are summarized in Table 3.

Table 1. Chemical and physical properties of MIP powder

| C, % | O, % | Si, % | S, % | +60 mesh, % | -60/+100 mesh, % | -100/+325 mesh, % | -325 mesh, % | Apparent density, g/cm³ | Flow, s/50g |
|---|---|---|---|---|---|---|---|---|---|
| 1.97 | 0.10 | 1.05 | 0.001 | Trace | 17 | 63 | 20 | 2.85 | 30 |

Table 2. Mix composition of MIP-A and MIP-B

| | P, % | Lube, % |
|---|---|---|
| MIP-A | 0 | 0.5 |
| MIP-B | 0.2 | 0.5 |

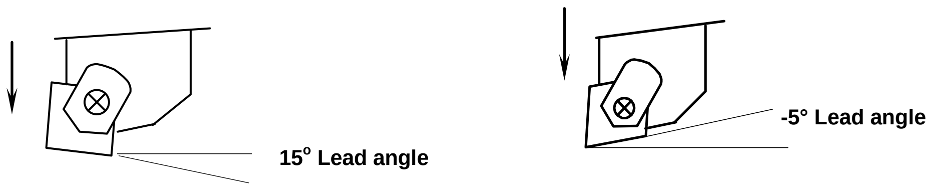



Fig. 1.Tool holder geometry

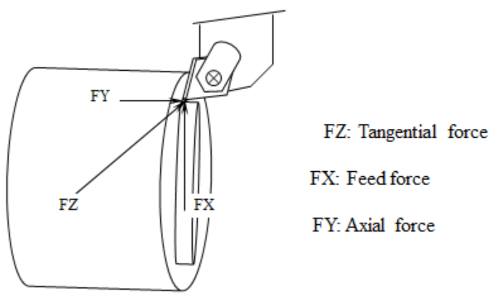



Fig. 2. Direction of the cutting forces measured by the dynamometer at the insert/workpiece point of contact

Table 3. Turning Test Parameters

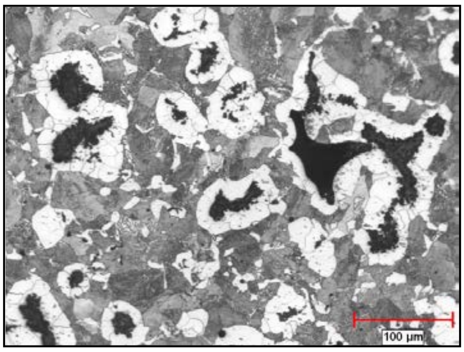
| Test | Material | Speed, m/min | Feed, mm/rev | DOC, mm |
|---|---|---|---|---|
| **Tests with tool holder/insert combination: DCLNL16 4D CNMG120408M5 - VP5515 (-5° lead angle)** | | | | |
| 1 | Ferritic MIP-A | 183 | 0.254 | 1.52 |
| 2 | MIP-A | 183 | 0.254 | 1.52 |
| 3 | MIP-B | 183 | 0.254 | 1.52 |
| 4 | DI-65-45-12 | 183 | 0.254 | 1.52 |
| 5 | DI-80-55-06 | 183 | 0.254 | 1.52 |
| 6 | FC-0205 PF-0.3MnS | 183 | 0.254 | 1.52 |
| 7 | Ferritic MIP-A | 274 | 0.254 | 1.52 |
| 8 | MIP-A | 274 | 0.254 | 1.52 |
| 9 | MIP-B | 274 | 0.254 | 1.52 |
| 10 | DI-65-45-12 | 274 | 0.254 | 1.52 |
| 11 | DI-80-55-06 | 274 | 0.254 | 1.52 |
| 12 | FC-0205 PF-0.3MnS | 274 | 0.254 | 1.52 |
| 13 | Ferritic MIP-A | 137 | 0.102 | 1.02 |
| 14 | MIP-A | 137 | 0.102 | 1.02 |
| 15 | MIP-B | 137 | 0.102 | 1.02 |
| 16 | DI-65-45-12 | 137 | 0.102 | 1.02 |
| 17 | DI-80-55-06 | 137 | 0.102 | 1.02 |
| 18 | FC-0205 PF-0.3MnS | 137 | 0.102 | 1.02 |
| **Tests with tool holder/insert combination: DCKNL16 4D CNMG120408M5 - VP5515 (15° lead angle)** | | | | |
| 19 | Ferritic MIP-A | 183 | 0.254 | 1.52 |
| 20 | MIP-A | 183 | 0.254 | 1.52 |
| 21 | MIP-B | 183 | 0.254 | 1.52 |
| 22 | DI-65-45-12 | 183 | 0.254 | 1.52 |
| 23 | DI-80-55-06 | 183 | 0.254 | 1.52 |
| 24 | FC-0205 PF-0.3MnS | 183 | 0.254 | 1.52 |
| 25 | Ferritic MIP-A | 274 | 0.254 | 1.52 |
| 26 | MIP-A | 274 | 0.254 | 1.52 |
| 27 | MIP-B | 274 | 0.254 | 1.52 |
| 28 | DI-65-45-12 | 274 | 0.254 | 1.52 |
| 29 | DI-80-55-06 | 274 | 0.254 | 1.52 |
| 30 | FC-0205 PF-0.3MnS | 274 | 0.254 | 1.52 |
| 31 | Ferritic MIP-A | 137 | 0.102 | 1.02 |
| 32 | MIP-A | 137 | 0.102 | 1.02 |
| 33 | MIP-B | 137 | 0.102 | 1.02 |
| 34 | DI-65-45-12 | 137 | 0.102 | 1.02 |
| 35 | DI-80-55-06 | 137 | 0.102 | 1.02 |
| 36 | FC-0205 PF-0.3MnS | 137 | 0.102 | 1.02 |

