

# **ENHANCED GREEN STRENGTH LUBRICATING SYSTEMS FOR GREEN MACHINING FERROUS MATERIALS**

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## **ABSTRACT**

Waxes and metallic stearates are very well known lubricants for P/M applications. However, the admixing of these lubricants into iron powder mixes significantly reduces the green strength of P/M components. Consequently, parts containing such lubricants cannot be easily green machined. It would therefore be beneficial to the P/M industry to develop new lubricating systems that will sufficiently enhance the green strength of P/M components to enable machining in the green state and achieve considerable cost reduction.

The objectives of this study are to describe new lubricating systems and evaluate their effects on green and sintered properties of F-0005 specimens pressed within a density range of 6.8 and 7.15 g/cm<sup>3</sup>, at compacting temperatures of 45°C to 65°C. Results showed that the green strength achieved with these new lubricating systems was increased by as much as two to five times compared to that of conventional wax lubricants while achieving similar sintered properties.

## **INTRODUCTION**

There is currently a need to develop new techniques that yield desirable green strength in order to minimize part failure and allow handling and machining prior to sintering. Indeed, with the advent of high performance materials that normally exhibit high apparent hardness and strength after sintering, green machining becomes a very attractive shaping process to increase tool life, productivity and maintain competitiveness [1].

It is well known that the addition of lubricants in powder mixes is primarily designed to reduce the frictional interaction between die walls and powder particles during compaction and ejection of parts. By ensuring a good transfer of the compacting force during the compaction stage, the admixed lubricant

improves the uniformity of densification throughout the part. Besides, it also lowers the force required to eject the compact from the die and reduces die wear. However, conventional lubricants such as synthetic waxes and metallic stearates significantly reduce the strength of green compacts. This is caused by the formation of a lubricating film having a low mechanical strength at the surface of powder particles, which could limit the microwelding during compaction [2,3].

In addition to warm pressing and pre-sintering techniques, the development of new polymeric lubricating systems is a new promising route to enhance the green strength and enable machining of parts prior to sintering. However, only a few studies have explored the feasibility of this new avenue [3,4,5]. In particular, the compressibility and lubrication behavior of metal powder mixes containing polymeric lubricants can be greatly influenced by the type of polymers and the process conditions (level of pressure, temperature, rate of compaction), which must be considered when choosing the adequate lubricant.

Depending on the polymer properties and on the required characteristics of the metal powder mixes, the polymeric lubricant can be added as a powder, as a coating by dissolution in a solvent or in the molten state. The advantage of polymeric lubricants is therefore that in some cases they can act both as a lubricant and a binder to reduce segregation and dusting of powder mixes. Polymeric binders can also be added either to adjust the flow, to reduce segregation in mixes or to further improve the green strength of parts.

This paper presents different enhancing green strength lubricating systems including polymeric lubricants as well as blends of polymeric lubricants and binders. Green and sintered properties of F-0005 specimens compacted with these new lubricating systems are compared to those obtained with ethylene bisstearamide (EBS) wax at different green densities and compacting temperatures. The benefit on the green strength is presented for as-compacted and/or heat treated specimens at a low temperature (< 350°C). Also, the lubricating properties obtained during the compaction and ejection of parts are reported from results obtained using an instrumented compacting die.

## **EXPERIMENTAL PROCEDURE**

### **Description of Materials and Mechanical Properties Testing**

Four different lubricating systems (TP-A, TP-B, TP-C and TP-C<sup>wb</sup>) were evaluated and compared to EBS wax at varying compacting temperatures and green densities. These lubricating systems in a powder form were admixed with ATOMET 1001 and 0.6 wt% graphite (SouthWest 1651). The TP-A and TP-B lubricating systems include the thermoplastic polymers, while the TP-C system combines thermoplastic polymers and a polymeric binder. The TP-C<sup>wb</sup> system contains the same organic compounds comprised in the TP-C system except the polymeric binder. This lubricating system was included in the test program to evaluate the effect of polymeric lubricants included in the TP-C system without any effect of the polymeric binder.

Standard transverse rupture strength specimens (TRS) were prepared for each system to determine green and sintered properties. The die and punch were heated to reach different compacting temperatures ranging from 45°C to 65°C in order to simulate frictional heat generated during typical production conditions. The cold powder mixes were transferred into the die cavity when thermal equilibrium was reached. Details of the compacting conditions are listed in Table 1. Mixes containing TP-A and TP-B lubricating systems were pressed to 7.0 g/cm<sup>3</sup> at 45, 55 and 65°C. The TP-C containing mix was pressed to different green densities from 6.8 to 7.15 g/cm<sup>3</sup> at 65°C, while the mix comprising the TP-C<sup>wb</sup> system

was pressed to 7.15 g/cm<sup>3</sup> at 65°C. Green specimens prepared from the TP-B and TP-C lubricating systems were also heat treated in air at 175°C for 1 hour.

**Table 1. Test Program**

<b>Designation</b>	<b>Type of Lubricant</b>	<b>Green Density (g/cm<sup>3</sup>)</b>	<b>Compacting Temperature (°C)</b>
<b>EBS wax</b>			
	ACRAWAX C atomized	7.0	45
		7.0	55
		7.0	65
<b>TP-A</b>			
	Thermoplastic A	7.0	45
		7.0	55
		7.0	65
<b>TP-B<sup>(1)</sup></b>			
	Thermoplastic B	7.0	45
		7.0	55
		7.0	65
<b>TP-C<sup>(1)</sup></b>			
	Thermoplastic C and Binder	6.8	65
		7.0	65
		7.15	65
<b>TP-C<sup>wb(1)</sup></b>			
	Thermoplastic C	7.15	65

(1) as-compacted specimens heat treated at 175°C for 1h in air

Green and sintered properties were evaluated according to MPIF standards 15 and 41 respectively. Sintering was carried out at 1120°C for 25 minutes in a conventional mesh belt furnace under a nitrogen rich atmosphere (90N<sub>2</sub>-10H<sub>2</sub>). The surface finish of green and sintered specimens was also evaluated with an optical microscope.

