

## The Utility of Nanographite Materials as Solid Phase, Integral Die Wall Lubricants in PM

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### **Abstract**

The use of fine particle size graphite materials in powder metallurgy is generally restricted to use as “carbon raiser”. Although graphite is considered a very effective solid phase lubricant, at the addition rates needed for most PM parts there is not enough graphite at the die wall-part interface to provide the degree of lubricity needed for proper part ejection. These same PM mixtures contain wax-based lubricants to provide the die wall lubricity necessary for efficient PM compact ejection. A study was performed to determine the utility of nanographite materials to provide effective die wall lubrication, reducing or eliminating the need for added wax, while also providing metallurgically reactive carbon in place of or in conjunction with conventional graphite powders. Test results indicate that nanographite powders provide significant die wall lubricity, have lubrication synergy with PM mixtures containing reduced levels of wax lubricant, and provide metallurgically active carbon during the sintering process.

### **Introduction**

In order to facilitate compaction processing of both ferrous and non-ferrous powder metallurgy materials, lubricants are routinely used. PM lubricants include a number of waxes such as stearic acid and metallic steric acid derivatives, as well as synthetic waxes. In most cases lubricant powders are mixed directly with metal powders and although their function as lubricants is limited primarily to the interface between the die wall and PM compact, the lubricant material is dispersed throughout the entire volume of the compact.

In practice PM lubricants function primarily to reduce the ejection force required to remove the PM compact from steel or carbide tooling. Without the use of these lubricants the high sidewall friction associated with uniaxial compacted metal powders can result in excessive tool wear, tool warping, cavity die-wall spalling, PM compact spalling, or even catastrophic tool failure.

Although the use of lubricants in PM materials is required for efficient compaction and ejection of PM parts, the addition of lubricants has some significant disadvantages. These disadvantages include, but are not limited to diminished green density, sooting and off-gassing problems during the de-lubrication stage of sintering, introduction of impurities, non-homogeneity of blends, introduction of porosity, and the formation of graphite/wax agglomerates during powder mixing operations.

Graphite is a minor but important component in many ferrous PM materials. Natural flake graphite, in nominal sizes from about 5um to 20um, provides the alloying carbon required to turn iron powder into steel parts. There are other applications, both PM and non-PM, where the

perfect basal cleavage, flexible lamellae, and soft grain surfaces of this same graphite material allow its use as a solid phase lubricant. However, the typical addition rate of graphite to a PM material is only about 0.7-0.9% by weight, so the volume-surface expression of graphite flakes at the die wall/PM part interface is not sufficient to provide the lubrication needed for efficient compact ejection and as a result wax-based lubricants are required even in graphite-containing PM powders.

A study utilizing nanographite powders, derived from fully graphitized feedstocks, was carried out to determine if nanographite materials can be used in place of, or to augment, conventional PM lubricants, while simultaneously satisfying the combined carbon requirements provided by conventional PM graphite carbon raisers. The bulk of this paper will cover the die wall lubricity question. A thorough analysis of the metallurgical/mechanical aspects of sintered parts containing these unique nanographite materials is beyond the scope of this paper and the technical qualifications of the author. The analysis provided below will be limited accordingly.

### **Graphite Nanomaterials and Lubrication**

The term “nano” is a generic term that is applied to particles whose largest dimensions are in the nanometer size range ( $1\text{nm} = 10^{-9}\text{m}$ ). When applied to carbonaceous substances, those considered to be true nanomaterials are typically in the 2-100nm size range. Carbon-based nanomaterials can have very different morphologies including but not limited to tubes and capped tubes (carbon nanotubes), whiskers, platelets, cones, spheres, etc. The material under investigation in this study is restricted to nanocarbon platelets, also known as nanographite platelets. These are manufactured materials, which are produced from fully graphitized parent carbons.

