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GREEN MACHINING OF P/M PARTS USING ENHANCED GREEN STRENGTH LUBRICATING SYSTEMS

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ABSTRACT

P/M parts are often machined after sintering to meet tight dimensional tolerances or accommodate design features that cannot be molded during compaction. The development of new polymeric lubricants opens the possibility of machining P/M components prior to sintering, which could result in a considerable reduction of machining costs.

This study compares the green and ejection characteristics of binder-treated FC-0205 mixes containing either a new high green strength lubricating system or conventional EBS wax. The comparison was carried out on TRS specimens and gears pressed from 6.8 to 7.2 g/cm^3 on laboratory and production scale presses. The influence of these lubricating systems on green machining was also determined on gear shape specimens pressed to 6.8 and 7.0 g/cm^3. Results showed that mixes containing the new lubricating system exhibit similar compressibility and a better lubrication behavior than mixes admixed with the conventional EBS wax. Moreover, the green strength of gears produced with the new lubricating system was sufficiently high to enable machining in the green state.

INTRODUCTION

The development of new techniques to enable machining of parts prior to sintering could be of great advantages to the P/M industry. Indeed, with the advent of high performance materials that exhibit high apparent hardness and strength after sintering, green machining becomes a very attractive process to improve tool life, increase productivity and promote competitiveness [1]. A recent study clearly demonstrated that typical stresses applied on tooling, when drilling F-0005 parts in a green state, is reduced by a factor of 8 to 10 as compared to drilling executed after sintering [2]; this may be even more pronounced for parts made from sinter hardening materials.

In addition to warm pressing and pre-sintering techniques, the development of new polymeric lubricating systems is a promising avenue to enable machining of parts prior to sintering. A few studies have recently explored the feasibility of using specific polymers, with adequate lubricating properties, that enhance the green strength sufficiently to minimize part failure or enable machining in the green state [3-6]. The increase in green strength is explained by the higher intrinsic mechanical properties of these polymeric lubricants as compared to standard lubricants such as synthetic waxes and metallic stearates. These polymeric additives soften at a given temperature and have the ability to form a strong network, more or less continuous, that strengthens the green specimens during compaction and/or when using a curing treatment. Additionally, unlike conventional lubricants which tend to be distributed at the surface of metallic powders during the mixing step, polymeric lubricants most often have a lower deformability and remain as discrete particles. This can potentially favor the formation of interlocking or microwelding between the metal powder particles during the compaction step, and, therefore, increase the green strength [7].

This study compares the compaction and lubrication behaviors of mixes containing a new polymeric lubricating system to those of powder admixed with conventional EBS wax as well as green properties of parts pressed on lab and production presses. The effect of these systems on green machining is also reported for gears pressed to 6.8 and 7.0 g/cm^3 on a production press.

EXPERIMENTAL PROCEDURE

Materials and Laboratory Scale Evaluation

The green properties of binder-treated FC-0205 mixes containing either the new lubricating system (BM system) or a conventional EBS wax were compared using a laboratory press. These mixes were prepared from ATOMET 1001, 2.0 wt% copper, 0.60 wt% graphite as well as 0.65 and 0.80 wt% of the respective lubricating system. Details of these lubricating/binding systems are given in Table 1.

TABLE 1
Composition of binder-treated FC-0205 mixes

Type of Mix	Lubricating / binding System
New BM mix	0.65 wt% lubricants + binder
EBS mix	0.80 wt% Acrawax C atomized + binder

Standard transverse rupture (TRS) specimens were prepared to compare green and ejection properties of the mixes. The ejection characteristics were determined with 1.27 cm (½ in) thick TRS specimens. The die set was heated to reach 55°C in order to simulate the frictional heat generated during typical production conditions. Cold powder mixes were fed into the die cavity when thermal equilibrium was reached. The mixes were then pressed to reach green densities of 6.8, 7.0 and 7.2 g/cm^3. Several specimens pressed with the new BM system to 6.8 g/cm^3 were also cured in air at 175°C for 1 hour. Details of the compacting conditions are listed in Table 2.

The ejection properties were evaluated using an automatic data acquisition system. The force required to eject the TRS specimens was measured throughout the ejection step. By dividing the load by the area of the compact in contact with die walls, it was possible to determine the stripping and sliding pressures needed to eject the specimens. The stripping pressure corresponds to the shearing stress required to initiate the ejection, while the sliding pressure represents the mean stress needed to move parts to the die entrance. Green properties were evaluated according to the MPIF standard test procedure Nº15.

