EFFECTS OF POWDER PROPERTIES & PROCESSING ON SOFT MAGNETIC PERFORMANCE OF 400-SERIES STAINLESS STEEL PARTS

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ABSTRACT

With the advent of growth in soft magnetic applications suitable to Powder Metallurgy, powder manufacturers parts fabricators and end users of such parts must gain a better understanding of the relationships between powders, processing and the ultimate performance of soft magnetic P/M parts.

Studies have been conducted and valuable data extracted on the subjects of pure iron, iron-phosphorus, iron-silicon and pre-alloyed iron-nickel alloys as they relate to magnetic properties. With the identification of applications requiring corrosion resistance as well as mechanical and magnetic properties, including the Anti-lock Brake System (ABS) tone wheel, industry is investigating ferritic stainless steel solutions. This study represents an effort to provide some initial answers to questions regarding the "real world" capability of P/M production of high quality, ferritic stainless steel parts that exhibit excellent magnetic properties.

INTRODUCTION

A study was performed to gain an understanding of the suitability of P/M 400-series stainless steels for soft magnetic applications by determining: the relative merits of 410L, 430L, and 434L as base materials to be selected for soft magnetic applications; the effect of density on magnetic properties; the effects of several P/M processing variables on both magnetic performance and finished part chemistry, including:

1) sintering temperature
2) sintering time
3) sintering atmosphere
4) lubricant content
5) lubricant type

The intent of this study is to provide useful information that will help end-users: a) select an appropriate corrosion-resistant alloy for a given magnetic application; b) set effective, achievable magnetic property specification limits on parts; and c) gain an understanding of the processing factors that impact the magnetic performance of 400-series stainless steel P/M parts. Likewise, the data will assist parts fabricators to identify processing variables that are the most critical to control in order to produce parts with optimized mechanical, chemical and magnetic properties.

TEST CONDITIONS

Samples for magnetic testing were blended, compacted, sintered and measured utilizing varying test conditions to allow the examination of the following parameters on magnetic properties:

- base powder type
- lubricant level (percent by weight)
- lubricant type
- part density
- sintering time
- sintering temperature
- atmosphere type

The test specimen utilized was a nominal 3.6 cm OD, 2.23 cm ID toroid compacted to a height of 0.62 cm in a laboratory compacting press. It is important to note that all of the sintering for this study was performed in production furnaces that are essentially, but not solely, used for processing stainless steel parts. Production sintering represents an integral component of this examination since a primary goal of the study is to obtain realistic data typical of a production environment. In order to achieve this goal, this investigation employed equipment and processing typical of a production environment.

After sintering, primary and secondary windings (25 turns each) of #28 AWG wire were applied to the toroids. DC hysteresis loops were generated on an LDJ Model 3500 hysteresigraph; a microprocessor-controlled measurement device capable of obtaining a complete hysteresis loop including the initial curve. Drive fields (H_{max}) of 15 and 30 oersteds were utilized during the testing. Magnetic property values of interest generated by this instrument include:

1) coercive force (H_c)
2) maximum induction (B_{max})
3) residual induction (B_r)
4) maximum permeability (μ_{max})

It is not the intention of this paper to explore the theoretical explanations of these properties. The reader is referred to several excellent sources that contain relevant information.

Typically, maximum induction levels measured at even 30 oersteds are not representative of the saturation induction of a material. For a given material, the maximum induction level measured at 30 oersteds can be dependent on the permeability of the material and not be indicative of the saturation induction. The saturation induction is important in applications where the P/M part acts as a flux carrier for a permanent magnet. Most permanent magnet materials will supply ample flux density to saturate the P/M part. In order to present accurate saturation induction values, selected materials from the study were analyzed utilizing an LDJ SM-8100 Saturation Induction Measuring System.

Lubricated blends were prepared from Ancor® 410L, 430L and 434L stainless steels in an effort to determine the optimal base material. The base chemistries of the powders used in the experiments are listed in Table I. The powders were mixed with 1% lithium stearate and compacted into toroids at 30, 40, and 50 tsi. The resulting toroids were then sintered in a production furnace at 1260°C (2300°F) for 30 minutes at temperature in a pure hydrogen atmosphere. The results of this experiment allow evaluation of the effects of base material chemistry on the magnetic property levels attainable for each of the alloys at a given set of processing parameters. The effect of density on magnetic properties can also be derived from these findings.

The remainder of the study was performed using 410L. Selection of 410L was based on its position as the dominant alloy in the stainless steel magnetic business. However, the effects demonstrated by changing various processing parameters can easily be transferred to other alloy Systems.

Evaluation of the effect of sintering temperature on properties was performed by compacting samples of 410L with 1% lithium stearate at 30, 40, and 50 tsi. The toroids were then production sintered at 1260°C (2300°F), 1200°C (2200°F), and 1120°C (2050°F). These results offer further insight into the effect of density on magnetic properties.

The effect of sintering time was investigated by compacting samples of 410L mixed with 1% lithium stearate at 50 tsi. These samples were production sintered at 1260°C (2300°F) in pure hydrogen for 30 and 60 minutes at temperature. The outcome of this test case will address the assumption that a lengthened sintering cycle has a beneficial effect on magnetic properties.

TABLE I
Chemical Analysis of Stainless Steel Base Materials

Wt. %	410L	430L	434L
C	0.020	0.018	0.028

N	0.019	0.035	0.025
O	0.13	0.19	0.25
S	0.006	0.010	0.005
P	0.02	0.02	0.02
Si	0.9	0.9	0.9
Mn	0.1	0.1	0.2
Cr	12.4	16.8	17.2
Mo	--	--	1.2
Fe	Bal.	Bal.	Bal.

As a means of evaluating the effect of sintering atmosphere on magnetic properties, mixes of 410L with 1% lithium stearate were compacted at 50 tsi. The resulting toroids were production sintered at 1260°C (2300°F) in pure hydrogen, 75% H_2/25%N_2 (synthetic dissociated ammonia), and 10% H_2/90% N_2 (forming gas).

In an effort to study the effect of lubricant quantity on magnetic properties, blends of 410L containing 0.75%, 1.0%, and 1.25% lithium stearate were compacted at 50 tsi. The toroids were production sintered at 1260°C (2300°F) for 30 minutes at temperature in pure hydrogen.

Additionally, an investigation into the effect of different lubricants on properties was undertaken. Mixes of 410L containing 1% Acrawax C, 1% zinc stearate, and 1% Kenolube were compacted at 50 tsi into toroids which were production sintered at 1260°C (2300°F) for 30 minutes at temperature in pure hydrogen. The results of these experiments are compared to those of the 1 % lithium stearate blend mentioned previously.

RESULTS

Effect of Materials and Density

The green densities of the 410L, 430L and 434L samples are indicated in Figure 1. As expected, the 410L exhibited the highest green density of the group, followed by the 430L and 434L, respectively. The increased alloy content of the 430L and 434L results in a particle that work hardens at a more rapid rate and thereby yields a tower green density. Table II lists the sintered density and magnetic properties of the

TABLE II
Sintered Density and Magnetic Properties for Various Ancor Stainless Steel Grades Compacted with 1% Lithium Stearate and Sintered at 1260°C for 30 Minutes in Hydrogen

Material type	Compaction Pressure	Sintered Density	H_{c-15} (Oe)	B_{max-15} (kG)	B_{r-15} (kG)	μ_{max}	H_{c-30} (Oe)	B_{max-30} (kG)	B_{r-30} (kG)	Saturation Induction

	(tsi)	(g/cm^3)								(kG)
	30	6.88	1.60	10.26	6.54	1916	1.60	11.66	6.62	14.67
410L	40	7.09	1.96	10.68	6.18	1630	1.95	12.24	6.19	15.10
	50	7.23	1.92	10.86	6.83	1717	1.92	12.62	6.98	15.43
	30	6.71	1.49	9.25	5.84	1846	1.50	11.01	6.04	13.32
430L	40	6.94	1.82	9.53	5.27	1526	1.83	11.33	5.36	13.83
	50	7.10	1.93	9.60	5.20	1431	1.98	11.86	5.35	14.19
	30	6.67	1.44	8.93	5.35	1805	1.42	10.26	5.38	12.90
434L	40	6.91	1.64	9.41	5.65	1702	1.64	10.74	5.77	13.59
	50	7.08	1.90	9.45	5.19	1494	1.90	11.12	5.22	13.77