All graphite materials, regardless of their bulk appearance, have a flaky or layered microstructure. In most cases when particle size is reduced below about 50um this laminar microstructure becomes clearly visible in SEM images. Figure 1 and Figure 2 below, show the flaky morphology of two different synthetic graphite products that differ in particle size by two to three orders of magnitude. Both of these products were manufactured from the same granular, acicular synthetic graphite parent carbon. The material in Figure 1 is a nominal 8um powder, while the material in Figure 2 is composed of 1um agglomerated graphite lamellae that have a primary particle size of about 10-250nm across. These images illustrate the planer or layered substructure of graphite, upon which all graphite macrostructures are based. Correspondingly, these flaky micro and nano structures are based on single graphene layers.

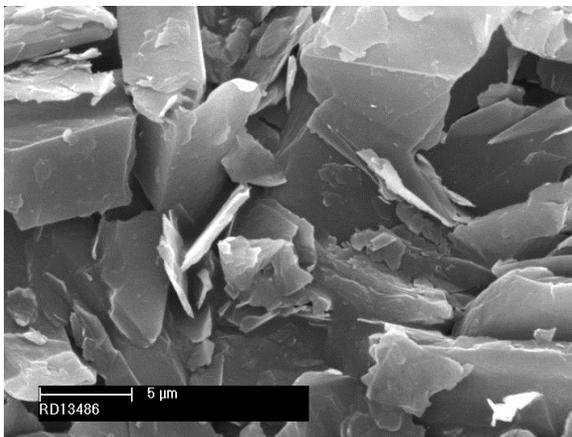


Figure 1: 8um synthetic graphite GTC301

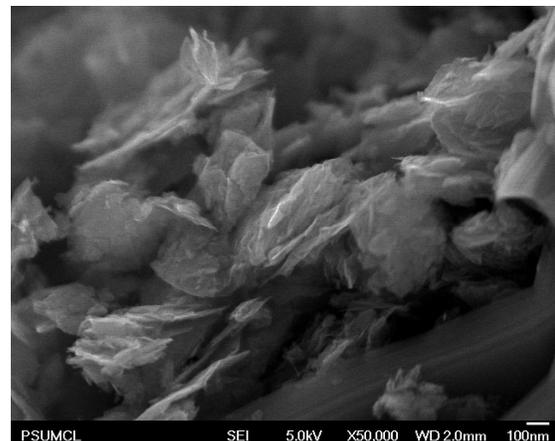


Figure 2: Nanographite platelets NTC307

To provide some perspective between Fig 1 and Fig 2, and the “graphene-layer structural unit”, consider the following: The through plane thickness of the 8 $\mu$ m synthetic graphite flakes in Figure 1 is approximately 0.25-0.50 $\mu$ m. This thickness requires a stack of about 750-1500 sheets of graphene (planer sp<sup>2</sup>-carbon atoms). In contrast, the synthetic graphite nano-flakes imaged in Figure 2, are approximately 10nm thick, which is equivalent to only about 30 sheets of graphene (planer sp<sup>2</sup>-carbon atoms).

The behavior of graphite as a lubricating material is reasonably well understood. Graphite, in all forms, when exposed to wear forces will yield “shear plates” composed of multi-layered, tough sheets of sp<sup>2</sup>-type carbon atoms arranged in large hexagonal ring arrays. These layers provide effective barrier layer lubrication at the friction interface. Graphitic carbon materials exhibit a strong form-and-function relationship dictated by the microstructure, which maintains a layered or foliated morphology even when approaching the nanometer (nm) particle size scale. In general, larger particles or domains of graphite are more lubricious than smaller particles or domains. However, the weak interlayer bonding that results in the perfect basal cleavage and high lubricity associated with graphite is maintained even in graphite nanoplatelet structures. This means that it is likely nanographite platelets which have a reduced number of graphite layer planes (graphene layers), will provide lubricity if exposed to shear or other forces that would normally result in the formation of a lubricating film.