Production Scale Evaluation

A total of 900 gears with a hub were produced on a Gasbarre 150 tons mechanical press from each binder-treated mix at a green density of either 6.8 or 7.0 g/cm^3. The gear had an outer diameter of 5.08 cm (2.0 in) as well as an overall height (OAH) of 2.41 cm (0.95 in) with a hub section 0.89 cm (0.35 in) high. The outer diameter and wall thickness of the hub section were 2.03 cm (0.80 in) and 0.38 cm (0.15 inch) respectively. An illustration of the gear is shown in Figure 1. For this part, the frictional area between the gear and the die walls is significantly higher than that of standard 0.64 cm (¼ in) thick TRS specimens, i.e. 39.0 cm^2 versus 5.7 cm^2.

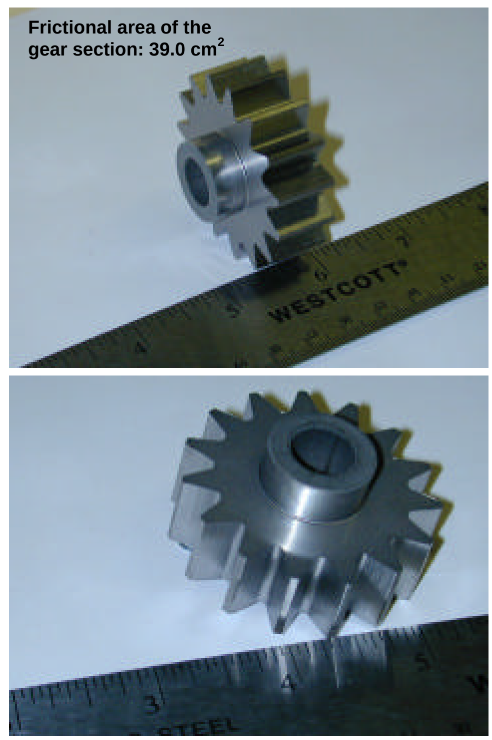

Figure 1. Illustration of the gear with a hub.

The mechanical press was set to produce 7.5 gears per minute. Prior to the production run, die and punches were heated to the temperature obtained during typical production conditions, i.e. about 55°C. The temperature of parts was measured with a contact probe immediately at the exit of the die cavity at a frequency of once every 50 parts. The tonnage and ejection curves were recorded during the production run by using an automated data acquisition system.

The green strength and machinability of gears pressed to 6.8 and 7.0 g/cm^3 with the new BM system were compared to those of gears made from the EBS containing mix. Several gears pressed to 6.8 g/cm^3 with the new system were also submitted to different curing treatments and compared to as-compacted gears produced from the same mix. The curing was carried out in air at either 175 or 230^{o}C for 0.5 to 3 hours. Details of the experiments are given in Table 2.

TABLE 2
Green density and curing treatment conditions for TRS bars and gears pressed from BM and EBS lubricating systems

Type of Part	Type of Mix	Green Density (g/cm^3)	Curing Treatment	
			T(^{o}C)	Time (h)
TRS	BM	6.8	-	-
		6.8	175	1
		7.0	-	-
		7.2	-	-
	EBS	6.8	-	-
		7.0	-	-
		7.2	-	-
Gear	BM	6.8	-	-
		7.0	-	-
		6.8	175	0.5
		6.8	175	1
		6.8	175	2
		6.8	175	3
		6.8	230	0.5
		6.8	230	1
	EBS	6.8	-	-
		7.0	-	-

Machinability Evaluation

Machinability was evaluated with an instrumented drilling set-up, whose detailed description is given elsewhere [8]. This set-up is equipped with devices which allow the monitoring of drilling parameters, i.e. feed rate (mm/revolution), cutting speed (rpm) and cutting forces, i.e. thrust force transmitted to the specimen and torque applied on the tool. Each one of these data was acquired at a frequency of nine times per second.

One important parameter to evaluate the feasibility of machining green parts is the quality of the surface finish at the exit of the tool. This is carried out visually by comparing the break-out zone obtained for the various materials. Finally, the effect of green strength on machinability was qualitatively evaluated by determining the minimum wall thickness, which is defined as the minimum thickness of material to be left on parts wall to avoid breakage during drilling.