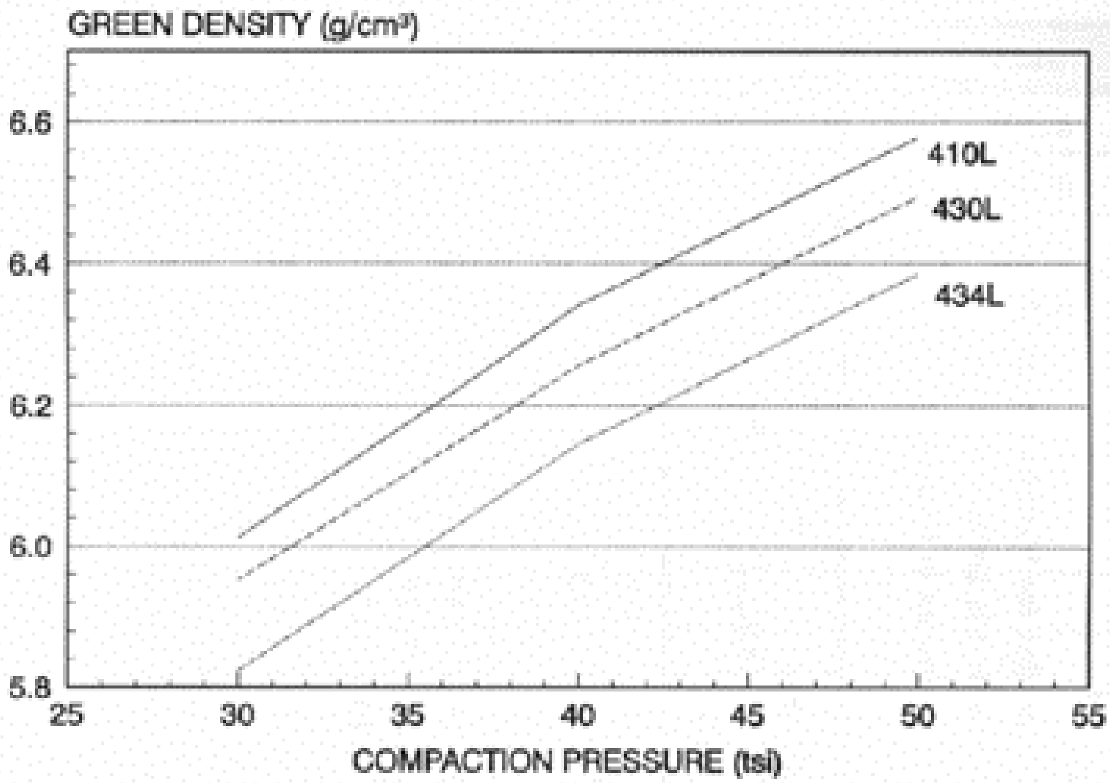

FIGURE 1: GREEN DENSITY OF VARIOUS STAINLESS STEEL POWDERS COMPACTED WITH 1% LITHIUM STEARATE

materials following sintering at 1260°C (2300°F) for 30 minutes at temperature in pure hydrogen. The sintered density values (Figure 2) correspond with the green density results cited above. The fact that 410L far exceeds 430L and 434L in both green and sintered density explains to some degree its overwhelming preference among current producers of ferritic stainless steel parts. Magnetic property test results for the three alloys are graphically presented in Figures 3 through 5. Maximum induction values measured at a field strength of 30 oersteds (Figure 3) follow the same trends as the density curves. The 410L not only exhibits the highest density and the highest maximum induction, but it also demonstrates the highest induction for a given sintered density. This is the result of increased alloy content lowering the saturation induction level for the more highly alloyed materials (see below).

The coercive force at 30 oersteds and the maximum permeability (Figures 4 and 5) also indicate that 410L exceeds 430L and 434L in terms of critical magnetic properties. Interestingly, all three materials reflect declining permeability and increasing coercive force with compaction pressure and density increases. This result was not anticipated. The results may be explained by the retained carbon, nitrogen and oxygen, listed in Table III. The oxygen and nitrogen levels are higher in those parts pressed at the highest compaction pressures. This suggests that the toroids with the highest green densities did not experience sufficient oxide reduction and nitrogen removal

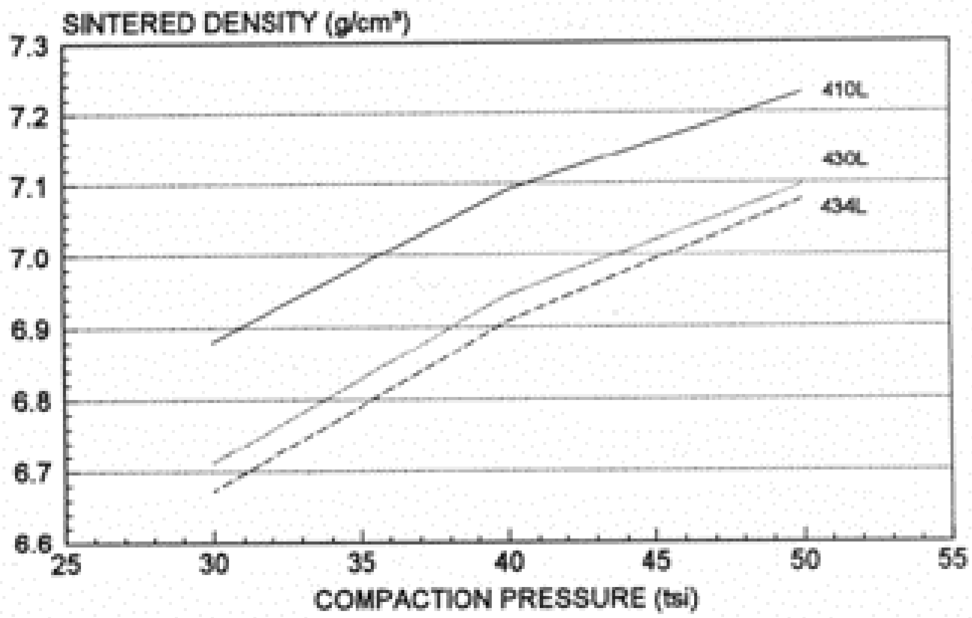

FIGURE 2: SINTERED DENSITY FOR VARIOUS STAINLESS STEEL GRADES COMPACTED WITH 1% LITHIUM STEARATE AND SINTERED AT 1260°C FOR 30 MINUTES IN HYDROGEN

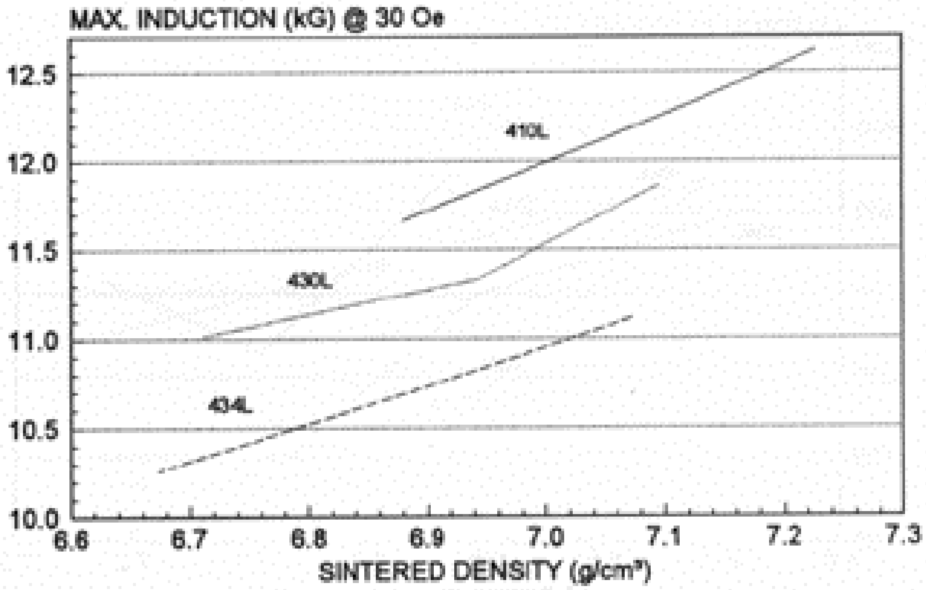

FIGURE 3: MAXIMUM INDUCTION FOR VARIOUS STAINLESS STEEL GRADES COMPACTED WITH 1% LITHIUM STEARATE AND SINTERED AT 1260°C FOR 30 MINUTES IN HYDROGEN