The formation of new graphite surfaces at the expense of larger graphite particles results in an increase in surface area. For example, a nominal 8 $\mu$ m graphite powder, like the one imaged in Figure 1, will have a BET surface area of approximately 11m<sup>2</sup>/gram. In contrast the same parent graphite reduced in size to a nominal 100nm powder, like the material imaged in Figure 2, will have a BET surface area of 350m<sup>2</sup>/gram. Since graphite has perfect basal cleavage parallel with the {0001} basal plane this is the easiest surface to generate mechanically and in general is the most prominent surface visible in graphite materials of any size below about 50 $\mu$ m. The flat surfaces visible in Fig 1 and Fig 2 above are {0001} basal planes. Regardless of the mode of attrition, as smaller particles are generated, the thickness of residual graphite lamellae becomes reduced. Correspondingly, the number of particles per unit mass increases significantly with a resultant decrease in bulk density. Throughout this process, however, lubricating, albeit thin, graphite lamellae remain.

As stated previously, the concentration of conventional graphite particles at the die wall-PM part interface is not high enough to provide sufficient die wall lubrication. However if the mass of conventional graphite used in a PM part were replaced with the same mass of nanographite platelets, would the increase in the number of added particles result in sufficient surface exposure of graphite lamellae to provide an acceptable degree of die wall lubrication even in the absence of wax additives? This question is the basis of this research paper.

### **Experimental Procedure/Methods/Materials**

A number of different PM mixtures containing nanographite powder, conventional graphite powder, and wax lubricant were evaluated and compared. The force required to eject a powder compact from either a TRS or tensile bar fixture was used to gauge the relative performance of each additive as a die wall lubricant. In order to determine the metallurgical activity of the nanographite additives, the TRS compacts used in the ejection study were then sintered and their basic mechanical properties measured.

**Graphite/Nanographite Materials Evaluated in this Study**

Two conventional flake graphite products and four nanographite materials were evaluated and compared. Standard “PM” flake graphite grades were used to simulate conventional PM powders. The conventional flake graphite used represented nominal 3um and 9um powders. The primary particle size of the four nanographite powders evaluated was indexed to BET surface area. Conventional particle size, as determined by laser particle size analysis techniques, does not provided clearly defined primary particle size values for nanographite materials. Nanographite platelets tend to form micrometer sized agglomerations during manufacturing resulting in “laser particle size” values that are skewed as a result. In general, the true primary particle size of nanographite materials can be determined only by image analysis and inference to other properties.

When providing particle size information about nanographite materials BET surface area seems to be a more reliable index to relative size. The BET surface area can also be used to calculate a rough “lamella thickness index” (LTI). This value will provide a crude estimation of the average thickness of a specific nanographite flake, and is somewhat indicative of particle size. The LTI is calculated by dividing the measured BET surface area of a nanographite powder into the theoretical surface area of a fully delaminated graphite material, i.e. pure graphene, which is about 2600m<sup>2</sup>/gram. For example, the LTI of sample N2299, from Table 1, is equal to 2600/400 = 6.5 (layers thick), which is equivalent to an average lamella thickness of about 2.5nm assuming an inter-graphene layer spacing of 0.335 nm. Table 1, below, indentifies the parent carbon, carbon content, and particle size parameters of the graphite/nanographite materials used in this study. Note that in the case of the four nanographite materials the primary particle size is not accurately provided by the Microtrac data.

Table 1: Graphite and Nanographite parent carbon identification, nominal carbon content, and particle size characteristics.

Grade	Type or Parent Carbon	Nanographite	LTI	Carbon Content (LOI) Mass %	Typical Measured particle size Microtrac	BET SA m <sup>2</sup> /gram
G1651	Natural Flake	No	***	~95	10µm	7.4
G3442	Natural Flake	No	***	~95	3.7 µm	14.5
N3062	Natural	Yes	22	~95	1.9 µm	120
N4827	Synthetic	Yes	10	~99	1.6 µm	249
NTC307	Synthetic	Yes	7	~99	2.6 µm	352
N2299	Natural	Yes	6	~97	2.1 µm	402

**Powder Ejection Force Evaluation**

This study consisted of a series of individual trials designed to determine the ability of nanographite powders to function as die wall lubricants. As noted above, the ability of the same material to provide metallurgical active carbon to the sintered part was also of interest and will be briefly discussed in this report.

In all test mixes prepared, the concentration of graphite/nanographite was chosen to mimic the amount of graphite typically used in conventional iron-graphite PM powders, 0.9 mass percent.