The test parameters used in this program are listed in Table 3. All machinability tests were carried out on gear specimens treated under various conditions as described in Table 2. Two drill diameters were used for the tests. These were black oxide high speed steel drill bits with an helix angle of 112°. The 6.35 mm diameter tools were used to characterize machinability in the core of the gears while the 3.18 mm ones were utilized to pierce holes in the teeth and to determine the minimum wall thickness values (Figure 2).

TABLE 3
Drilling test parameters

Drill Dia. (mm)	Feed Rate (mm/rev)	Cutting Speed (rpm)	Evaluation Criterion		
			Cutting Forces	Exit Break -out	Wall Thick-ness
3.18	0.12	2220	x	x	x
	0.20	2220	x	x	x
	0.20	3420	x	x	x
6.35	0.20	3420	x	x	-

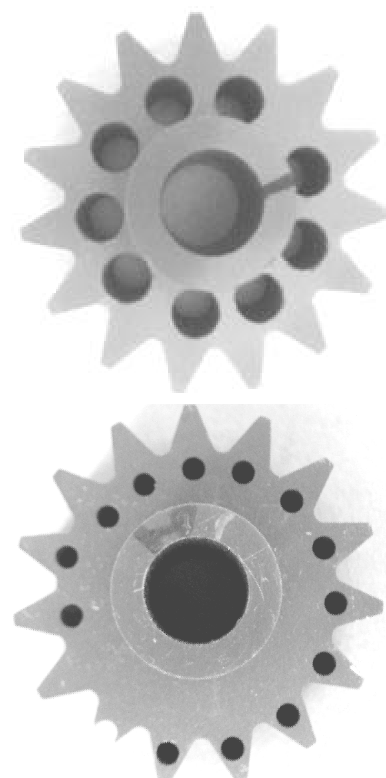

Figure 2. Location of a) 6.34 mm and b) 3.18 mm diameter holes drilled for machinability evaluation.

RESULTS AND DISCUSSION

Compaction and Lubrication Behavior

Figure 3 presents the compressibility of mixes containing either the new BM system or the EBS lubricating system measured on 0.64 cm thick TRS specimens compacted on a lab press. The compacting pressure needed to press these mixes on a production press to a green density of 7.0 g/cm^3 is also given.

It is seen that the compressibility of mixes with the BM lubricating system is either similar or slightly better compared to that of the EBS containing mix. For example, the compacting pressure required to reach 7.0 g/cm^3 is equivalent regardless of the lubricating system for either TRS specimens or gears pressed on lab and production presses. Additionally, it is shown in Figure 3 that the use of the new BM lubricating system slightly improves the compressibility of mixes when the green density increases from 7.0 to 7.2 g/cm^3. For instance, when pressing TRS specimens, the compacting pressure required to reach 7.2 g/cm^3 with mixes containing the BM system is 662 MPa as compared to 717 MPa with the conventional EBS mix.

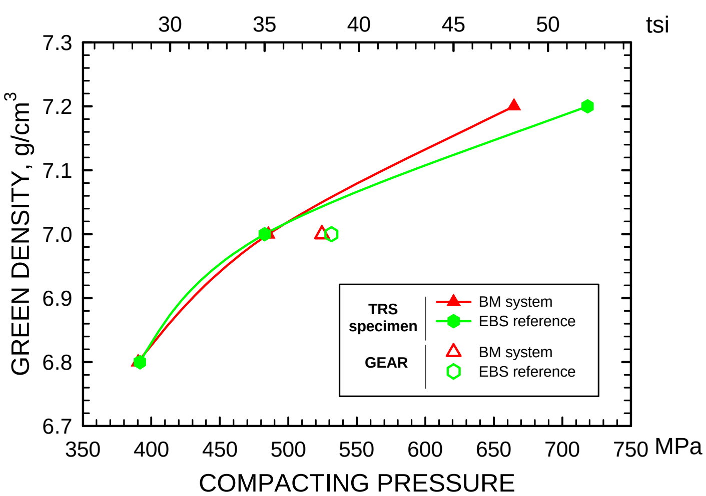

Figure 3. Compressibility of mixes containing BM and EBS lubricating systems on lab and production presses.