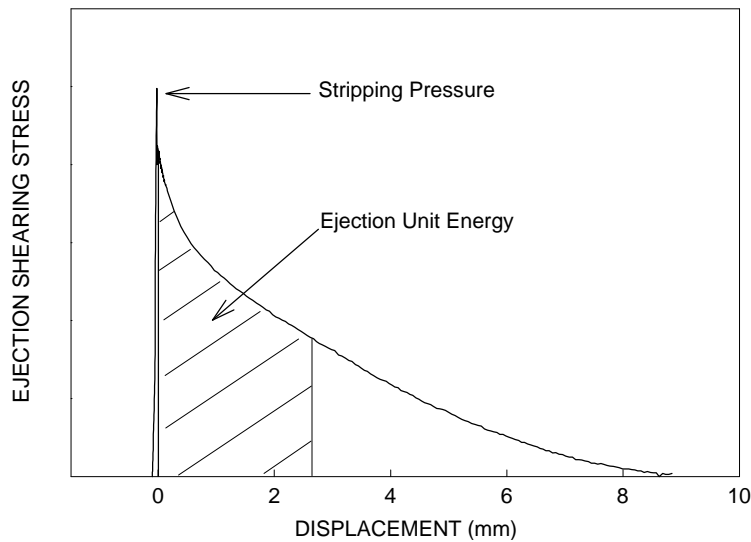
### Compaction and Ejection Performances Measurement

The behavior of the powder mixes including the different enhanced lubricating systems (TP-A, TP-B and TP-C) and the EBS wax lubricant during compaction and ejection was evaluated using a Powder Testing Centre (model PTC-03DT) manufactured by KZK Powder Technologies Corp. This apparatus consists of an instrumented cylindrical die operating in a single action mode. The applied and transmitted pressures through the compact are measured by two independent load cells. The measure of the displacement of the mobile (lower) punch is converted to give the average density of the part by assuming a rigid behavior of the H13 steel die of 9.525 mm diameter.

In the present study, cylindrical specimens of about 8.0 mm height were pressed at 45°C and 65°C and at an applied pressure of 620 MPa. For each mix, the die was conditioned by compacting three specimens. At least three other specimens were also compacted for each lubricating system. Results presented in this study show good reproducibility and correspond to average values obtained from three specimens. The

lubricant behavior during compaction was evaluated through the determination of the slide coefficient. This parameter is directly related to the loss of pressure between the applied pressure and the transmitted pressure through the compact due to friction between metal powders and friction between the surface of the compact and the die walls [6]. Its numerical value varies between 0 and 1. Values of slide coefficient reported in this study correspond to the values obtained at the end of the compaction for a pressure of 620 MPa. In these conditions, the higher the slide coefficient, the lower is the level of friction at the die walls.

During ejection, the measure of the ejection load as a function of the displacement inside the die can give valuable information about the performance of lubricants. By dividing the force by the cylindrical area of the compact causing the friction phenomenon, the ejection shearing stress can be evaluated throughout the ejection as shown in Figure 1. The stripping pressure corresponds to the shearing stress required to start the ejection. The ejection unit energy corresponds to the energy to move the part to the die entrance (2.54 mm) and corresponds to the area below this portion of the ejection curve (ejection shearing stress vs. displacement) divided by the displacement of the part to the die entrance (2.54 mm).



**Figure 1 : Typical Ejection Curve**

## **RESULTS AND DISCUSSION**

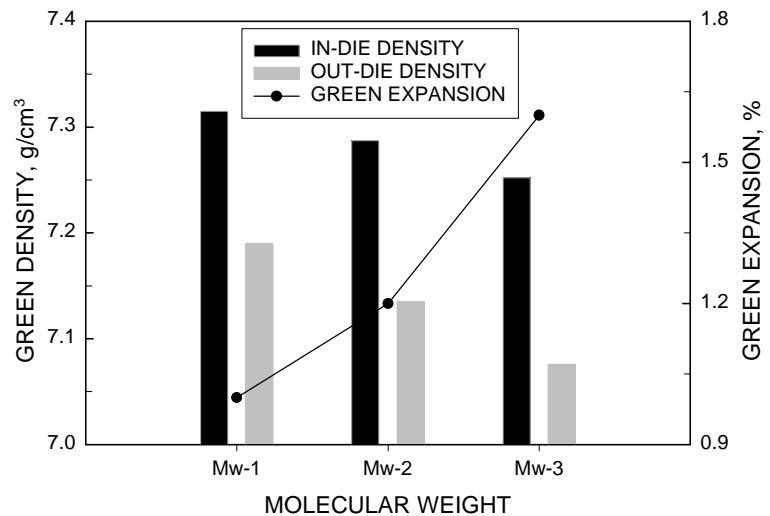
### **Selection of Potential Enhanced Green Strength Lubricating Systems**

Different lubricating systems (TP-A, TP-B, TP-C) including polymeric lubricants were tested during this study to increase green strength, while maintaining compressibility and sintered properties to the level obtained with the conventional EBS wax lubricant. The selection of polymeric lubricants contained in these systems was based on their ability to strengthen the green compacts with or without the use of a thermal treatment and also on their capacity to shear under pressure and to lubricate parts in conditions that simulate most production applications in terms of compacting temperature and green density.

It is believed that the polymeric lubricants could be potential candidate to enhance the green strength due to their higher intrinsic mechanical properties compared to conventional lubricants. In particular, polymers differ from most conventional lubricants since they are composed of macromolecular chains, which consist of numerous repeating fundamental units, called monomers. Besides, this type of compound has a lower deformability than conventional lubricants and thus has a lower tendency to form a continuous lubricating film at the surface of powder particles during mixing or compaction, which could potentially favor the formation of stronger bonds between the steel powder particles. As already reported, the green strength may be controlled by the formation of solid contacts or microwelding between the powder particles [7]. Also, these polymeric lubricants could be admixed with the steel powder and a polymeric binder to further improve the green strength of parts submitted to a thermal treatment. Indeed, depending on the nature of lubricants and binders, there could be formation of crosslinking or complexation between these compounds through covalent bonds or strong intermolecular interactions.

However, it is worth mentioning that not all polymeric lubricants exhibit adequate shear resistance as well as lubricating properties during compaction and ejection. It is believed that the ability of some polymers of having adequate lubricating properties may be related to the regular arrangement of macromolecular chains and their possibility to slide over one another when submitted to a shear stress. Typically, polymers having lubricating properties include thermoplastic polymers such as polytetrafluoroethylene, polyethylenes, polyethers such as polyethylene glycol or poly(ethylene oxide), polyesters and polyamides. As a function of their nature, structure and molecular weight, which is related to the length of the macromolecular chains, polymeric lubricants may have different inherent mechanical and thermal properties (glass transition temperature, softening temperature, melting temperature, etc.) and in particular different shear resistances and lubricating properties under pressure. Additionally, these properties may vary greatly depending on the processing conditions such as the level of pressure, temperature and rate of compaction and thus have to be taken into account in the choice of the adequate polymeric lubricant.