## Results

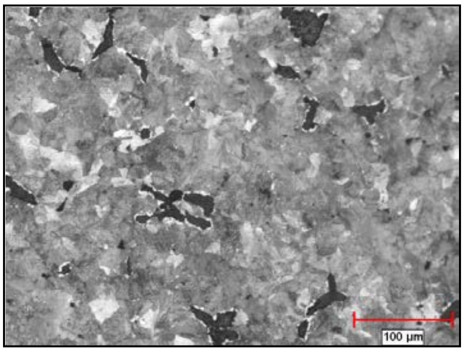
The etched microstructures of the tested MIP materials are presented in Fig. 3. The as-sintered ferritic MIP-A shows a pearlitic matrix with about 20% of ferritic grains surrounding the graphite particles. The fraction of ferrite decreased significantly after normalization as depicted in the micrograph of normalized MIP-A. The normalized MIP-B contains a larger number of graphite particles when compared to MIP-A.

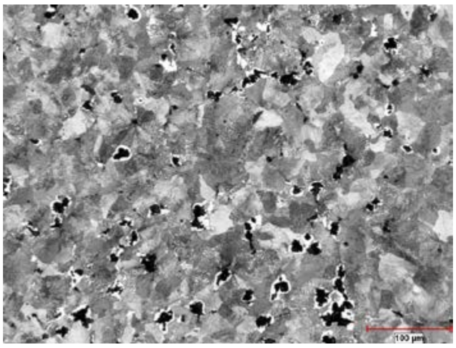
The results of machining performance in terms of tangential and feed force variations versus cutting speed for all studied materials are presented in Fig. 4 and Fig. 5. It can be seen that the machinability of ferritic MIP-A is comparable to that of DI 65-45-12 and better than the other materials in terms of tangential force. This good performance resulted from the higher ferrite content of these two materials improving the machinability. MIP-B showed superior performance than FC-0205 PF+MnS and comparable to that of DI 80-55-06 at high cutting speed (274 m/min). The machinability of normalized MIP-A was comparable to that of FC-0205 PF+MnS in regards to tangential forces but inferior to ferritic MIP-A, MIP-B and both ductile iron grades. All materials showed superior face turning performance at high speed and at 15° lead angle. This force reduction is due to the increase of the cutting temperature as the cutting speed is increased resulting in a softening action on the work material.

Therefore, it is recommended to perform machining at this speed (274 m/min) in order to increase the tool life. The small reduction in the magnitude of tangential force observed when using the 15° lead angle tool holder could be attributed to the thinning effect imposed on the cut chip by increasing the chip contact length. The feed force required to machine ferritic MIP-A and DI 65-45-12 was significantly lower than for the other studied materials. The performance of MIP-B was comparable to FC-0205PF+MnS but inferior to the other materials. It was also found that although the tangential force was lower for DI 80-55-06 compared to FC-0205PF+MnS, it has a lower performance in terms of feed force.