With regards to the ejection performance, it is seen in Figures 4a and 4b that the new BM system exhibits excellent lubricating properties even if the amount of organic compounds in this system is reduced from 0.80 to 0.65 wt% as compared to the EBS containing mix. Indeed, the stripping pressure (shearing stress to start the ejection) is significantly reduced when using the BM system (Figure 4a), while the sliding pressure is equivalent for both the BM and EBS lubricating systems (Figure 4b). It is seen that the stripping pressure of 1.27 cm thick TRS bars made from the new BM system is 16 to 19 % lower than with the EBS mix at any green density between 6.8 and 7.0 g/cm^3. Regarding the production of gears on a production press, the stripping pressure was reduced by 14 % when using this new BM system.

Therefore, the powder mix containing the new BM lubricating system exhibits good compressibility and excellent lubricating performance both on a lab press or when compacting complex parts on a production press. This can be attributed to the good shear resistance during compaction along with superior lubricating properties of the different components of the new BM system compared to the conventional EBS wax.

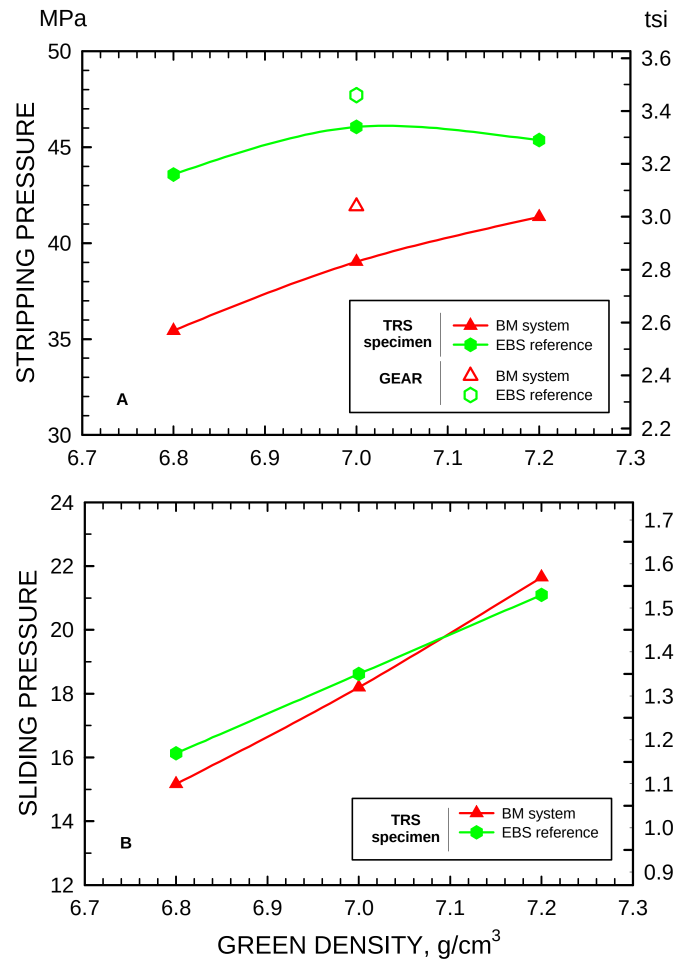

Figure 4. Stripping and sliding pressures required to eject TRS and gears made from BM and EBS lubricating systems.

Green Strength

Figure 5 compares the green strength of specimens made from the BM and EBS lubricating systems as a function of green density.

It is obvious that, whatever the green density, the strength values of 0.64 cm thick bars compacted from the BM system containing mix are significantly higher than those obtained with the EBS containing mix. Indeed, the green strength reaches 19, 24 and 31 MPa at 6.8, 7.0 and 7.2 g/cm^3 respectively, which is 50 to 70 % higher than the ones achieved with the EBS system. The increase in green strength may be explained by the higher mechanical properties of the polymeric lubricant and by the possibility to form stronger bonds between the steel particles due to the lower distribution of the polymeric lubricant at the surface of metallic powders during mixing as compared to mixes containing the conventional EBS lubricant.

Green strength also significantly improves by simply increasing the thickness of TRS specimens from 0.64 to 1.27 cm (Figure 5). It should be noted that both 0.64 and 1.27 cm thick TRS bars are recommended by MPIF for the evaluation of green strength (standard N^{o}15). In this study, the green strengths measured on 1.27 cm thick TRS specimens containing the new BM system are 28 and 44 MPa at 6.8 and 7.2 g/cm^3 respectively, which is about 40 % higher than the one measured on 0.64 cm thick TRS specimens. Therefore, it is strongly believed that the green strength resulting from the use of the new system is sufficiently high to prevent part failure during the ejection of complex parts and to enable machining operations in the green condition.