Figures 2 and 3 show typical examples of the effect of the molecular weight on the green density and ejection performance for a polymeric type lubricating system. This evaluation was performed using a Powder Testing Center (PTC) for more accuracy. Steel powder particles were coated with the lubricating system to avoid any effect of the particle size and compacted at a temperature close to the softening temperature of the lubricating system.

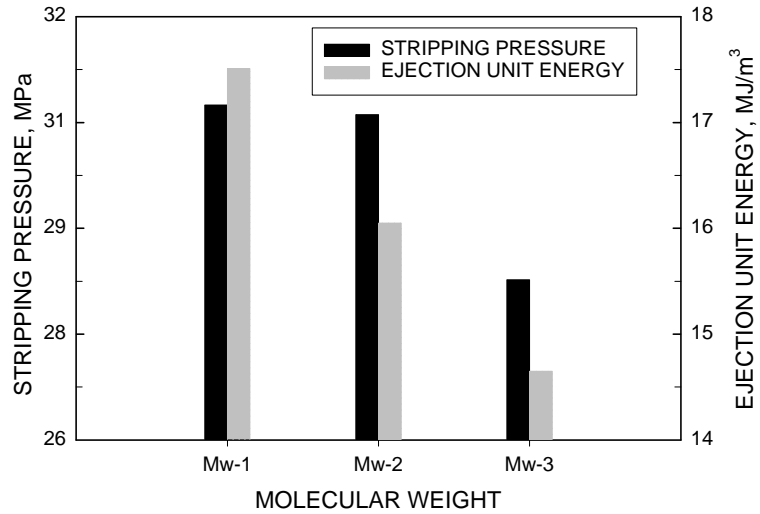


**Figure 2 : Effect of the Molecular Weight of a Polymeric Type Lubricating System on Green Density and Green Expansion. Mw-3 > Mw-2 > Mw-1**

It can be seen that the out-die green density noticeably decreases by raising the molecular weight of a polymeric lubricating system (Figure 2). This is related both to a decrease of the in-die density of mixes and an increase of the green expansion of parts as the molecular weight increases. As similar friction behavior at the die walls was observed regardless of the molecular weight, with sliding coefficient values around 0.66-0.67, the decrease of the in-die density may be mainly explained by the presence of the admixed lubricating system

that interferes with the densification of the powder mixes when the molecular weight of the polymeric lubricant is increased.

On the other hand, even if similar friction behavior was observed during compaction whatever the molecular weight of the polymeric lubricant, the increase of the molecular weight significantly enhanced the ejection performance during the production of parts. Indeed, it appears that under the process conditions used, the stripping pressure and energy required to move the specimen to the upper edge of the die cavity are both significantly decreased by raising the molecular weight (Figure 3). It is worth mentioning that this may not be valid if a molecular weight which is too high is used and/or if the compacting temperature is lower than the softening temperature of the polymeric lubricant. In this instance,

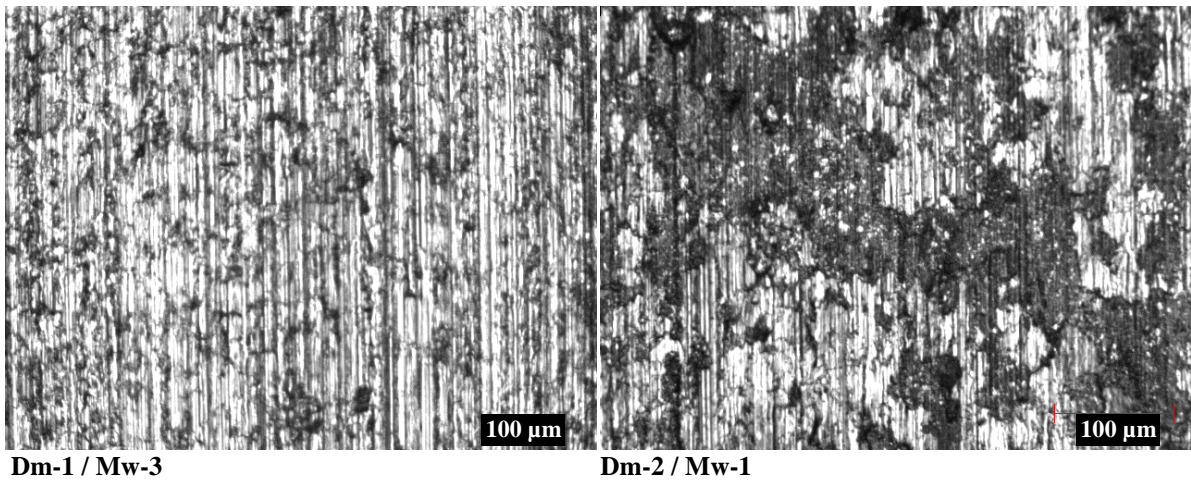


**Figure 3 : Effect of the Molecular Weight of a Polymeric Type Lubricating System on Stripping and Ejection Unit Energy. Mw-3 > Mw-2 > Mw-1**

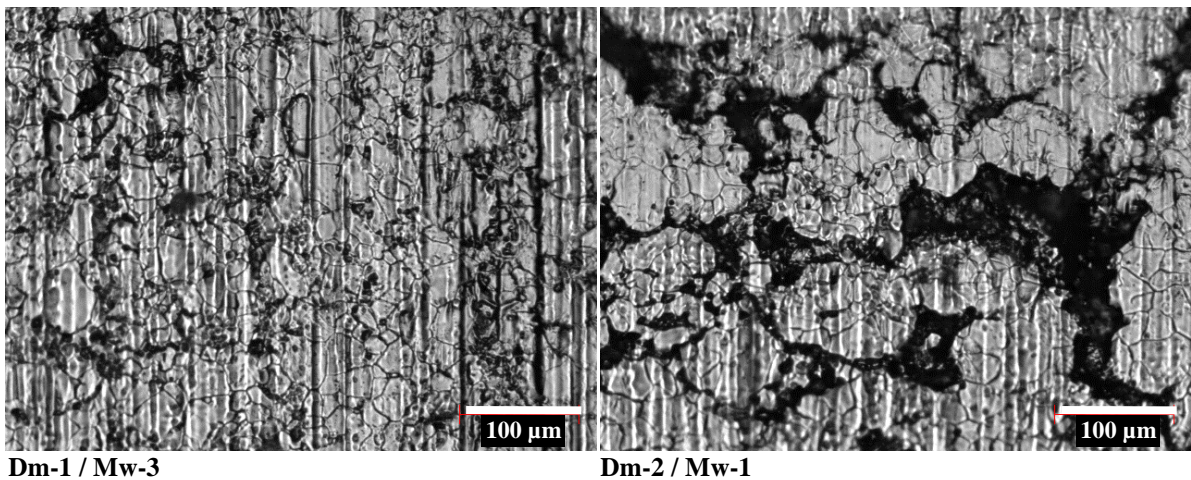
a low deformation of the polymeric lubricant may lead to a lack of lubricant in some areas and to the formation of numerous iron-iron contacts at the interface between the compacted part and the die walls, and thus resulting in poor ejection performance.