Trial #1: Comparison of standard PM grade G1651 with nanographite powder N2299, and NTC307, in TRS bar ejection.

Trial #1 consisted of a series of powder compaction and ejection cycles in which the force required to eject powder compacts was measured. PM compacts were formed using a TRS tool-set with a nominal 0.5 in.X1.25 in. cavity dimension. The die-set was scrubbed between samples using an un-lubricated iron powder (H1000B). Five consecutive scrubs were performed before and after testing each powder mixture. “Scrub parts” were compacted to 30 tsi.

All test samples were compacted to 30 tsi using a Tinius Olsen testing machine. Ejection force was measured using a gauge graduated in 200 lb increments. Iron/graphite mixtures were wax-free and composed of 99.1% H1000B iron and 0.9% graphite or nanographite. An FC208 mixture, containing 0.75% Acrawax was prepared and tested to provide a baseline for comparison to the wax-free test bars. Powder mixtures were prepared by mixing for 15 minutes in a Patterson Kelley “V” blender. Table 2 below presents the ejection force data for trial #1. The ejection force for the die scrubbing cycle for Trial 1 varied from about 9000-25,000 lbs, with most values falling between 14,000-25,000 lbs. Scrub part ejection values are omitted from the table.

Table 2: Ejection force results for Trial #1(TRS bars)

Blend	G1651 flake (FC208 + Wax) baseline mix	G1651 flake 0.9%	N2299 nano 0.9%	NTC307 nano 0.9%
Test Bar	Eject Force lbs	Eject Force lbs	Eject Force lbs	Eject Force lbs
1	4000	9900	8200	7700
2	4200	11,200	7300	7700
3	5000	14,200	6800	7300
4	5100	15,100	6500	7600
5	5100	17,000	6500	5700
Average	<b>4680</b>	<b>13,900</b>	<b>7000</b>	<b>7200</b>
Deviation from BL	<b>BL</b>	<b>+9220</b>	<b>+2320</b>	<b>+2520</b>

Trial #1 Results and Discussion:

The lowest ejection forces measured in Trial 1 occurred in the baseline mixture composed of conventional, lubricated FC208 powder. The average ejection force for the 5 sample parts was 4680 lbs. The average force required to eject the wax-free mixture containing conventional 9um flake graphite (G1651) was 13,900 lbs. The two wax-free mixtures containing nanographite powders showed average ejection forces of approximately 7000 lbs.

Both mixtures containing nanographite particles as the graphite source show significant decreases in ejection force compared to the mixture containing 9um conventional graphite flake #G1651. Although these nanographite mixtures do not exhibit ejection forces as low as the standard, baseline lubricated product, the results do indicate that nanographite platelets are providing die

wall lubrication to the system. Also, although additional data is required for verification, the trend in ejection force reduction for nanographite N2299 may be indicative of a process involving surface impregnation of the die wall by nanographite platelets: the result being the formation of a semi-permanent layer of lubricating graphite nano-particles. It is suspected that the nano-powders selected for this study contain graphite lamellae composed of as few as five or less graphene layers. This may provide a lubricating particle that is able to interact with, or impregnate surface disparities not accessible to larger, conventional graphite materials.

Trial #2: Ejection force comparison (Tensile bars) between standard PM grades G1651 and N3442, and nanographite powders N2299, NTC307, and N4827.

In Trial #2 the force required to eject MPIF Standard 10 tensile bars (dog-bone configuration) was measured. Tensile bar thickness was held constant at 0.73 in. Graphite and nanographite/iron mixtures were compacted to 30 tsi. Powder samples were mixed for 15 minutes in a Patterson Kelly V blender, and were composed of 99.1% H1000B iron, and 0.9% graphite or nanographite. Five tensile bars were evaluated for each mixture. All mixtures were wax-free. The die set was scrubbed three times before and after each powder was tested by compaction and ejection of unlubricated H1000B iron powder. Scrub bars were compacted to only 10 tsi in Trial 2 in order to avoid damage to the die set. In Trial 2 a wax-free baseline mixture containing only conventional flake graphite G1651 (10  $\mu$ m) was used. A blend containing a nominal 3-5 $\mu$ m flake graphite powder was also added for comparison. The ejection force results for Trial #2 are presented below in Table 3.