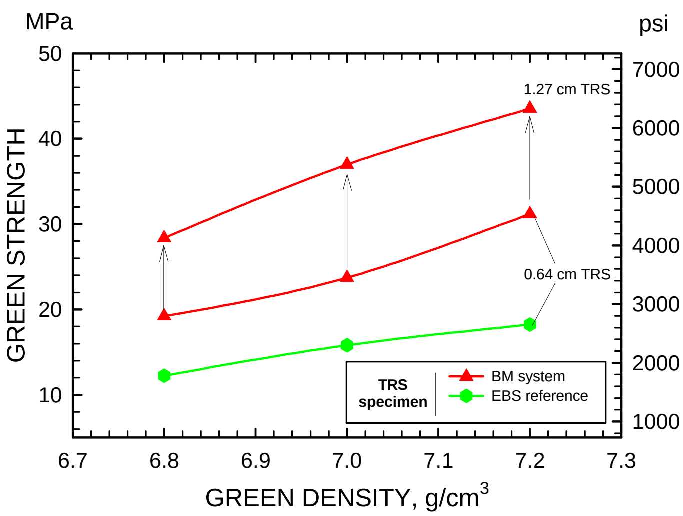

Figure 5. Green strength of specimens pressed from the BM system and the EBS reference as a function of green density.

It is worth mentioning that curing the specimens pressed with the new BM system in air further improves the green strength. For instance, the green strength easily reaches 55 MPa for specimens pressed to 6.8 g/cm^3 and cured in air at 175^{o}C for 1 hour. This is more than five times higher than that of the EBS mix, as seen in Figure 6. This high green strength is explained by the ability of the polymeric lubricant contained in the BM system to flow through the porosity during the curing treatment and to create a strong continuous polymeric network that strengthens the green specimens, as illustrated in Figure 7.

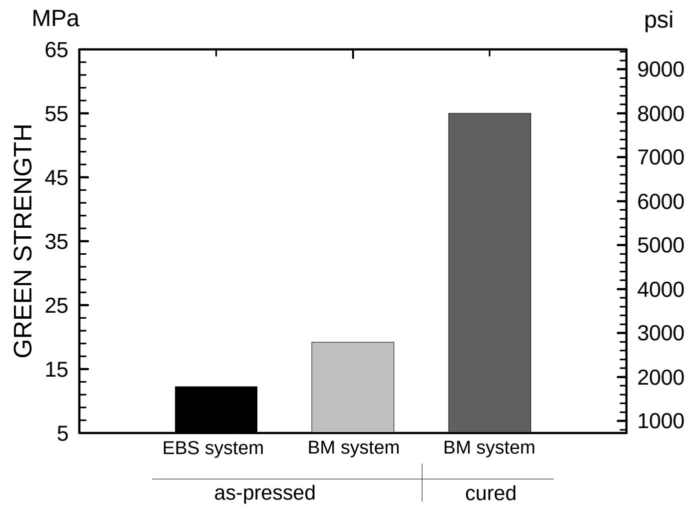

Figure 6. Effect of the curing treatment on green strength of 0.64 cm thick specimens pressed from the BM system and comparison with the EBS system.

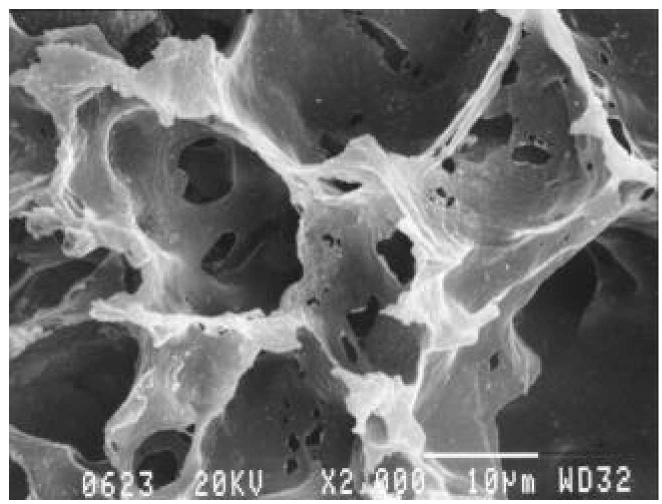

Figure 7. Illustration of the thin network of lubricant throughout cured TRS specimens pressed from the BM system.