Additionally, it should be emphasized that when powder mixes are compacted at temperatures close to the softening point of polymers included in the lubricating system, adequate choice of the polymer in terms of particle size and molecular weight has to be done to prevent deterioration of the surface finish. Indeed, the use of lubricants, which are too coarse and/or too low in molecular weight at the softening point, may lead to a significant deterioration of the surface finish. As shown in Figure 4, these conditions are favorable to a significant formation of sticky residues composed of a mixture of lubricant, graphite and steel powder at the lateral sliding surfaces. These residues can be a real barrier to the ejection of specimens and can also favor the formation of cavities at the surface of specimens, when the lubricant is burned-off during sintering (Figure 5).

Hence, these results strongly suggest that the selection of the polymeric lubricating systems have to take into account several characteristics such as the molecular weight, softening temperature and particle size of the polymer. In particular, this selection has to be done so as to achieve a compromise between the compressibility and lubricating properties of the powder mixes, while maintaining good surface finish of the parts. In some cases, the use of a mixture of lubricants may be required to optimize these properties.



**Figure 4 : Effect of the Particle Size (Dm) and Molecular Weight (Mw) of a Polymeric Type Lubricating System on the Surface Finish of Green Specimens. Dm-2 > Dm-1, Mw-3 > Mw-1**



**Figure 5 : Effect of the Particle Size (Dm) and Molecular Weight (Mw) of a Polymeric Type Lubricating System on the Surface Finish of Sintered Specimens. Dm-2 > Dm-1, Mw-3 > Mw-1**

### **Compaction and Lubrication Behavior of Selected Polymeric Lubricating Systems**

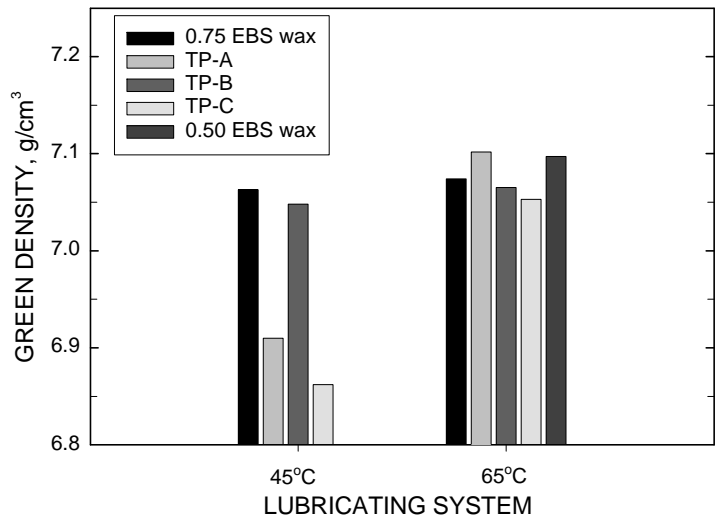
The green density and lubricating properties of the three selected polymeric systems TP-A, TP-B and TP-C were determined using the Powder Testing Center (PTC) and compared to those obtained with either 0.50 wt% or 0.75 wt% EBS wax. Results are shown in Figures 6, 7 and 8 for specimens pressed at 45°C and 65°C. This compacting temperature range simulates conditions found in actual production. It is well known that some heat is generated due to the occurrence of friction between powder particles and against the die walls. The temperature of green parts can easily attain 65°C during compaction [3].

As seen in Figure 6, the green density obtained for specimens pressed with the TP-A and TP-C systems is lower by up to 0.20 g/cm<sup>3</sup> than that obtained with the TP-B and conventional EBS wax systems at 45°C. The TP-B system enables reaching a green density similar to that of specimens pressed with the conventional wax lubricant.

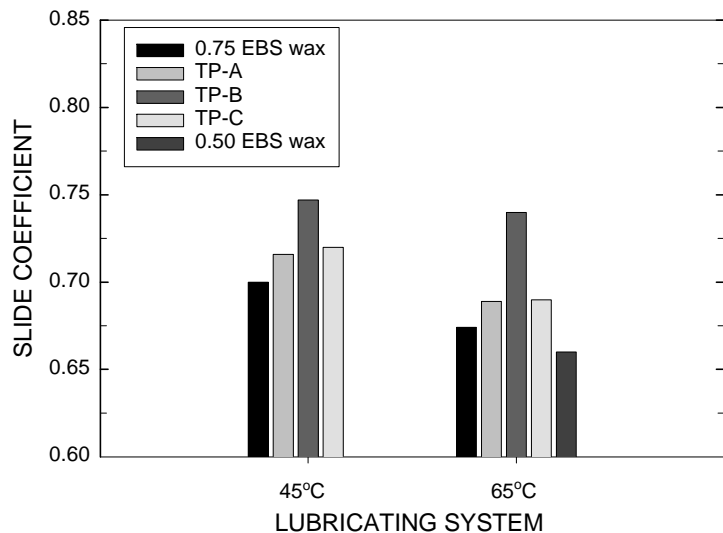
However, the green density obtained with TP-A and TP-C systems is noticeably improved by raising the compacting temperature from 45°C to 65°C, i.e. when the compacting temperature is higher than the softening temperature of polymers comprised in these systems. In fact, the green density achieved with the TP-A system is similar to that obtained for specimens containing a low amount of EBS wax, i.e. 0.50 wt%.

On the other hand, it can be seen in Figures 7 and 8 that all of the polymeric lubricating systems examined during this study exhibit adequate lubricating properties during compacting and ejection at 45°C or 65°C. For instance, the slide coefficient measured with the TP-A, TP-B and TP-C systems is either slightly or noticeably higher than that obtained with 0.75 wt% EBS wax, which indicates that equivalent or superior lubricating properties can be achieved with these polymeric lubricating systems during compaction (Figure 7). The TP-B system demonstrated the best ability to lubricate parts during compaction at 45°C or 65°C.