Ferritic MIP-A



Normalized MIP-A

Normalized MIP-B

Fig. 3. Etched microstructures of MIP materials

For the finishing operation performed at a cutting speed of 137 m/min, the machinability in terms of tangential and feed force was superior for ferritic MIP-A and DI-65-45-12 but similar for all other materials, as depicted in Fig. 6 and Fig. 7. Although MIP-B had a comparable face turning performance to DI 80-55-06 and FC-0205 PF+MnS materials, MIP-A showed a slightly lower performance. For ferritic MIP-A and DI 65-45-12, the tangential force showed a slight decrease in magnitude when switching from the -5° to the 15° lead angle as shown in Fig. 6 for the finishing operation. However, the opposite behavior was found for the other studied materials. The feed force was similar or lower at 15° lead angle for ferritic MIP-A, ductile iron grades and FC-0205 PF+MnS but slightly higher for MIP-A and MIP-B materials (Fig. 7).

The microstructures of DI 65-45-12, DI 80-55-06 and FC-0205 PF+MnS are shown in Fig. 8. The structures of ductile iron grades are formed of a pearlitic matrix in which graphite nodules are distributed. DI 65-45-12 shows the highest ferrite fraction of all tested materials. Powder forged FC-0205+MnS contains both ferrite and pearlite grains with a finer average size compared to the ductile iron grades. The mechanical properties of the studied materials are presented in Table 4. While ferritic MIP-A and DI 65-45-12 had better machining performances than normalized MIP grades, DI 80-55-06, and FC-0205 PF+MnS, they present lower tensile properties and hardness. MIP-B had a comparable performance to DI 80-55-06 but better mechanical properties which could be attributed to its finer microstructure. The mechanical properties of FC-0205 PF+MnS are comparable to those of MIP materials. Meanwhile, the lower machinability of MIP-A can be related to its lower content of graphite clusters compared to MIP-B. The graphite particles in MIP parts can act as lubricant in the machining operations improving the machinability on these materials.

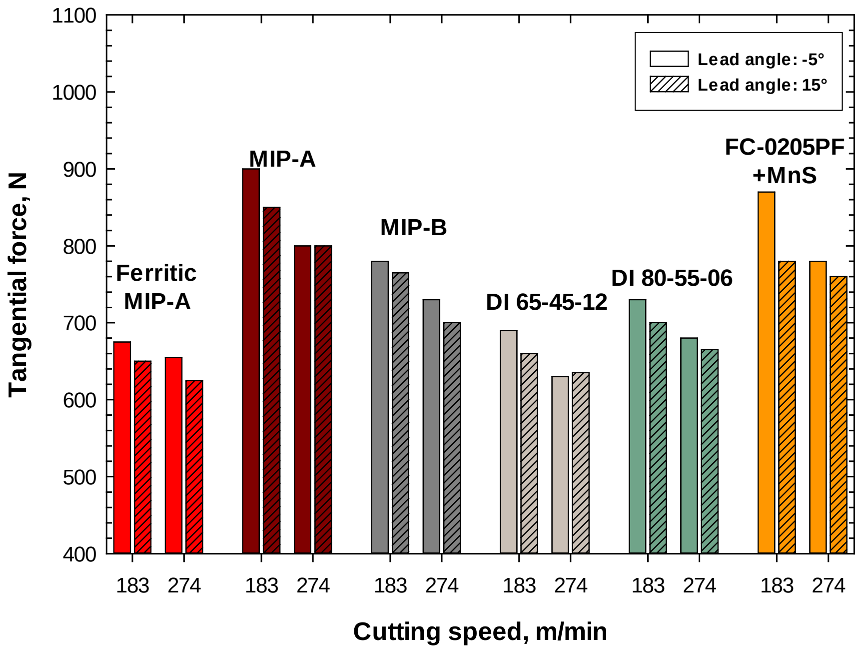



Fig. 4. Tangential force versus cutting speed of MIP materials compared to ductile iron castings and FC-0205 PF+MnS at two different lead angles; semi-roughing operation