Machinability of Gears

The capability of as-compacted materials containing EBS or the new BM lubricant system to withstand green machining was compared on gears pressed to a density of 7.0 g/cm^3. This was achieved by examining the damage occurring at the exit of the tool. Figure 8 shows the results for 6.35 mm and 3.18 mm diameter holes. It is clearly observed that the material with the new BM system was not as severely damaged as the one containing EBS as lubricant. In the latter, the damaged zone around the hole is more than double the size of the one seen in the material with the BM lubricant. As indicated in a previous section, the 3.18 mm diameter holes were drilled in the teeth, with the objective of determining the minimum wall thickness needed to avoid breakage of the tooth. Comparing Figures 8a and 8b confirms the superior ability of the parts containing BM lubricant to maintain the part integrity. This evaluation was carried out at various feeds and speeds. As seen in Table 4, the EBS based material remains fragile, whatever the cutting parameters. However, the minimum wall thickness required for machining the BM containing parts is reduced as the feed rate is decreased, while a reduction in cutting speed, within the range of this investigation, has no significant effect. This indicates that improvement in machining behavior can be achieved by adjusting the machining parameters for the BM containing material while the machinability of the EBS base material remains poor, regardless of the machining conditions.

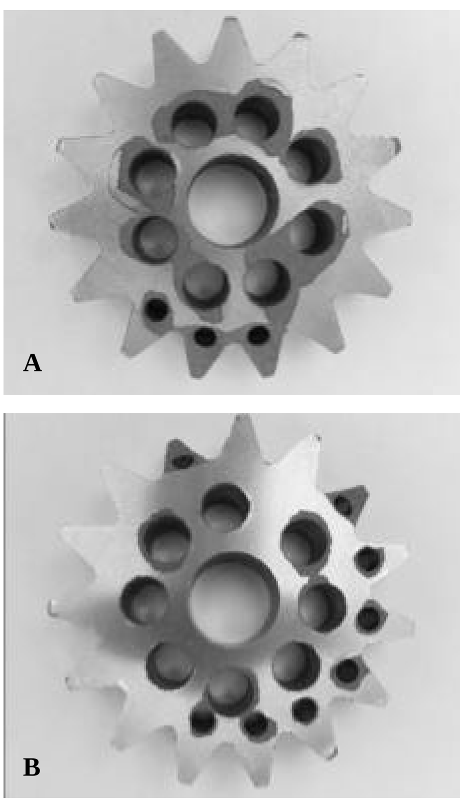

Figure 8. Break-out zones at the exit of the tools when drilling in materials containing A) EBS and B) the BM system as lubricant.

As previously indicated, the green strength of the material containing the BM lubricant system is increased by curing the component at relatively low temperature in air. As already stated, curing the part pressed to 6.8 g/cm^3 for 1 hour at 175°C in air increases the green strength from 20 MPa to 55 MPa. It is thus expected that this increase in green strength would improve the green machining behavior of the parts.

TABLE 4
Effect of drilling parameters on required minimum wall thickness for gears pressed to 7.0 g/cm^3

Feed Rate (mm/rev)	**Cutting Speed (rpm)**	**Minimum Wall Thickness (mm)**	
		EBS	**BM**
0.20	3420	1.78	1.20
0.20	2220	1.72	1.25
0.12	2220	1.76	0.95

The effect of curing time and drilling parameters on the cutting forces needed to drill 6.35 and 3.18 mm diameter holes is presented in Figure 9. Each point represents the average of the thrust force or torque values measured when drilling up to 35 holes. Variation around these average values was typically ± 5 % and no increasing trend from the first hole drilled to the last one was noticed, confirming that no significant wear occurred on the cutting edges of the tools. It is worth noting that the thrust force and torque values measured are low, whatever the test conditions, the highest values representing less than 10 % of those observed in sintered materials of the same composition [9]. For all drilling parameters studied, a slight increase in drilling forces is noticed as the curing time increases, and the augmentation is seen mainly for curing periods of 2 and 3 hours. This was reflected by the formation of larger, more ductile drilling chips. As expected, a reduction of the tool diameter from 6.35 to 3.18 mm reduced both the thrust force and torque. The larger relative reduction in torque is most probably related to the significantly smaller chips that are generated with the 3.18 mm tool. The change in cutting speed did not show the strong effect seen in sintered materials [9].