During ejection, it is seen that the stripping pressure obtained with these systems is equivalent or significantly lower than for specimens pressed with 0.75 wt% EBS wax at both compacting temperatures, 45°C and 65°C (Figure 8a). Additionally, it is clearly illustrated in Figure 8b that the level of energy required to eject specimens containing TP-B and TP-C systems is equivalent or significantly lower than with 0.75 wt% EBS wax at 45°C and 65°C. The use of the TP-A system leads to a slight decrease of this energy at 45°C versus the 0.75 wt% EBS system and an increase at 65°C. However, it is noteworthy that the level of energy needed to eject the TP-A specimens at 65°C is still lower than that of specimens pressed with 0.50 wt% EBS wax. Thus, it is believed that the use of this new system will not negatively impact the ejection performance during production of parts.

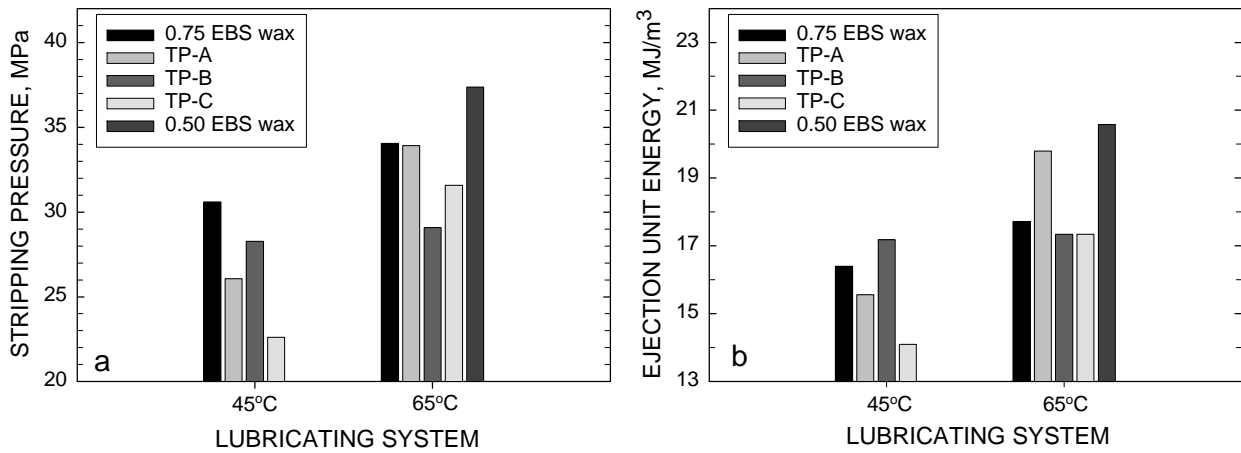


**Figure 6 : Effect of Different Lubricating Systems on Green Density at 45°C and 65°C.**



**Figure 7 : Effect of Different Lubricating Systems on the Slide Coefficient at 45°C and 65°C.**





**Figure 8 : Effect of Different Lubricating Systems on Stripping Pressure and Ejection Unit Energy at 45°C and 65°C.**

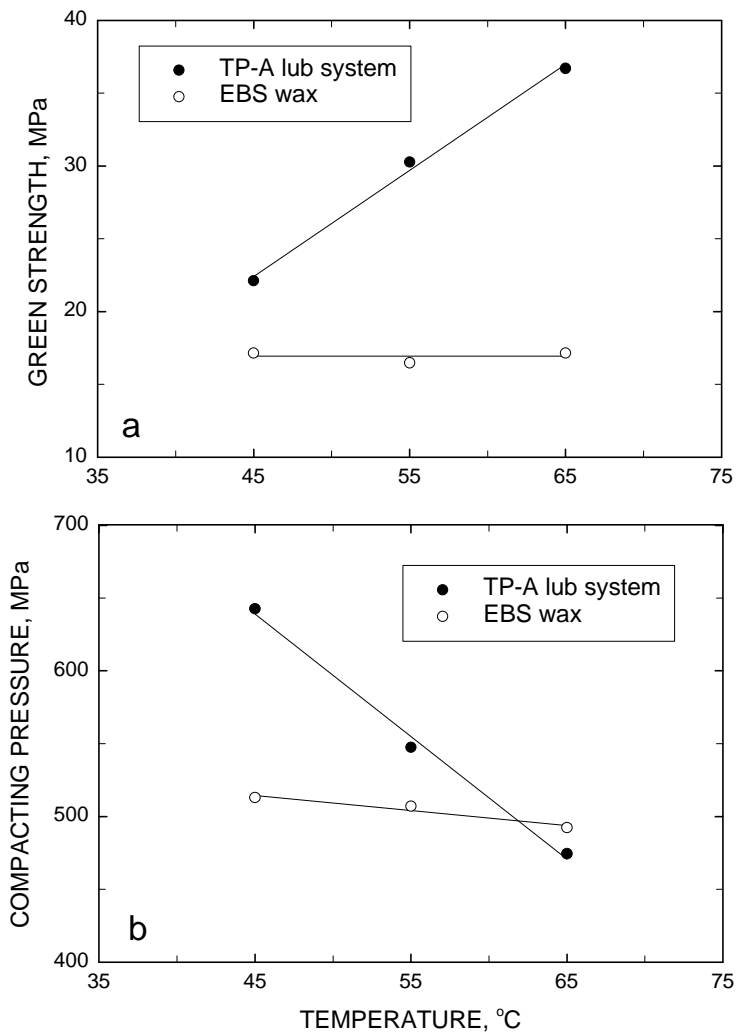
### Green and Sintered Properties Obtained with Polymeric Lubricating Systems

#### *TP-A lubricating system*

Figure 9 illustrates the green properties obtained with the TP-A lubricating system for specimens pressed to  $7.0 \text{ g/cm}^3$  at different compacting temperatures from 45°C to 65°C. Results obtained with 0.75 wt% EBS wax are also given for comparison purpose.