Table 3: Ejection force results for Trial #2 (Tensile bars)

Blend	G1651	G3442	N2299	NTC307	N4827
Mixture Fe/carbon	99.1/0.9	99.1/0.9	99.1/0.9	99.1/0.9	99.1/0.9
Test Bar	Eject Force lbs				
1	17,000	14,300	10,800	10,200	11,500
2	15,000	15,500	10,000	10,300	12,500
3	13,500	12,800	10,500	10,400	13,200
4	13,000	12,700	10,000	10,500	13,500
5	13,000	15,800	10,000	10,800	12,900
Average	<b>14,300</b>	<b>14,200</b>	<b>10,300</b>	<b>10,400</b>	<b>12,700</b>
Reduction WRT 1651	Baseline	No change	28% reduction	27% reduction	11% reduction

Trial #2 results and discussion

The iron/graphite mixture containing conventional 10 $\mu$ m PM graphite G1651 established an average baseline ejection force of 14,300 lbs. An iron/graphite mixture utilizing a finer (4 $\mu$ m vs 10 $\mu$ m) graphite powder, G3442, showed an almost identical average ejection force, indicating that no lubricating advantage was apparent for a 50% reduction in particle size and corresponding doubling of BET surface area, from 7 m<sup>2</sup>/gram to 14 m<sup>2</sup>/gram, in a conventional flake graphite.

The ejection force required for iron/nanographite blends showed a significant decrease over the baseline. The iron/N2299 mixture showed a decrease of 28%, while the NTC307 and N4827 mixtures showed a 27% reduction and 11% reduction, respectively, over the baseline mix.

Nanographite powders N2299, NTC307, and N4827 have nominal BET surface area values of 400 m<sup>2</sup>/gram, 350 m<sup>2</sup>/gram, and 250 m<sup>2</sup>/gram, respectively. Following the logic that higher surface area equates to more numerous and smaller dimensioned particles, supports the statement that the graphite nanopowder with the highest surface area in all likelihood contains the highest particle-count/mass value. Correspondingly, a higher BET surface area nanographite powder will contribute a higher graphite lamella count to its conjugate mixture. The result is that there should be potentially more lubricating graphite lamellae at the die wall-part interface to provide lubricity. This hypothesis is supported by the overall reduction in ejection force of the iron/nanographite mixtures compared to the baseline iron/G1651 mixture. The hypothesis is also supported, although the supporting data is limited, by the incremental decrease in lubricity coincident with the incremental decrease in BET surface area for each nanographite/iron mixture as indicated by the increase in ejection force required for the mixtures containing lower BET surface area nanographite powders NTC307 and N4827.

Trial #3: Comparison of the TRS bar ejection force between iron powder mixtures containing graphite/nanographite powder and reduced levels of admixed wax, and wax-free mixtures of iron-graphite/nanographite powders.

The purpose of Trial #3 was to determine if a lubrication synergy may exist between nanographite powders and wax, in iron powder mixtures containing reduced wax additions (for example 0.1% vs 0.7% wax ). To facilitate this comparison the ejection force for a baseline mixture containing only iron powder and 0.1% Acrawax, with no carbon, was measured. Subsequent measurements of the ejection force of mixtures containing 0.9% graphite or nanographite with no added wax, and 0.9% graphite or nanographite with 0.1% added wax were made.

TRS bars used in Trial #3 were compacted using a TRS tool-set different from the one used in Trial#1. The Trial#3 tool-set had a nominal 0.5 in.X 1.25in. cavity dimension. All TRS bars were maintained at 0.25 in. thickness, and were compacted at 30 tsi. Five TRS bars were pressed and ejected for each mixture. All scrub cycles were performed using neat H1000B powder compacted to 10 tsi. Two test mixture configurations were used; one configuration contained 99.1% iron mixed with 0.9% graphite or nanographite powder and the second configuration contained 99.0% iron, 0.9% graphite or nanographite powder, and 0.1%Acrawax lubricant. Baseline ejection force was determined by measuring the ejection force required for a mixture of 99.9% iron and 0.1% wax, with no carbon addition. Mixing time was 15 minutes and all mixes were prepared on a Patterson Kelly V blender. Table 4 and Table 5, below, present the data from Trial #3.