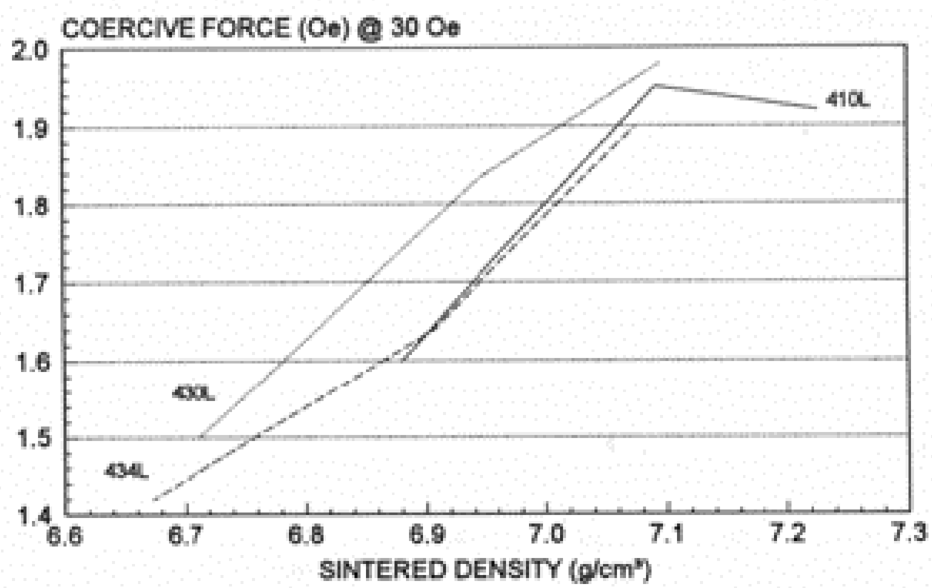

FIGURE 4: COERCIVE FORCE FOR VARIOUS STAINLESS STEEL GRADES COMPACTED WITH 1% LITHIUM STEARATE AND SINTERED AT 1260°C FOR 30 MINUTES IN HYDROGEN

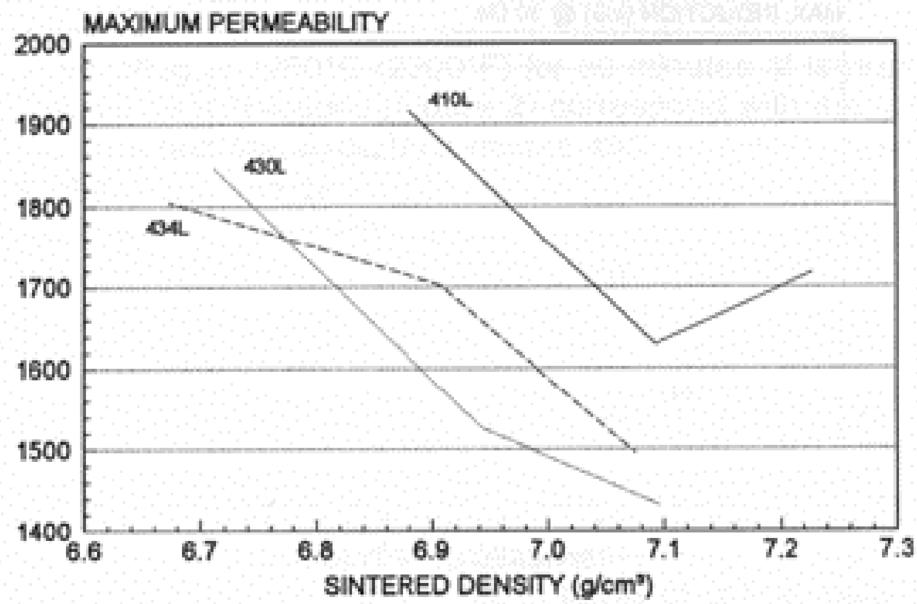

FIGURE 5: MAXIMUM PERMEABILITY FOR VARIOUS STAINLESS STEEL GRADES COMPACTED WITH 1% LITHIUM STEARATE AND SINTERED AT 1260°C FOR 30 MINUTES IN HYDROGEN

during sintering. It is important to note that these parts were sintered in production furnaces that are used to process materials in a cost effective manner. The results suggest that increased gas flow in the furnace may help to eliminate this phenomenon. Even still, the results - if not the trends with sintered density - indicate that all three 400-series alloys can be processed to meet the requirements of most magnetic applications.

TABLE III
Sintered Chemistry Results for Various Materials Compacted with 1% Lithium Stearate and Sintered at 1260°C for 30 Minutes In Hydrogen

Material Type	Compaction Pressure (tsi)	Carbon Wt.%	Oxygen Wt.%	Nitrogen Wt.%
410L	30	0.005	0.11	0.0022
	40	0.004	0.13	0.0055
	50	0.007	0.16	0.0066
430L	30	0.006	0.11	0.0033
	40	0.005	0.13	0.0038

	50	0.009	0.17	0.0120
434L	30 40 50	0.007 0.005 0.006	0.12 0.18 0.20	0.0021 0.0072 0.0140

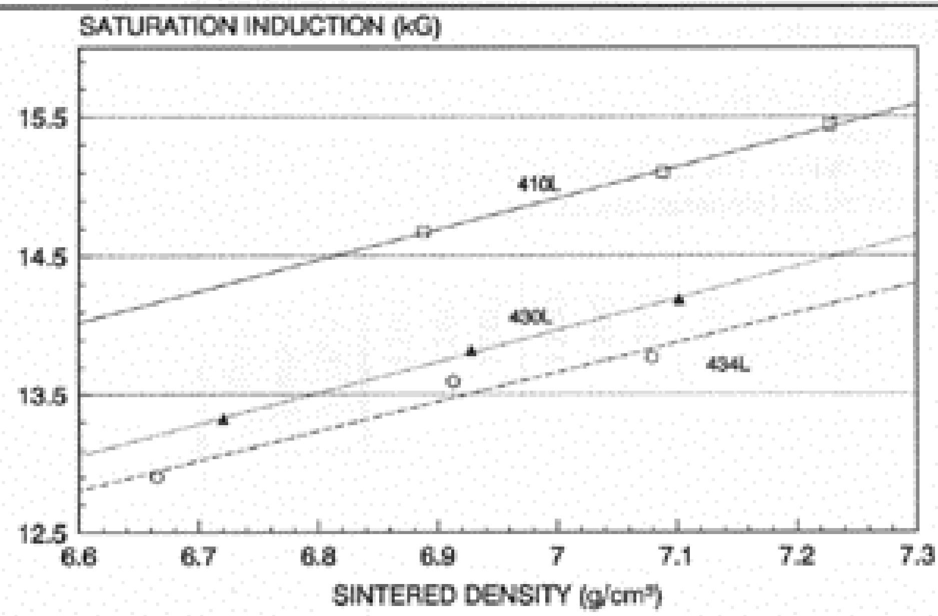

FIGURE 6: SATURATION INDUCTION OF VARIOUS MATERIALS COMPACTED WITH 1% LITHIUM STEARATE AND SINTERED AT 1260°C FOR 30 MINUTES IN HYDROGEN

Figure 6 illustrates the effect of sintered density and material type on the saturation induction. All three materials show approximately straight line relationships. As expected, additional alloy content lowers the saturation induction level. Lower density has the same effect, lowering the saturation induction of a given material.

Effect of Sintering Temperature and Density

Interest in the effect of sintering temperature on the properties of P/M stainless steels has resulted in the generation of a significant amount of literature. The growth in usage of 410L warrants a close look at this critical processing variable. Table IV lists the sintered density and properties of 410L with 1 % lithium stearate compacted at 30, 40, and 50 tsi and sintered in pure hydrogen at 1260°C (2300°F) for 30 minutes at temperature. Figure 7 indicates the effect of sintering temperature on the sintered density of 410L. Increasing the sintering temperature clearly results in higher sintered densities. The higher sintered density translates to a corresponding increase in maximum induction as measured at 30 oersteds (Figure 8). Raising the sintering temperature also results in improved maximum induction for a given sintered density. This result indicates that permeability improvements attributed to higher sintering temperatures can result in higher maximum induction levels at a given field strength.