It appears that the green strength achieved with the TP-A system is significantly higher than with the conventional wax lubricant and this is even more pronounced as the compacting temperature increases from 45°C to 65°C (Figure 9a). This property is around 30 % higher at 45°C (22 vs. 17 MPa) and close to 37 MPa at 65°C, which is twice as high as the level obtained with EBS wax. On the other hand, it is worth noticing that the compressibility obtained with this new lubricating system is significantly deteriorated by decreasing the compacting temperature from 65°C to 45°C for specimens pressed to  $7.0 \text{ g/cm}^3$ , while changing only slightly with EBS wax (Figure 9b). However, it is likely by considering the trend of the curves, that a compacting temperature of only 60°C is needed to get a compressibility similar to EBS wax. Moreover, the compressibility is better than with conventional wax above this compacting temperature.

The higher pressure required to reach  $7.0 \text{ g/cm}^3$  with the TP-A system below  $60^\circ\text{C}$  could certainly enhance the green strength, but it is assumed that this has a relatively minor effect since the gain in green strength compared to EBS wax is by far proportional to the extra tonnage applied to press TP-A containing mixes. It is believed that the higher green strength achieved with the TP-A system is primarily related to the fact that this lubricating system has a relatively high mechanical strength as compared to the EBS wax and that it may favor the formation of interlocking points or microwelding between steel powder particles. Indeed, contrary to EBS wax, lubricants comprised in the TP-A system do not tend to form a continuous film at the surface of metal particles during mixing and compaction. Besides, this lubricating system softens and probably moves into the open pores rather than dispersing through the entire compact. Thus, the end result could be pores saturated with lubricant and the formation of a strong discontinuous network of lubricant that does not interfere with the formation of particle-to-particle interlocking or microwelding. It is noteworthy that this discontinuous network also probably interacts strongly with the steel powder particles as compared to the conventional wax lubricant, when considering the molecular structure of lubricants comprised in the TP-A system.



**Figure 9 : Green Properties of Specimens Pressed to  $7.0 \text{ g/cm}^3$  with TP-A and EBS wax Lubricating Systems at Different Compacting Temperatures.**

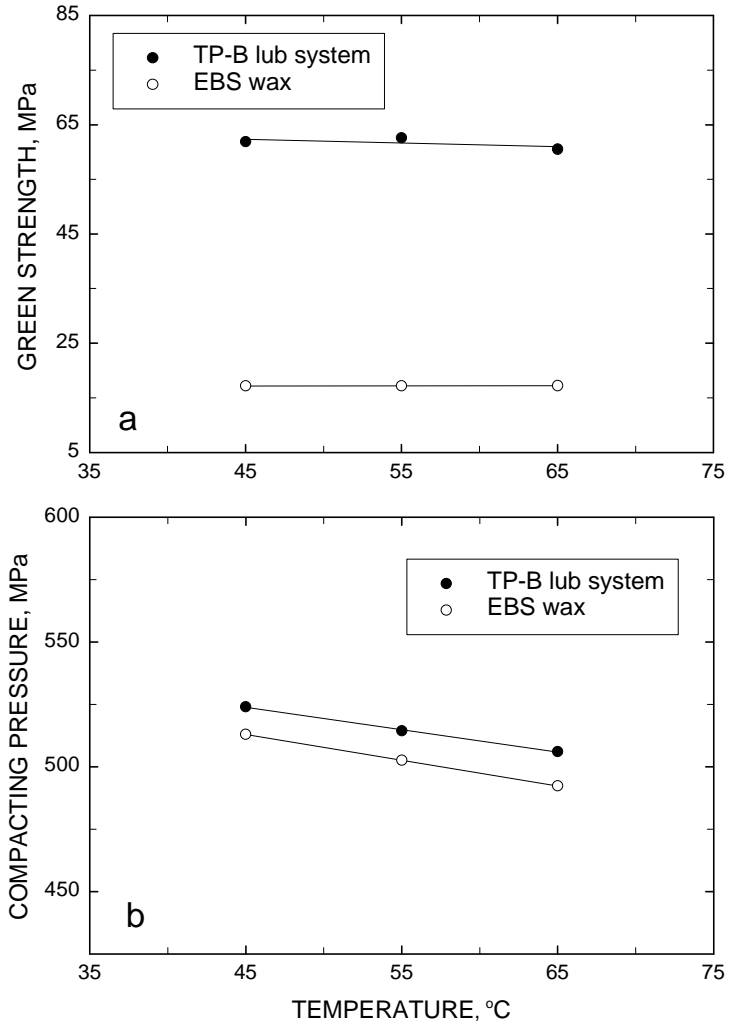
Sintered properties obtained with the TP-A system are relatively similar to those achieved with specimens pressed from the EBS wax system at  $65^\circ\text{C}$  (Table 2). The sintered strength is lower by only 3 % (700 vs. 725 MPa), the apparent hardness remains in the 52-54 HRB range, while the dimensional change is slightly more positive, 0.12 to 0.15 %. At  $45^\circ\text{C}$ , the dimensional change obtained with this new system is more positive than EBS wax by 0.06 %. The higher compacting pressure required to reach  $7.0 \text{ g/cm}^3$  at this temperature results in greater green expansion, which is not offset by sintering at  $1120^\circ\text{C}$ . The end result is an increase of the dimensional change and a slight reduction in sintered density, which also leads to a slight decrease in sintered strength (660 vs. 710 MPa).

### TP-B lubricating system

Figure 10 compares green properties obtained with TP-B and 0.75 wt% EBS wax lubricating systems for specimens pressed to  $7.0 \text{ g/cm}^3$  at different compacting temperatures from  $45^\circ\text{C}$  to  $65^\circ\text{C}$ . The sintered properties are also given in Table 2. The specimens compacted with the TP-B system were heat treated at  $175^\circ\text{C}$  for 1 hour in air to reach very high green strengths. It is worth mentioning that warm pressing could also be used to strengthen green compacts when using this lubricating system [5].