Another key characteristic of green machined parts is the capability of the parts to be shaped while maintaining their integrity. As previously seen in Figure 8, the new BM system significantly reduces the damage done at the exit of the drill. However, further increasing the strength of the material by curing virtually eliminates the break-out zone. This is illustrated in Figure 10 which compares break-out zones for materials cured from 0 to 3 hours. A clear improvement is seen after only 0.5

hour of curing at 175°C. A one hour treatment is adequate to eliminate break-outs at the exit of the drill. Longer curing time contributes little further improvement.

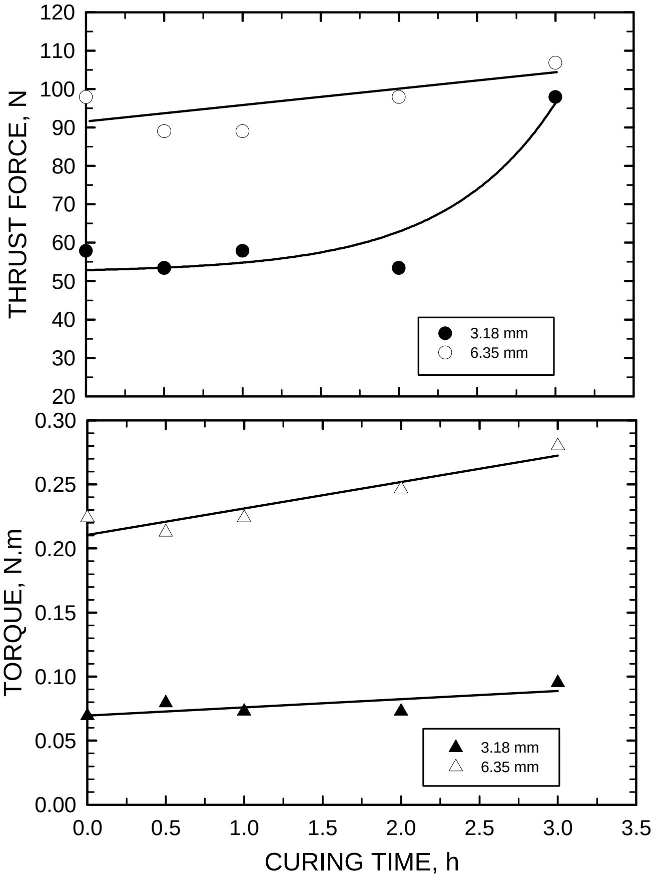

Figure 9. Effect of curing time at 175°C on a) Thrust force and b) Torque required to drill holes in material containing the new BM lubricant system (Speed: 3420 rpm).

The improvement in part integrity as the curing time increases is correlated to the reduction of wall thickness withstanding machining of 3.18 mm diameter holes in the gear teeth. As seen in Figure 11, the minimum wall thickness required to avoid tooth failure is reduced from 1.4 mm in the as-compacted parts to 0.8 mm after 1 hour curing at 175°C.

The green strength of the part containing the BM system may also be improved by increasing the curing temperature; in this case, the curing time may be reduced and represents a more economical route to increase green strength and machinability. As seen in Figure 12, the integrity of the parts cured at 230°C for 0.5 hour is comparable to that of the parts cured at 175°C for 1 hour (Figure 10c); no significant improvement is seen when the curing time is extended to 1 hour at 230°C.