Coercive force and maximum permeability (Figures 9 and 10) are improved with in-creases in sintering temperature. There is a significant difference in the property levels between the sample sintered at 1120°C (2050°F) and the sample sintered at 1200°C (2200°F). Clearly, the higher sintering temperature levels provided better property levels, although there is a less marked difference between 1260°C (2300°F) and 1200°C (2200°F). The chemical analysis reveals decreasing interstitial levels with higher sintering temperatures (Table V). The samples sintered at 1120°C (2050°F) indicate especially high levels of carbon and oxygen.

Higher sintering temperatures clearly impacted the sintered density and interstitial levels of the samples. This explains the relatively poor magnetic properties at the low temperature condition. These results add support to the belief that stainless steels should be sintered at temperatures as high as possible, practical, and economical.

TABLE IV
sintered Densities and Magnetic Properties for Ancor 410L Compacted with 1% Lithium Stearate and Sintered for 30 Minutes in Hydrogen

Compaction Pressure (tsi)	Sintering Temperature (°C)	Sintered Density (g/cm^3)	H_{c-15} (Oe)	B_{max-15} (kG)	B_{r-15} (kG)	μ_{max}	H_{c-30} (Oe)	B_{max-30} (kG)	B_{r-30} (kG)
30	1260	6.88	1.60	10.26	6.54	1916	1.60	11.66	6.62
40	1260	7.09	1.96	10.68	6.18	1630	1.95	12.24	6.19
50	1260	7.22	1.92	10.86	6.83	1717	1.92	12.62	6.98
30	1200	6.60	1.62	9.36	7.20	1946	1.62	10.57	7.18
40	1200	6.88	1.89	9.64	6.38	1600	1.90	11.31	6.54
50	1200	7.07	2.20	9.20	5.31	1253	2.24	11.37	5.48
30	1120	6.16	2.56	5.77	3.22	645	2.85	7.59	3.64
40	1120	6.55	2.62	6.34	3.49	695	2.86	8.70	3.93
50	1120	6.80	2.65	7.36	4.03	802	2.82	9.78	4.46

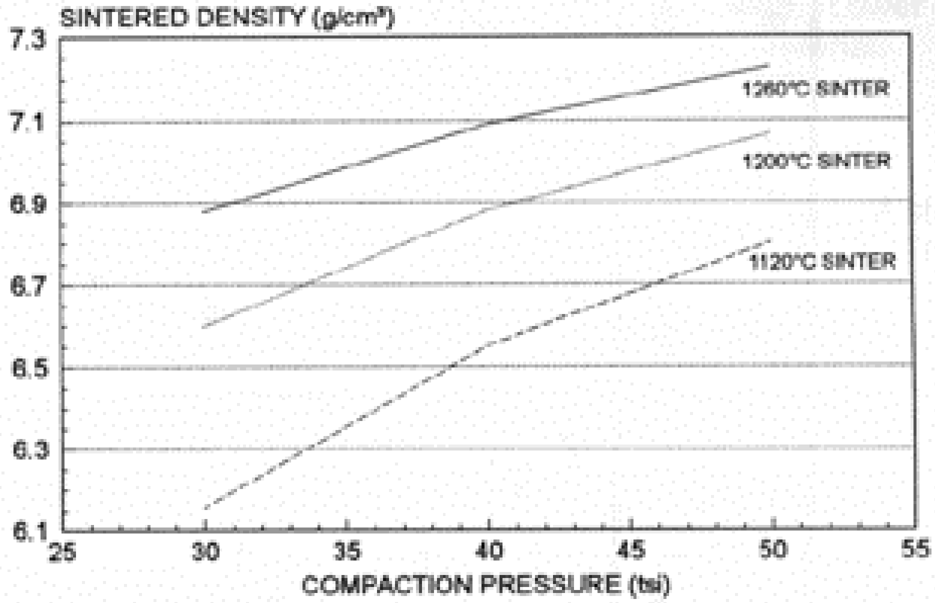

FIGURE 7: SINTERED DENSITY OF 410L COMPACTED WITH 1% LITHIUM STEARATE AND SINTERED FOR 30 MINUTES IN HYDROGEN AT VARIOUS TEMPERATURES

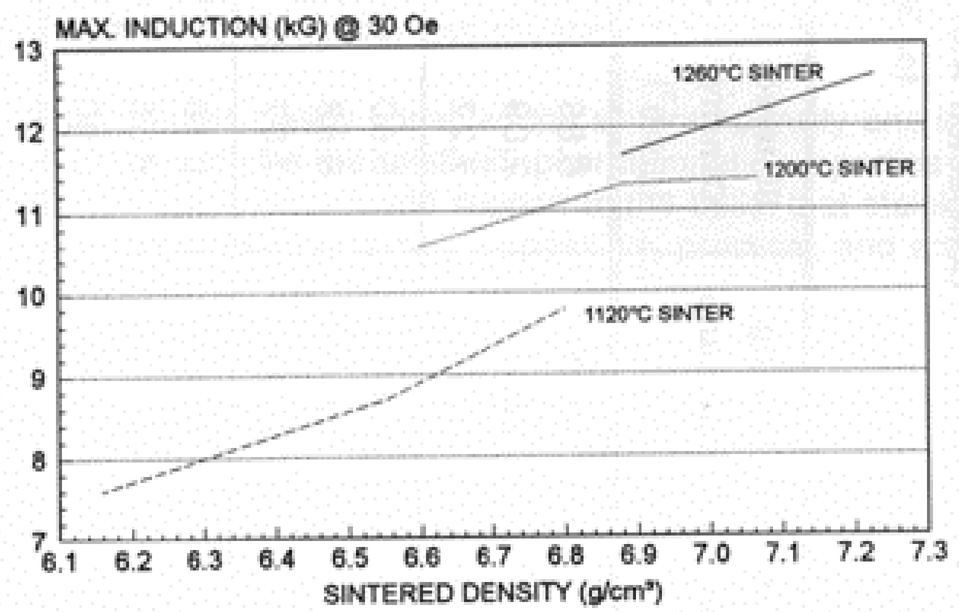

FIGURE 8: MAXIMUM INDUCTION OF 410L COMPACTED WITH 1% LITHIUM STEARATE AND SINTERED FOR 30 MINUTES IN HYDROGEN AT VARIOUS TEMPERATURES

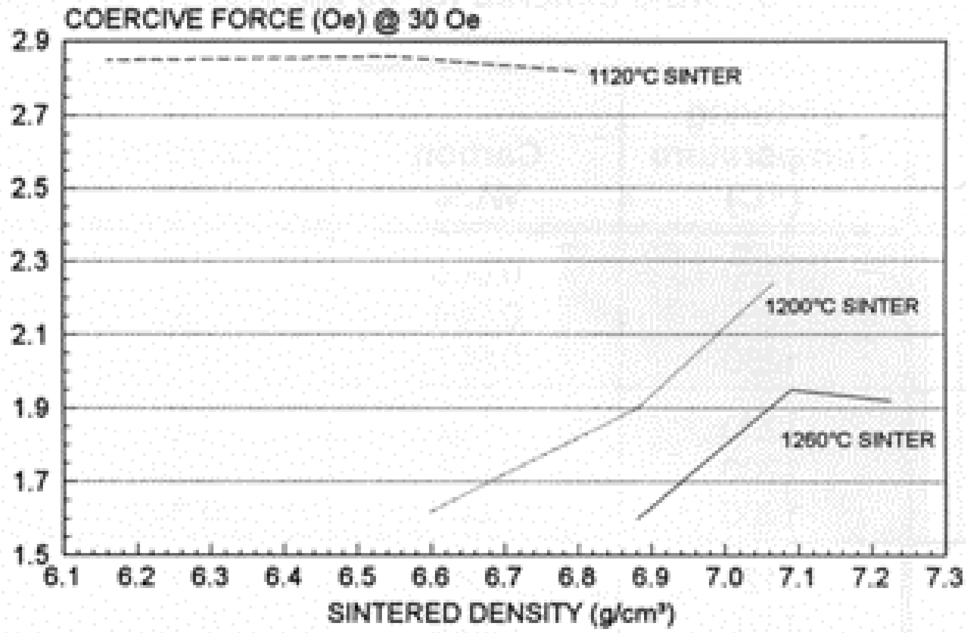

FIGURE 9: COERCIVE FORCE OF 410L COMPACTED WITH 1% LITHIUM STEARATE AND SINTERED FOR 30 MINUTES IN HYDROGEN AT VARIOUS TEMPERATURES