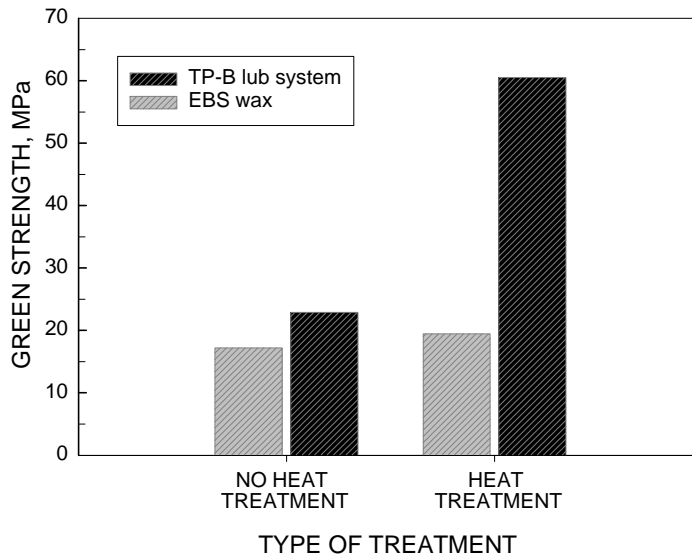
It is seen that the TP-B lubricating system gives much higher green strength than EBS wax, while maintaining similar compressibility and sintered properties. The green strength reached about 62 MPa at compacting temperatures from  $45^\circ\text{C}$  to  $65^\circ\text{C}$ , which is nearly four times higher than that obtained with the EBS wax system (Figure 10a). With regards to the compressibility, the compacting pressure required to reach  $7.0 \text{ g/cm}^3$  with the TP-B system is only slightly higher, by about 14 MPa, independently of the compacting temperature (Figure 10b). The sintered density and strength as well as the apparent hardness also remain comparable to that of the EBS wax system, while the dimensional change is only slightly more positive by 0.04 %.

It is worth mentioning that not all lubricating systems can remarkably enhance the green strength by using a thermal treatment. For instance, it is seen in Figure 11 that this property significantly increases from 23 MPa to 61 MPa by heat treating specimens containing the polymeric TP-B system, but only slightly changes when using conventional EBS wax. There exists few explanations for such a behavior. Firstly, it can be assumed that the conventional wax lubricant only tends to form a thin low strength lubricating film around the iron particles during the thermal treatment, which is not the case for the TP-B system. Indeed, the latter may flow into the open porosity during the thermal treatment and forms a scrawny network of lubricant sufficiently strong to enhance the green strength. Secondly, it is thought that some thermal oxidation welding could preferentially occur at the point of contact between metal particles by heat treating specimens containing the TP-B lubricating system in air [8].



**Figure 10 : Green Properties of Specimens Pressed to  $7.0 \text{ g/cm}^3$  with TP-B and EBS wax Lubricating Systems at Different Compacting Temperatures.**

Indeed, the latter may flow into the open porosity during the thermal treatment and forms a scrawny network of lubricant sufficiently strong to enhance the green strength. Secondly, it is thought that some thermal oxidation welding could preferentially occur at the point of contact between metal particles by heat treating specimens containing the TP-B lubricating system in air [8].



**Figure 11 : Effect of the Heat Treatment on Green Strength of Specimens Pressed with TP-B and EBS wax Lubricating Systems to 7.0 g/cm<sup>3</sup> at 65°C.**

**Table 2. Sintered Properties of Specimens Compacted to 7.0 g/cm<sup>3</sup> at Different Temperatures with TP-A, TP-B and EBS wax Lubricating Systems**

LUBRICATING SYSTEM	PROPERTY				
	Compacting temperature (°C)	Sintered Density (g/cm <sup>3</sup> )	Sintered Strength (MPa)	Dimensional Change (% from die size)	Apparent Hardness (HRB)
<b>TP-A</b>					
	45	6.94	660	+0.19	52
	65	6.95	700	+0.15	52
<b>TP-B<sup>(1)</sup></b>					
	45	6.98	730	+0.17	55
	65	6.97	725	+0.16	55
<b>EBS wax</b>					
	45	6.96	710	+0.13	54
	65	6.95	725	+0.12	53

(1) as-compacted specimens heat treated at 175°C for 1 h in air

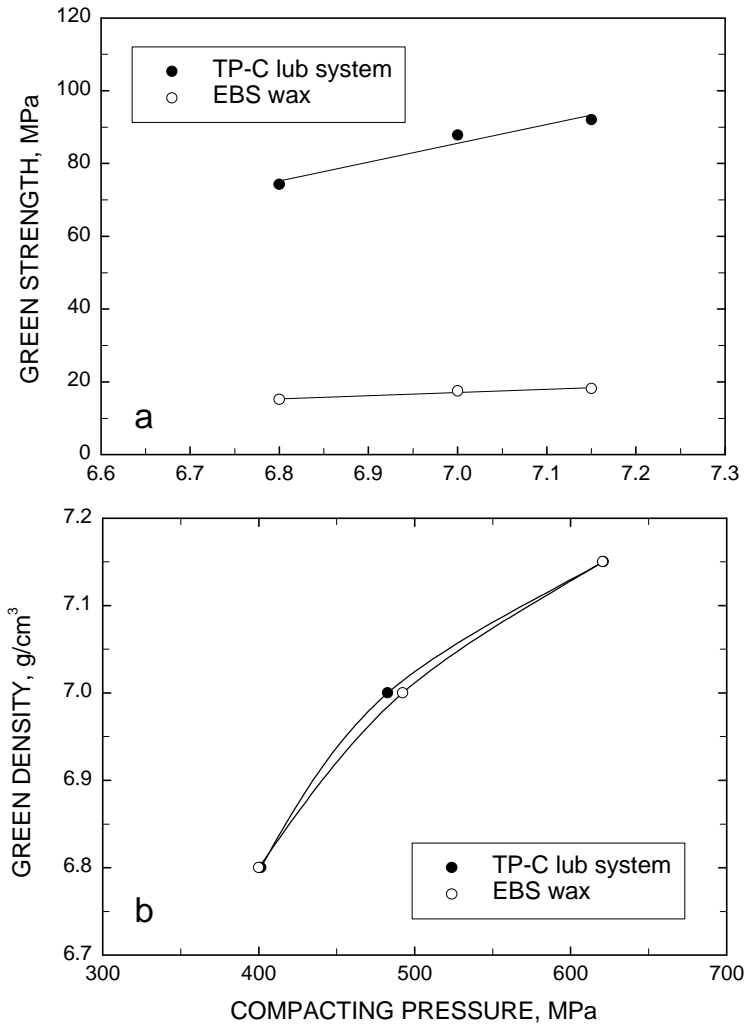
***TP-C lubricating system***

Figure 12 shows green properties obtained with TP-C and 0.75 wt% EBS wax lubricating systems for specimens pressed at different green densities from 6.8 to 7.15 g/cm<sup>3</sup> at 65°C. As for the TP-B system, the specimens compacted with the TP-C system were heat treated at 175°C for 1 hour in air. The sintered properties are also listed in Table 3.