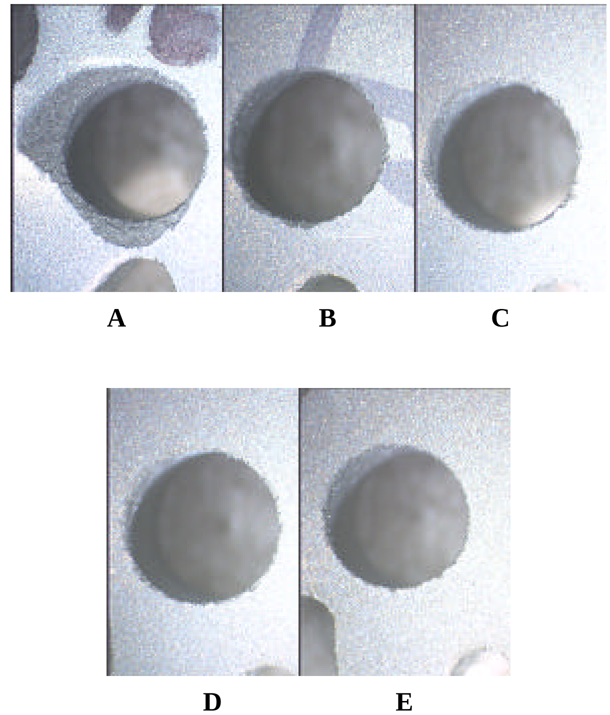

Figure 10. Break-out at the exit of 6.35 mm diameter holes drilled at a feed rate of 0.2 mm/rev and a cutting speed of 3420 rpm for material cured at 175°C for A) 0 h, B) 0.5 h, C) 1.0 h, D) 2.0 h and E) 3.0 h.

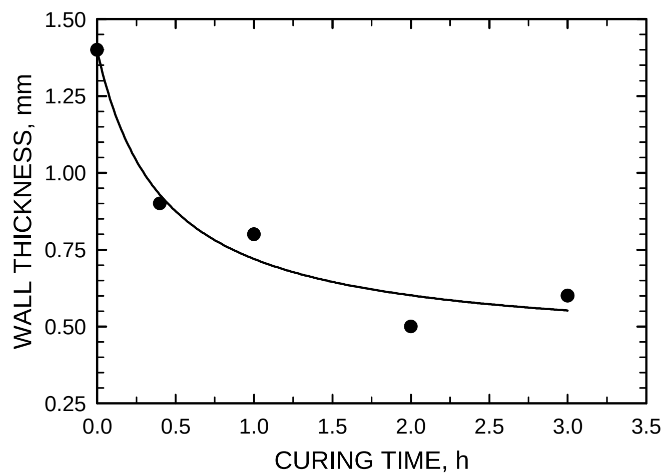

Figure 11. Effect of curing time on the minimum wall thickness required to drill 3.18 mm diameter holes in the gear teeth for part density of 6.8 g/cm^3 (Feed rate: 0.2 mm/rev, Speed: 3420 rpm).

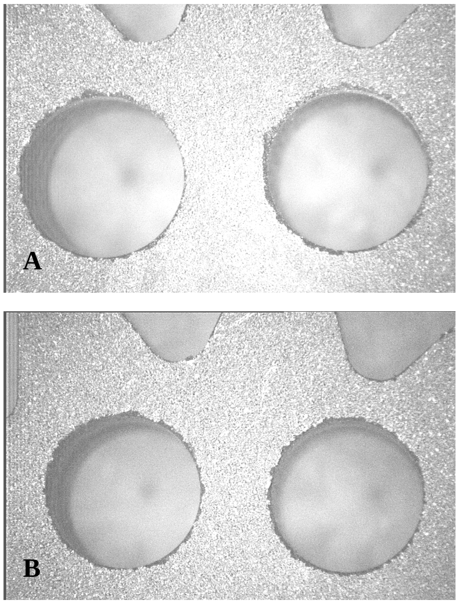

Figure 12. Break-out at the exit of 6.35 mm diameter holes drilled at a feed rate of 0.2 mm/rev and a cutting speed of 3420 rpm cured at 230°C for A) 0.5 h and B) 1.0 h.

Finally, in order to further demonstrate the excellent green machining behavior of parts containing the BM lubricant, some specimens cured at 175°C for 1 hour were submitted to different machining operations under industrial conditions. As seen in Figure 13, all parts successfully withstood the stresses induced by the operations, without showing any signs of failure or chipping.

Figure 13. Examples of industrial machining on gears cured at 175°C for 1 hour.

CONCLUSIONS

This study was undertaken to evaluate the feasibility of using a new polymeric lubricating system to enable machining operations in the green condition, while maintaining excellent compressibility and lubrication behavior during the ejection of parts. The following conclusions can be drawn:

- Mixes containing the new lubricating BM system exhibited similar compressibility and a better lubrication behavior than mixes admixed with the conventional EBS wax.
- Green strength of parts pressed with the new system to 7.0 g/cm^3 was sufficient to allow drilling in the green state when using appropriate parameters. The use of air curing (230^{o}C, 0.5 h) further improved both the green strength and machining behavior of the parts.
- The feasibility of using the new BM polymeric system to enable machining operations in the green condition was successfully validated under industrial conditions.

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