Table 4: Ejection force (TRS bars) for Iron-Wax baseline and Iron-Graphite/Nanographite (Wax-free) mixtures.

Blend	Acrawax only	Fe +G1651	Fe +N2299	Fe + N3062
Fe/wax/carbon	99.9/0.1/0	99.1/0/0.9	99.1/0/0.9	99.1/0/0.9
Test Bar	Eject Force lbs	Eject Force lbs	Eject Force lbs	Eject Force lbs
1	4000	7500 (excluded)	3500	4700
2	4200	5700	3100	3400
3	4200	5400	3000	3400
4	4000	5500	2900	3400
5	4500	4500	2700	4000
Average	<b>4180</b>	<b>5275</b>	<b>3040</b>	<b>3780</b>
Deviation	<b>Baseline</b>	<b>+26%</b>	<b>-27%</b>	<b>-10%</b>

Table 5: Ejection force (TRS bars) for Iron-Wax baseline and iron powder with added graphite or nanographite, and 0.1% wax lubricant.

Blend	Acrawax Only	G1651 + wax	G3442 + wax	N2299 + wax	NTC307 + wax	N4827 + wax	N3062 + wax
Fe/wax/C	99.9/0.1/0	99/0.1/0.9	99/0.1/0.9	99/0.1/0.9	99/0.1/0.9	99/0.1/0.9	99/0.1/0.9
Test Bar	Eject Force lbs						
1		3200	3400	2700	2900	3000	2700
2		3200	3700	2500	2800	2900	2600
3		3200	3700	2700	2700	2500	2700
4		3500	3700	2700	2500	2800	2700
5		3300	3400	2700	2800	2800	2600
Average	<b>4180</b>	<b>3320</b>	<b>3580</b>	<b>2660</b>	<b>2740</b>	<b>2800</b>	<b>2660</b>
Deviation	<b>Baseline</b>	<b>-21%</b>	<b>-14%</b>	<b>-36%</b>	<b>-34%</b>	<b>-33%</b>	<b>-36%</b>

### Trial #3 results and discussion

The baseline mixture containing 99.9% iron and 0.1% Acrawax required an average ejection force of 4180 lbs. In contrast the mixture containing 99.1% iron with 0.9% G1651 flake graphite required an average ejection force of 5275 lbs, a value 26% higher than the wax-containing mix.

The wax-free mixture containing 0.9% nanographite N2299 showed an average ejection value of 3040 pounds, or 27% below the baseline iron/wax blend. The lower surface area nanographite powder N3062 had an ejection force of 3780 pounds, only 10% lower than the baseline. Both nanographite powders appear to have provided more die wall lubrication compared to the mixture containing 0.1% Acrawax, the reduced-wax baseline mixture.

Nanographite N2299 has a much higher BET surface area than nanographite N3062, which may account for the more significant effect on die wall lubrication and resultant ejection force reduction. In this section of Trial#3 the trend of increasing apparent lubricity with increasing BET surface area is again reinforced.

The data for mixtures containing wax and nanographite powder, Table 5, show the highest reduction in ejection force. Iron powder with added conventional graphite, G3442, and 0.1% wax

showed the lowest reduction in ejection force, while iron powder with added nanographite, N2299, and 0.1% wax had the highest reduction in ejection force. However, although there is a significant improvement in lubricity of all mixtures containing nanographite powder, the trend of increased lubricity with increasing BET surface area is not apparent in this Trial where a reduced level of Acrawax is has also been included in the mixture.

Based on the ejection force measurements there is significant increase in die wall lubricity when both conventional and nanographite powders are used in conjunction with reduced levels of lubricating wax. The behavior observed may indicate a synergy of mixture between wax and graphite, and wax and nanographite powders.