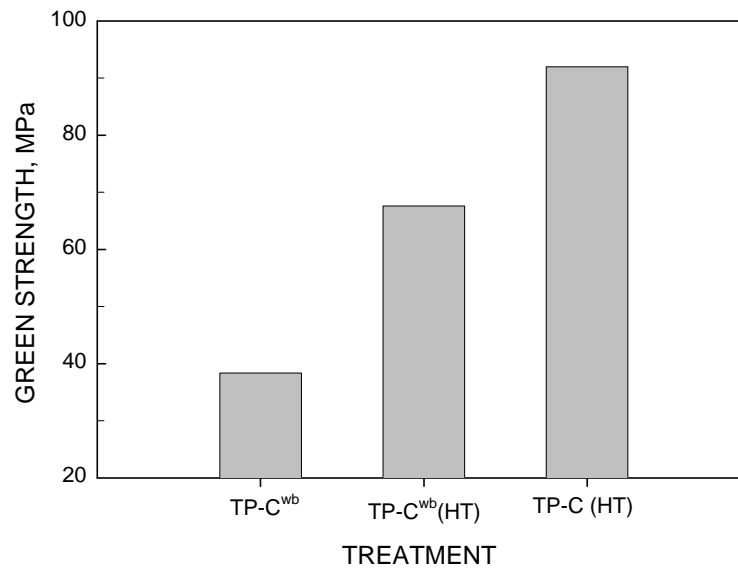
Figure 12a clearly illustrates that the green strength can be significantly improved compared to the EBS wax system by compacting and heat treating green specimens with the TP-C system at any green density from 6.8 to 7.15 g/cm<sup>3</sup>. The compressibility and sintered properties also remain comparable (Figure 12b and Table 3).

The green strength reaches 74 MPa and 92 MPa for densities of 6.8 and 7.15 g/cm<sup>3</sup> respectively, which is about five times higher than that achieved with EBS wax system. It should also be noted that the green strength attained with this system is significantly higher than the previously described lubricating systems for specimens pressed to a density of 7.0 g/cm<sup>3</sup>. Green strength of 88 MPa is achieved with the TP-C system compared to 37 MPa and 61 MPa for TP-A and TP-B systems respectively (Figures 9a, 10a and 12a).

It is believed that the improvement in green strength by heat treating specimens containing the TP-C lubricating system is due to a combination of several factors such as the inherent mechanical properties of the thermoplastic polymers comprised in this system and also to the ability of these thermoplastic polymers to crosslink or to form interpolymer complexes with the polymeric binder included in this system. As presented in Figure 13, the green strength significantly improved by around 76 % to reach 68 MPa by heat treating green specimens containing only the thermoplastic polymers at 7.15 g/cm<sup>3</sup> (TP-C<sup>wb</sup>), while it further increases from 68 MPa to 92 MPa by adding a polymeric binder in the system (TP-C). It is believed that the thermoplastic polymers comprised in the TP-C system have the ability to form a strong scrawny network of lubricant during the thermal treatment similar to the TP-B lubricating system. They could also interact with the polymeric binder via the formation of sufficiently strong intermolecular interactions to further strengthen the green compact.



**Figure 12 : Green Properties of Specimens Pressed with TP-C and EBS wax Lubricating Systems at 65°C.**



**Figure 13 : Green Strength of Specimens Pressed to 7.15 g/cm<sup>3</sup> at 65°C with TP-C<sup>wb</sup> and TP-C Lubricating Systems with and without a Heat Treatment (HT).**

**Table 3. Sintered Properties Obtained for Specimens Pressed at 65°C to Different Green Densities with TP-C and EBS wax Lubricating Systems**

LUBRICATING SYSTEM	PROPERTY				
	Green Density (g/cm <sup>3</sup> )	Sintered Density (g/cm <sup>3</sup> )	Sintered Strength (MPa)	Dimensional Change (% from die size)	Apparent Hardness (HRB)
<b>TP-C<sup>(1)</sup></b>					
	6.8	6.76	600	+0.06	42
	7.0	6.96	725	+0.11	53
	7.15	7.12	855	+0.16	61
<b>EBS wax</b>					
	6.8	6.75	580	+0.06	43
	7.0	6.94	725	+0.12	53
	7.15	7.11	830	+0.18	60

(1) as-compacted specimens heat treated at 175°C for 1 h in air

## CONCLUSIONS

This study was undertaken to develop new polymeric lubricating systems that will enhance the green strength and enable machining of parts prior to sintering. The polymeric lubricants comprised in this type of system were selected based on their ability to strengthen the green compacts with or without the use of a thermal treatment at a low temperature, and also by taking into consideration their capacity to shear and lubricate parts during compaction and ejection in conditions similar to that found in actual production. It

was demonstrated that the compressibility and lubrication behavior of metal powder mixes containing polymeric lubricants, as well as the surface finish of green and sintered specimens, can be greatly influenced by the particle size and the intrinsic properties of polymers (molecular weight, softening temperature) and thus must be considered when choosing polymeric lubricants.

The green strength of specimens pressed with these newly developed polymeric lubricating systems were significantly enhanced compared to the conventional EBS wax lubricant, while maintaining similar sintered properties. The most relevant conclusions that can be drawn for each polymeric lubricating systems that was studied are summarized as follows:

- The green strength obtained with the TP-A lubricating system significantly improved by raising the compacting temperature from 45°C to 65°C at a density of 7.0 g/cm<sup>3</sup>. This property reached 37 MPa for specimens pressed at a compacting temperature of 65°C, which is twice as high as the level achieved with 0.75 wt% EBS wax. The compressibility obtained with this system was also equivalent to the EBS wax lubricant for a compacting temperature equal or higher than 60°C. This temperature is usually attained during compaction of parts due to the heat generated by the friction between powder particles and against the die walls.
- The use of the TP-B lubricating system enabled reaching a green strength of about 62 MPa at 7.0 g/cm<sup>3</sup>, while maintaining a similar compressibility to 0.75 wt% EBS wax at compacting temperatures from 45 °C to 65°C. The green strength is two and four times higher than that obtained with TP-A and 0.75 wt% EBS wax systems respectively. The as-compacted specimens were heat treated at a relatively low temperature (175°C) in air in order to reach such a high green strength. This improvement may be related to the formation of a strong lubricant network during the thermal treatment
- The highest green strength was achieved by using the TP-C lubricating system at 65°C. This new lubricating system enabled reaching green strengths of 74 MPa and 92 MPa for specimens pressed to 6.8 and 7.15 g/cm<sup>3</sup> respectively, which is about five times higher than the conventional wax lubricant. As for the TP-B system, the as-compacted specimens were heat treated at 175°C in air to form a strong network of lubricant.

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