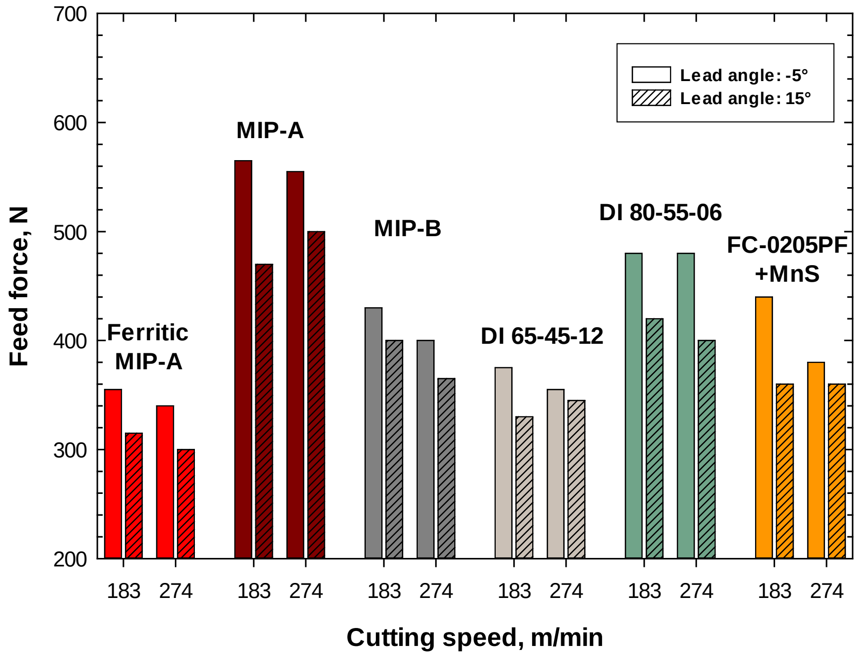



Fig. 5. Feed force versus cutting speed of MIP materials compared to ductile iron castings and FC-0205 PF+MnS at two different lead angles; semi-roughing operation

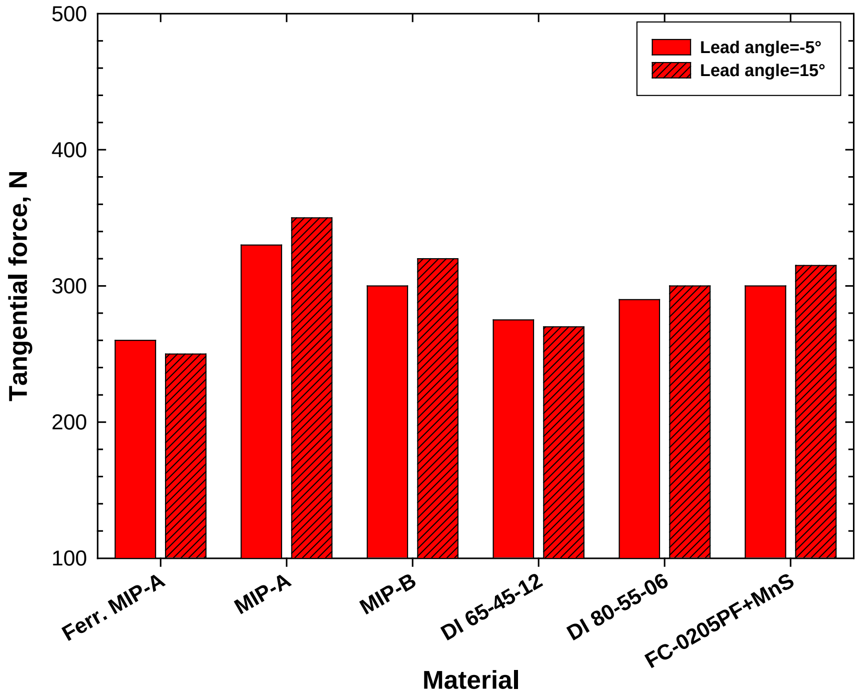



Fig. 6. Tangential force of MIP-A and MIP-B compared to ductile iron castings and FC-0205 PF+MnS at two different lead angles; finishing operation