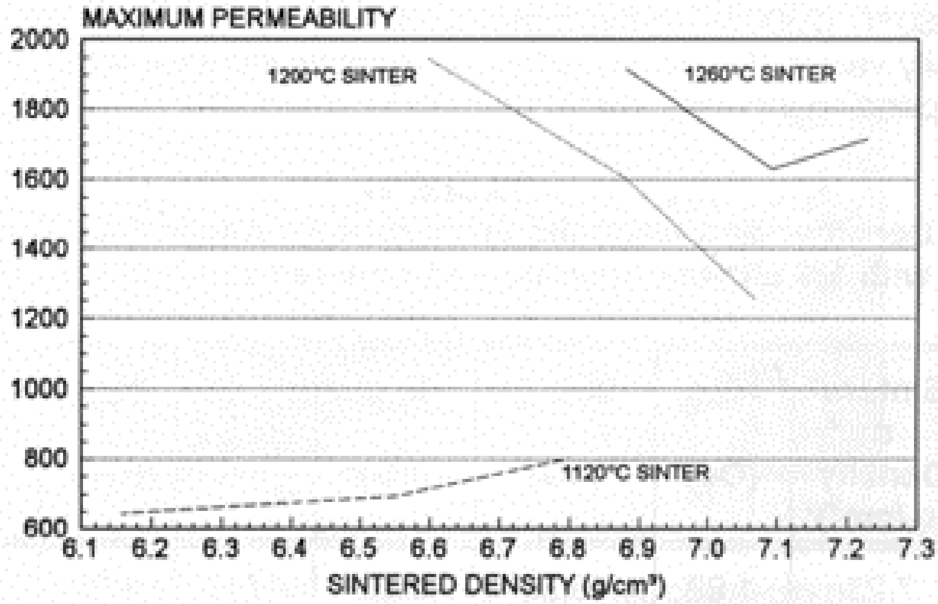

FIGURE 10: MAXIMUM PERMEABILITY OF 410L COMPACTED WITH 1% LITHIUM STEARATE AND SINTERED FOR 30 MINUTES IN HYDROGEN AT VARIOUS TEMPERATURES

TABLE V
Sintered Chemistry Results for Ancor 410L with
1% Lithium Stearate Sintered for 30 Minutes in Hydrogen

Compaction Pressure (tsi)	Sintering Temperature (°C)	Carbon Wt.%	Oxygen Wt.%	Nitrogen Wt.%
30	1260	0.005	0.11	0.0022
40	1260	0.004	0.13	0.0055
50	1260	0.007	0.15	0.0066
30	1200	0.009	0.12	0.0020
40	1200	0.008	0.18	0.0028
50	1200	0.007	0.19	0.0050
30	1120	0.045	0.16	0.0079
40	1120	0.029	0.18	0.0096
50	1120	0.025	0.16	0.0087

Effect of Sintering Time

It is widely understood that increasing sintering time will have a positive impact on critical physical properties of P/M parts such as elongation and strength. The effect of lengthened sintering cycles on magnetic properties is investigated in this study. Table VI lists the results of 410L containing 1% lithium stearate compacted at 50 tsi and sintered at 1260°C (2300°F) in hydrogen for 30 and 60 minutes at temperature. Sintered density values (Figure 11) reflect a moderate increase with a lengthened cycle. A corresponding increase in maximum induction is also noted (Figure 12).

TABLE VI
Sintered Densities and Magnetic Properties for Ancor 410L Compacted at 50 tsi with 1% Lithium Stearate and Sintered at 1260°C in Hydrogen.

Sintering Time (min.)	Sintered Density (g/cm^3)	H_{c-15} (Oe)	B_{max-15} (kG)	B_{r-15} (kG)	μ_{max}	H_{c-30} (Oe)	B_{max-30} (kG)	B_{r-30} (kG)
30	7.23	1.92	10.86	6.83	1717	1.92	12.62	6.96
60	7.29	1.68	11.47	7.69	2166	1.67	13.07	7.78

Even more substantial is the improvement in coercive force and maximum permeability (Figures 13 and 14) due to increased time at temperature. The improvement in properties, especially permeability, is beyond those anticipated considering the

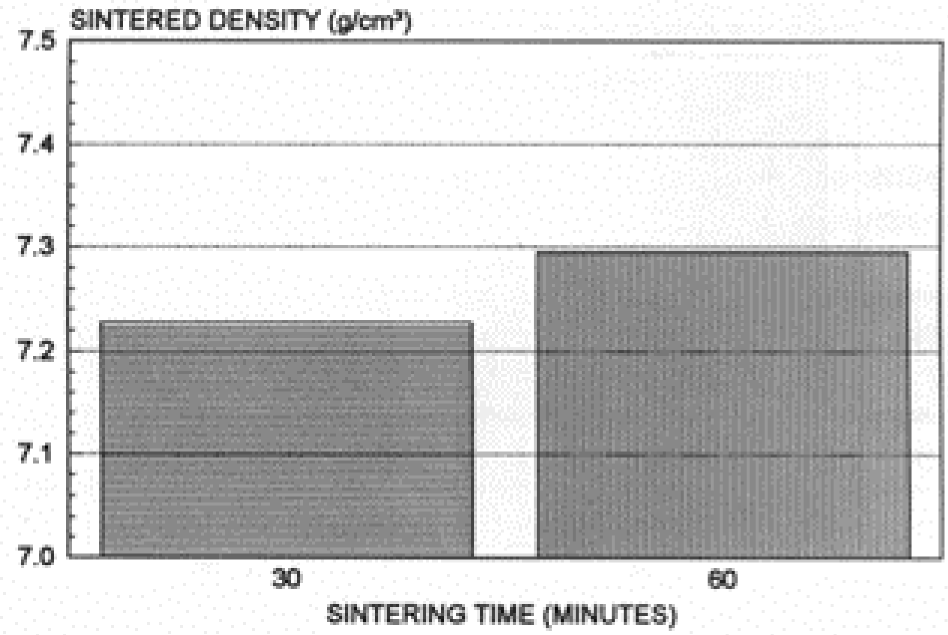

FIGURE 11: SINTERED DENSITY OF 410L COMPACTED AT 50 tsi WITH 1% LITHIUM STEARATE AND SINTERED AT 1260°C IN HYDROGEN FOR 30 AND 60 MINUTES

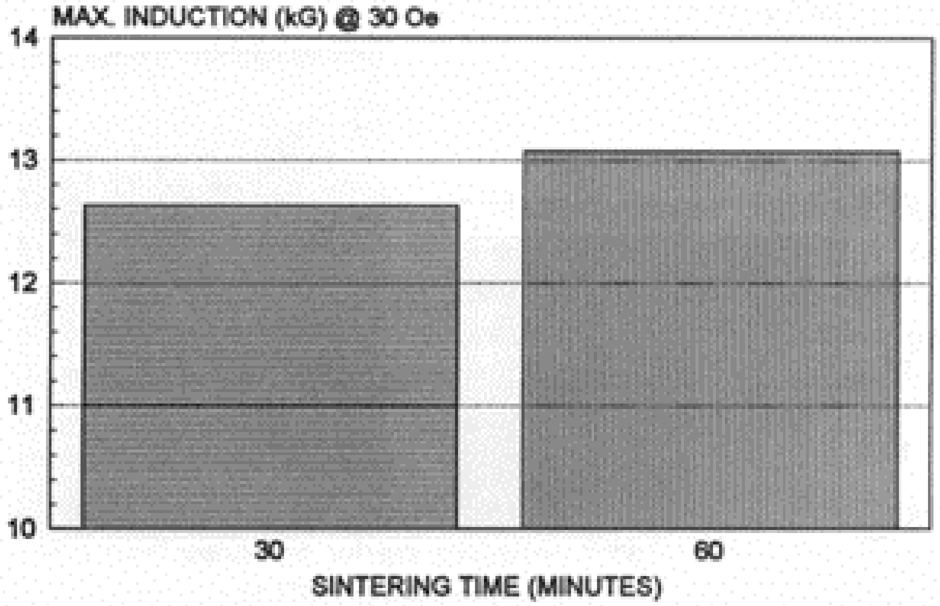

FIGURE 12: MAXIMUM INDUCTION FOR 410L COMPACTED AT 50 tsi WITH 1% LITHIUM STEARATE AND SINTERED AT 1260°C IN HYDROGEN FOR 30 AND 60 MINUTES