**Sintered TRS Data**

Further to the TRS ejection measurements test bars were sintered and their hardness, density, and transverse rupture strength measured. All bars were sintered at 2050 F for 30 minutes in an atmosphere of dissociated ammonia. Three bars from each sample set were selected for testing and the three data points averaged. The averaged TRS property measurements are presented below in Table 6.

Table 6: TRS bar Mechanical Properties

Sample Comp	Nanographite (Yes/No)	Density g/cc	Hardness HRB	Transverse Rupture Strength ksi	Approx Deviation from Expected Stand 35 TRS (density basis)
Neat F-0000 Fe	N	6.70	Below Scale	54	+4 ksi
0.9% G1651	N	6.60	59	84	+10 ksi
0.9% N2299	Y	6.70	53	76	-4 ksi
0.9% N3062	Y	6.70	63	95	+15 ksi
0.1% wax-0.9% G3442	N	6.57	63	90	+14 ksi
0.1% wax-0.9% G1651	N	6.63	61	84	+8 ksi
0.1% wax-0.9% N2299	Y	6.61	46	66	-9 ksi
0.1% wax-0.9% N4827	Y	6.54	62	83	+8 ksi
0.1% wax-0.9% N3062	Y	6.50	55	76	+3 ksi
0.1%wax-0.9% NTC307	Y	6.55	59	71	-4 ksi

**TRS Sinter Data: Results and Discussion**

A technical analysis of the sintered mechanical properties of Trial #1 and Trial #3 TRS bars is outside of the authors’ field of technical expertise. The data tabulated in Table 6 is being provided to show that the nanocarbon materials utilized in this study were metallurgically active,

and did “go into solution” as indicated by the increase in hardness and TRS values over the neat sintered iron.

Based on this limited set of data, the nanographite which showed the most significant positive effect on die wall lubricity, N2299, had a negative impact on transverse rupture strength when compared the expected TRS value of a nominal F0008 product at the density indicated. In contrast, the nanographite powder that had less of an impact on die wall lubricity when used in a wax-free mixture, N3062, resulted in sintered parts which had acceptable TRS values based on the same F0008 criteria. Further testing is needed to verify the behavior of these materials in sintered iron parts.

### **Conclusions**

A study to determine the utility of nanographite materials as integral die wall lubricants, while at the same time provide metallurgically active carbon to the sinter reaction was undertaken. The metric chosen to rank or verify the effective die wall lubricity of the graphite and nanographite materials studied was the force required to eject a PM powder compact from either a TRS , or tensile bar tool-set. The metallurgical activity, or lack of, was based on the resultant hardness and transverse rupture strength measured on TRS bars sintered using conventional methods.

Based on the data generated in three compaction-ejection trials the following conclusions are offered:

1. Conventional 5um and 10um flake graphite does not perform well as a die wall lubricant in the absence of wax.
2. Nanographite powders do provide significant die will lubricity in the absence of wax.
3. The effectiveness of nanographite materials to act as die wall lubricants appears to be related to BET surface area; Powders with higher BET surface area values appear to be more effective die wall lubricants.
4. There appears to be a “synergy of lubrication” between Acrawax and conventional graphite powders (5um and 10um), and Acrawax and nanographite powders. The effective lubrication is significantly higher in mixtures containing nanographite powder and wax.

Based on the mechanical properties measured on sintered TRS bars from Trial#1 and Trial#3 the following conclusions are offered.

1. The increase in Rockwell hardness of TRS bars containing nanographite powder, compared to the hardness of the baseline sintered neat iron part indicates that nanographite powder provided metallurgically active carbon to the system.
2. The increase in transverse rupture strength of TRS bars containing nanographite powder, compared to the transverse rupture strength of the baseline sintered neat iron part indicates that nanographite powder provided metallurgically active carbon to the system.

The properties of nanomaterials can be very different from their macroscopic precursors. Enhanced reactivity, high relative surface area, unique surface features, and other attributes can result in unexpected performance characteristics that in some cases are the combined effect of macroscopic and microscopic properties. The use of nanographite platelet materials in powder metallurgy may provide the PM industry with new, multifunctional carbon and graphite additives for both current and future PM applications.

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