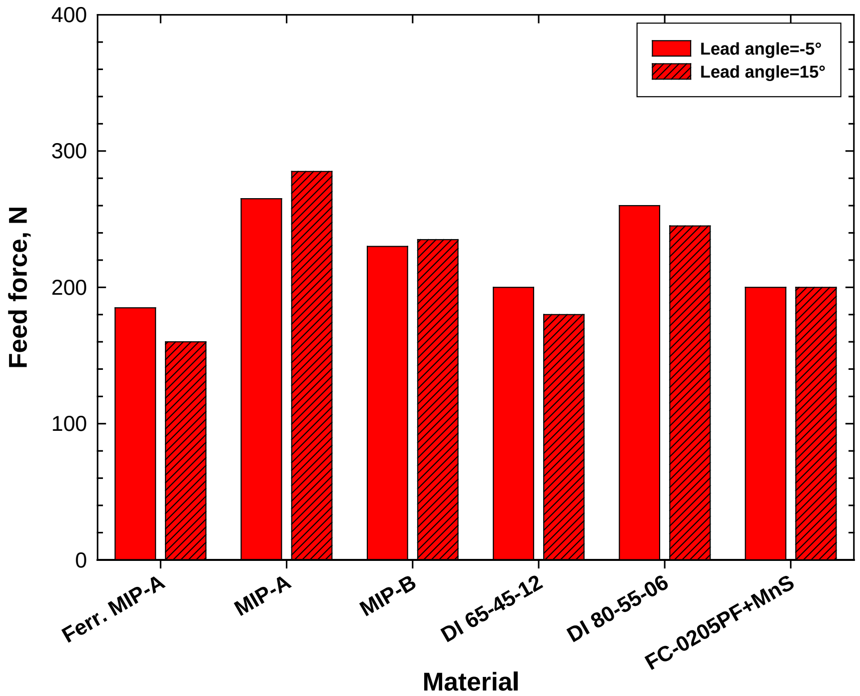
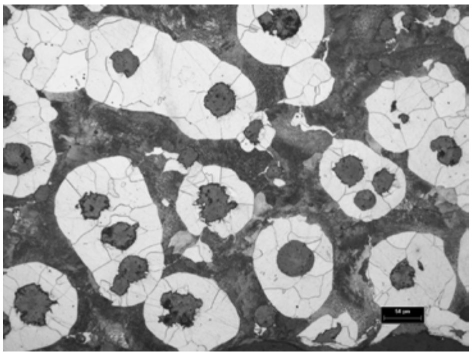
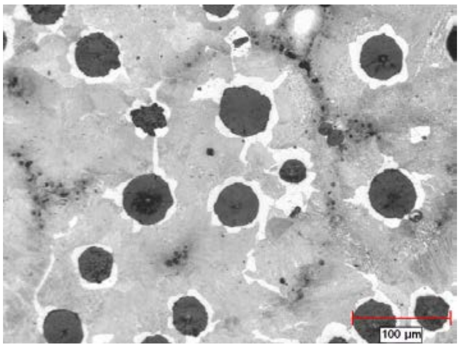


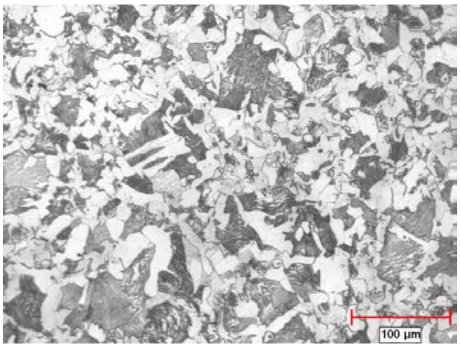

Fig. 7. Feed force of MIP-A and MIP-B compared to ductile iron castings and FC-0205 PF+MnS at two different lead angles; finishing operation



DI 65-45-12




DI 80-55-06




FC-0205 PF+MnS

Fig. 8. Microstructures of ductile iron grades and FC-0205 PF+MnS

Table 4.Tensile properties of the various materials compared

| Materials | Tensile strength, MPa | Yield strength, MPa | Elongation, % | Hardness, HRA |
|---|---|---|---|---|
| MIP-A ferritic | 565 | 303 | 4.2 | 52 |
| MIP-A | 795 | 572 | 1.8 | 65 |
| MIP-B | 868 | 592 | 2.5 | 64 |
| DI 65-45-12 [5] | 500 | 350 | 17 | 55 |
| DI 80-55-06 [5] | 700 | 470 | 8 | 62 |
| FC-0205 PF+MnS [6] | 860 | 560 | 15 | 62 |

**Conclusions**

1. Based on tangential and feed force measurements, ferritic MIP-A, MIP-B and DI 65-45-12 exhibited comparable machining performance and the machinability of these three materials was better than the other materials tested.
2. The good performance of ferritic MIP-A and DI 65-45-12 can be attributed to their higher ferrite content compared to the other materials. The large number of graphite nodules in MIP-B is suggested as the reason for its superior machining performance compared to MIP-A, DI 80-55-06 and powder forged FC-0205+MnS as graphite nodules could act as lubricant and consequently improve the machining performance.
3. Under the conditions studied, normalized MIP-A exhibited slightly lower machining performance than DI 80-55-06 and the powder forged material tested. This could be related to its lower ferrite content as compared to the other materials.
4. The mechanical properties of normalized MIP materials were superior to ductile iron grades and comparable to powder forged FC-0205+MnS except for the percentage of elongation.

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