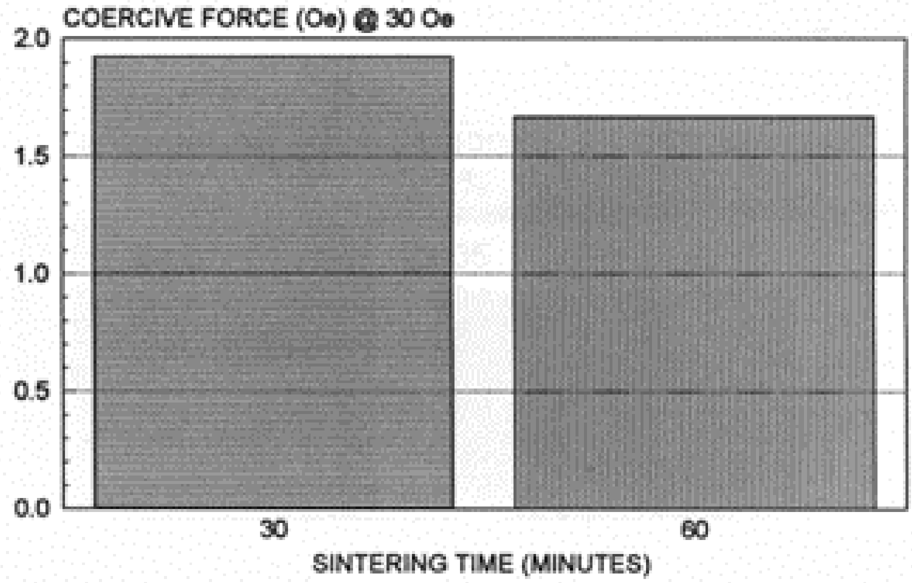

FIGURE 13: COERCIVE FORCE OF 410L COMPACTED AT 50 tsi WITH 1% LITHIUM STEARATE AND SINTERED AT 1260°C IN HYDROGEN FOR 30 AND 60 MINUTES

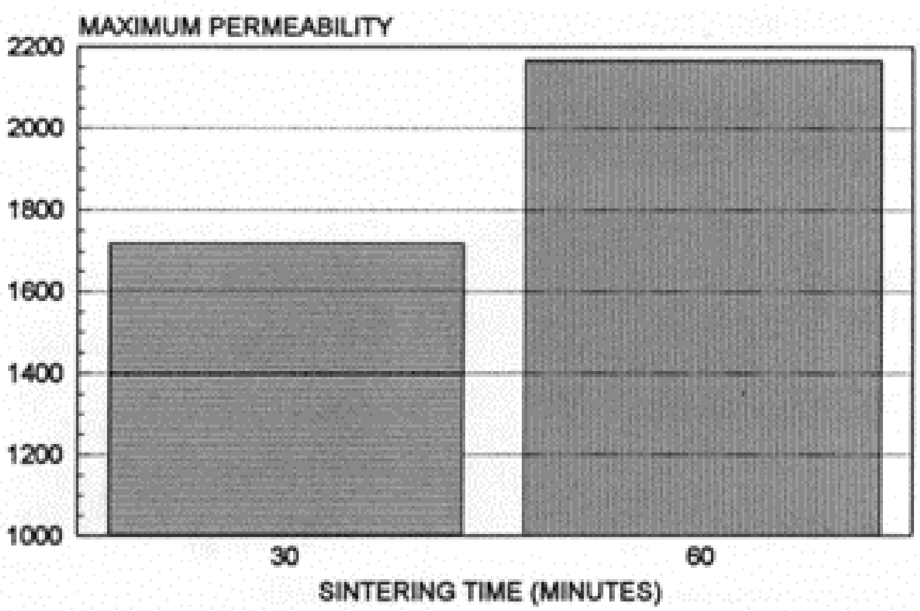

FIGURE 14: MAXIMUM PERMEABILITY OF 410L COMPACTED AT 50 tsi WITH 1% LITHIUM STEARATE AND SINTERED AT 1260°C IN HYDROGEN FOR 30 AND 60 MINUTES

relatively small increase in sintered density. Enhancement of these structure-related magnetic properties is the result of oxide reduction, grain growth, pore rounding, as well as densification. Chemical analysis (Table VII) helps to explain the magnetic property enhancement, as the level of nitrogen and carbon is far lower in the samples sintered for 60 minutes than in those sintered for 30 minutes.

TABLE VII
Sintered Chemistry Results for Ancor 410L Compacted at 50 tsi with 1% Lithium Stearate and Sintered at 1260°C in Hydrogen

Sintering Time (min.)	Carbon Wt.%	Oxygen Wt.%	Nitrogen Wt.%
30	0.007	0.16	0.0066
60	0.004	0.16	0.0059

Effect of Sintering Atmosphere

The use of atmospheres other than pure hydrogen or vacuum in sintering high quality stainless steel parts has been examined in depth. In processing for optimal magnetic performance, use of atmospheres other than hydrogen or vacuum has been shown to be inferior. However, market pricing pressures and the need for cost controls warrant the investigation and comparison of alternative atmospheres and their effects on the magnetic properties of 410L. Table VIII lists the sintered density and magnetic properties of 410L with 1% lithium stearate compacted at 50 tsi and sintered for 30 minutes at 1260°C (2300°F) in a variety of atmospheres.

The synthetic dissociated ammonia (75% H_2/25% N_2) atmosphere produced a slightly lower density value than pure hydrogen (Figure 15). However, the 10% H_2/90% N_2 atmosphere proved to be far worse, with significantly lower sintered density and extremely low maximum induction (Figure 16). Even the synthetic D.A. maximum induction value represents a serious decline relative to that of the hydrogen sintered material. These results are not surprising, since previous work in this area generated similar results, virtually eliminating the use of nitrogen-bearing atmospheres for the sintering of magnetic stainless steel parts.

Coercive force and permeability values (Figures 17 and 18) also indicate a significant reduction in magnetic performance when sintering in nitrogen-containing atmospheres. Sintered chemistry results (Table IX) explain the cause of the property degradation to be retained nitrogen. A six-fold increase in nitrogen content (hydrogen versus D.A.) results in almost a four-fold decrease in permeability and a near doubling of coercive force at 30 oersteds. Nitrogen, oxygen and carbon levels determined in the 10% H_2/90% N_2 sintered samples are unacceptably high as reflected by the poor magnetic properties.

TABLE VIII
Sintered Density and Magnetic Properties for Ancor 410L Compacted at 50 tsi with 1% Lithium Stearate and Sintered at 1260°C for 30 Minutes

Sintering Atmosphere	Sintered Density (g/cm^3)	H_{c-15} (Oe)	B_{max-15} (kG)	B_{r-15} (kG)	μ_{max}	H_{c-30} (Oe)	B_{max-30} (kG)	B_{r-30} (kG)	Saturation Induction (kG)
H_2	7.23	1.92	10.86	6.83	1717	1.92	12.62	6.98	15.43
75% H_2/25% N_2	7.16	2.93	5.13	2.58	4.82	3.49	7.91	3.22	15.36
10% H_2/90% N_2	6.70	15.30	0.51	0.09	231	11.59	2.28	9.86	14.16

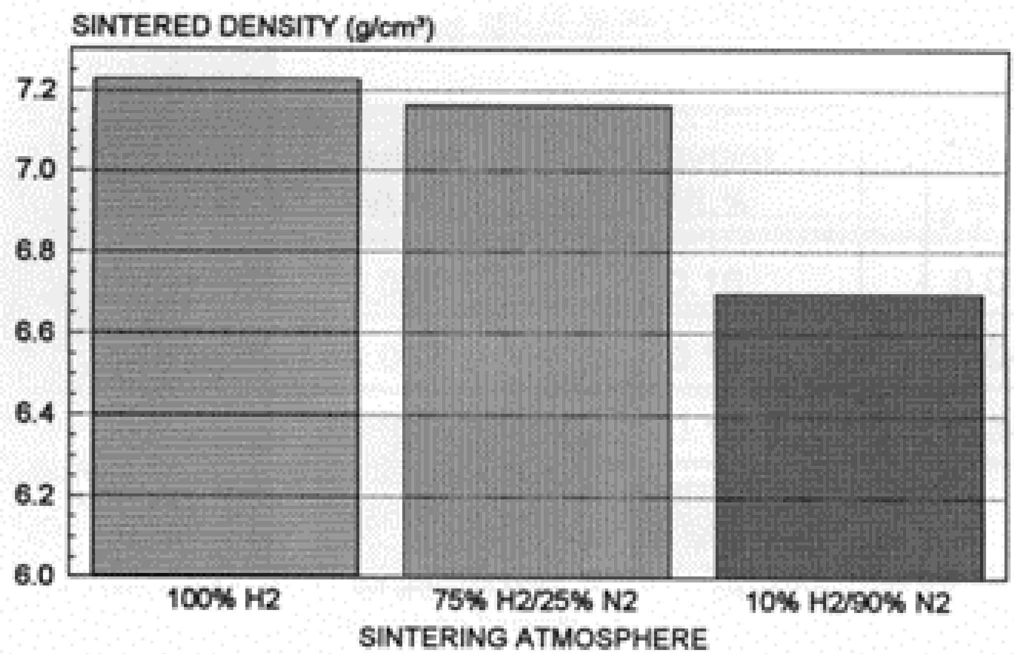

FIGURE 15: SINTERED DENSITY OF 410L COMPACTED AT 50 tsi WITH 1% LITHIUM STEARATE AND SINTERED AT 1260°C FOR 30 MINUTES IN VARIOUS ATMOSPHERES

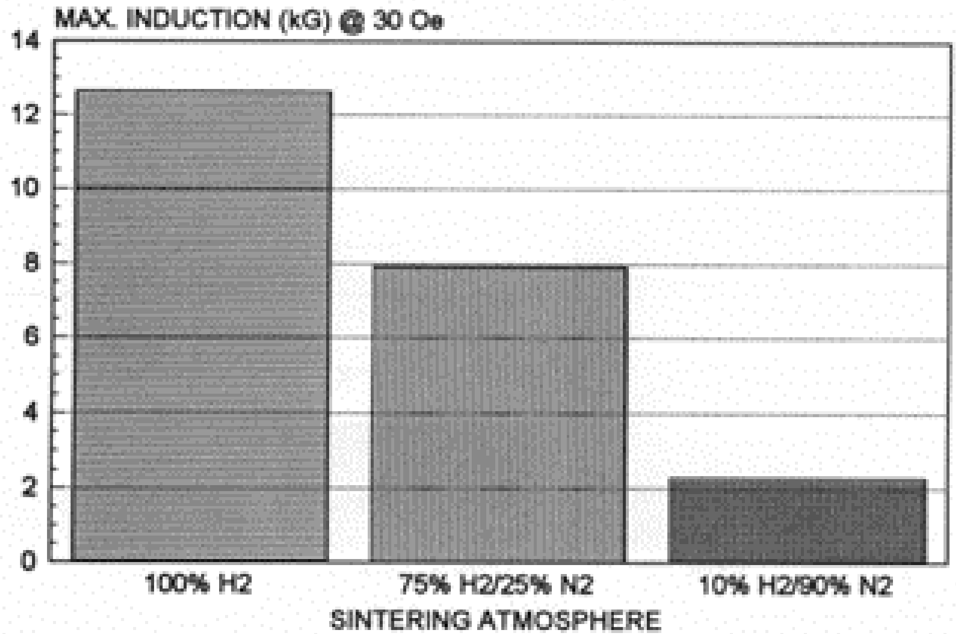

FIGURE 16: MAXIMUM INDUCTION FOR 410L COMPACTED AT 50 tsi WITH 1% LITHIUM STEARATE AND SINTERED AT 1260°C FOR 30 MINUTES IN VARIOUS ATMOSPHERES

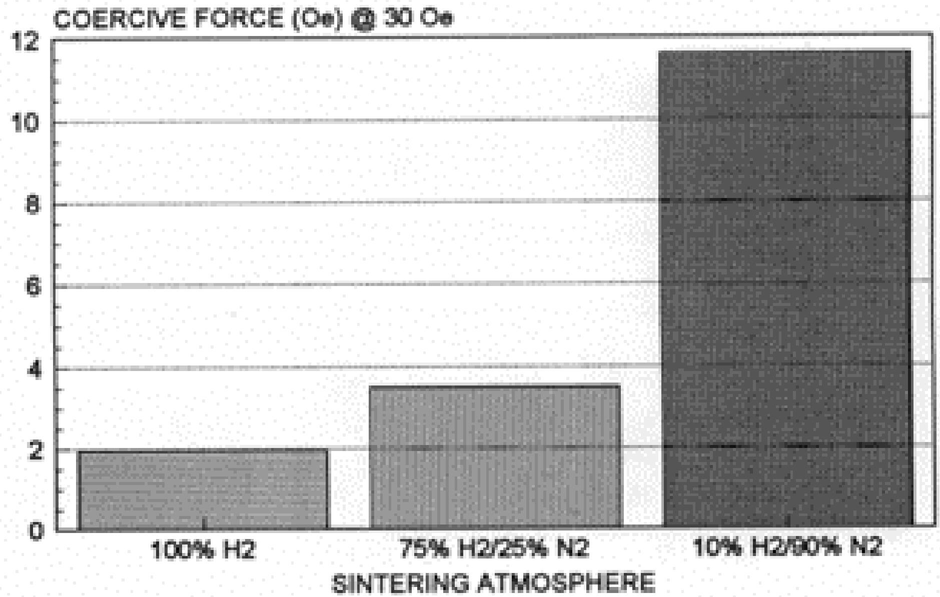

FIGURE 17: COERCIVE FORCE OF 410L COMPACTED AT 50 tsi WITH 1% LITHIUM STEARATE AND SINTERED AT 1260°C FOR 30 MINUTES IN VARIOUS ATMOSPHERES

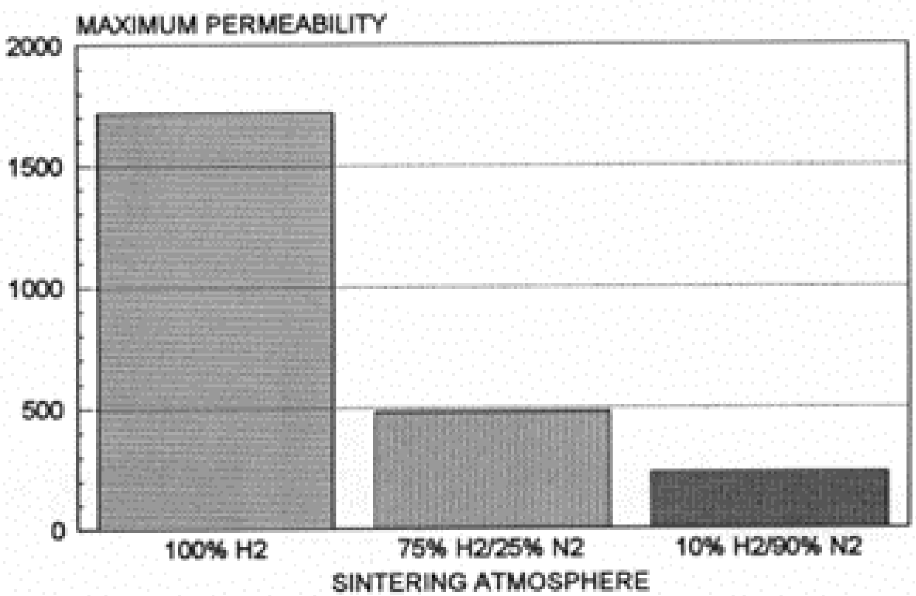

FIGURE 18: MAXIMUM PERMEABILITY OF 410L COMPACTED AT 50 tsi WITH 1% LITHIUM STEARATE AND SINTERED AT 1260°C FOR 30 MINUTES IN VARIOUS ATMOSPHERES

TABLE IX
Sintered Chemistry Results for Ancor 410L Compacted at 60 tsi with 1% Lithium Stearate and Sintered at 1260°C for 30 Minutes

Sintering Atmosphere	Carbon Wt.%	Oxygen Wt.%	Nitrogen Wt.%
H_2	0.007	0.16	0.0066
75% H_2/25% N_2	0.007	0.15	0.0430
10% H_2/90% N_2	0.025	0.19	0.3800

Figure 19 presents the saturation induction as a function of sintered density for the 410L material sintered in several atmospheres. It is interesting to note that a plot of data points for each atmosphere illustrates an excellent correlation between part density and saturation induction for a given material. While it has been demonstrated that the presence of interstitial elements greatly affects structure-related magnetic properties such as coercive force and permeability, there is no effect on saturation induction values.

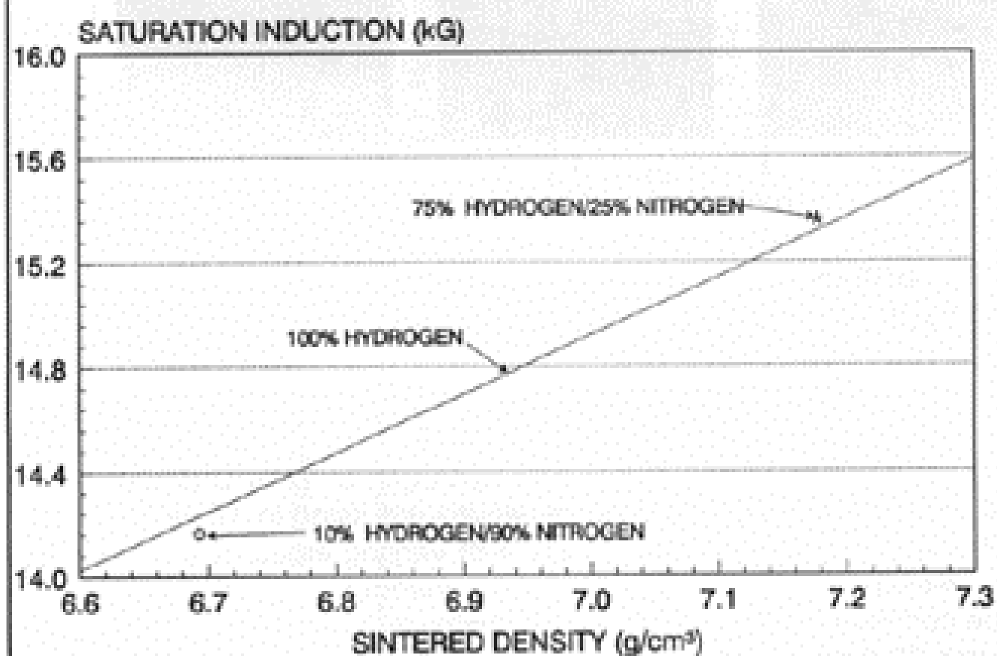

FIGURE 19: SATURATION INDUCTION OF 410L COMPACTED AT 50 tsi WITH 1% LITHIUM STEARATE AND SINTERED AT 1260°C FOR 30 MINUTES IN VARIOUS ATMOSPHERES

<u>Effect of Lubricant Content</u>

Lubricant additions might be considered a necessary "evil" in the processing of stainless steel P/M parts. Stainless steels typically exhibit poor pressing characteristics and therefore can require as much as 2.0% lubricant content by weight to ensure smooth ejection from the die. During sintering, the lubricant must be removed completely to ensure part performance. In order to determine the potential effects of varying lube contents on magnetic properties, samples of 410L were prepared with 0.75%, 1.0% and 1.25% lithium stearate and were compacted at 50 tsi. The effect of increased lithium stearate content on green density is minimal (Figure 20).

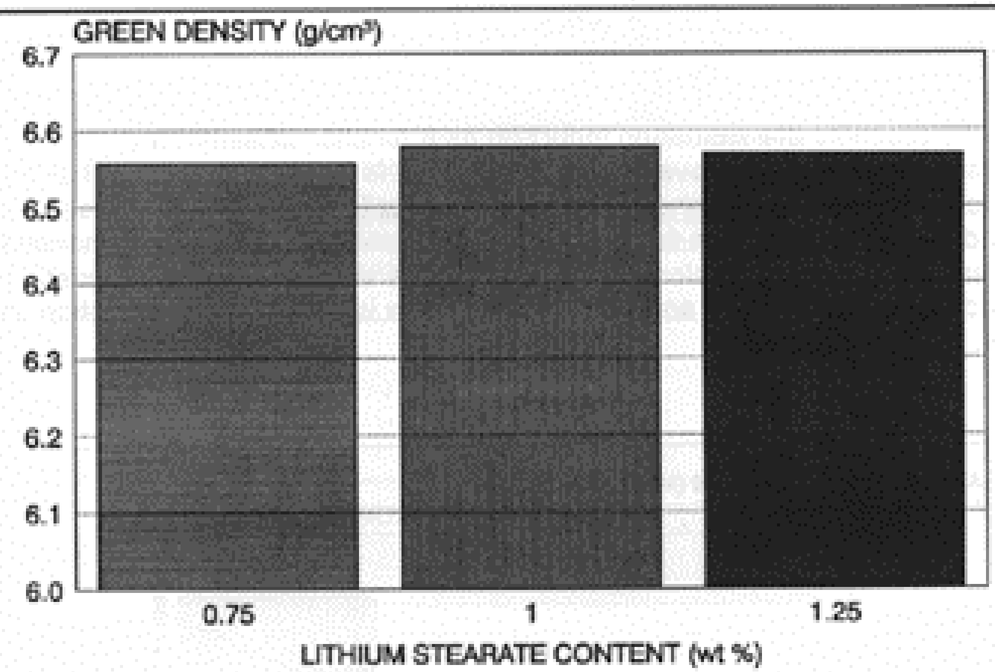

FIGURE 20: GREEN DENSITY OF 410L COMPACTED AT 50 tsi WITH VARIOUS LEVELS OF LITHIUM STEARATE

The samples were sintered for 30 minutes in pure hydrogen at 1260°C (2300°F). The resulting sintered density and magnetic property values are listed in Table X. There is no significant impact on sintered density with varying amounts of lithium stearate (Figure 21). Likewise, the results indicate minor changes in magnetic properties from different lube contents, as the lowest level exhibits only marginally better magnetic response (Figures 22 through 24). A sintered chemistry comparison (Table XI) helps to explain the slight difference in magnetic properties, as the 0.75% lubricant level sample contains less nitrogen and oxygen than the higher lubricant levels.

TABLE X

Sintered Densities and Magnetic Properties for Ancor 410L Compacted at 50tsi and Sintered at 1260°C for 30 Minutes in Hydrogen

Lubricant Type	Lubricant Level (%)	Sintered Density (g/cm^3)	H_{c-15} (Oe)	B_{max-15} (kG)	B_{r-15} (kG)	μ_{max}	H_{c-30} (Oe)	B_{max-30} (kG)	B_{r-30} (kG)
Lithium Stearate	0.75	7.21	1.82	10.55	6.61	1768	1.83	12.22	6.66
Lithium Stearate	1.00	7.23	1.92	10.86	6.83	1717	1.92	12.62	6.98
Lithium Stearate	1.25	7.21	1.92	10.68	6.72	1718	1.92	12.27	6.78

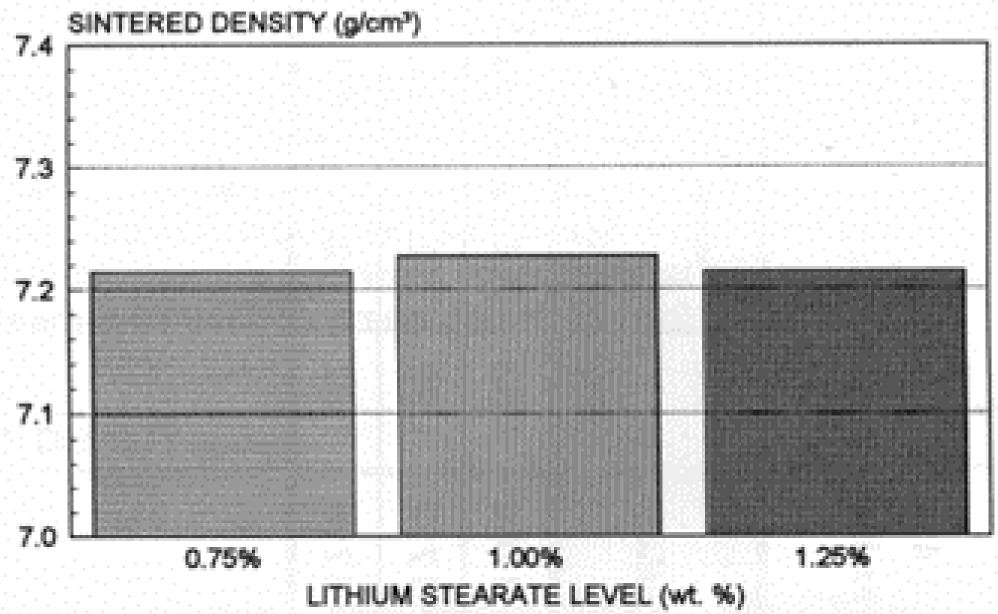

FIGURE 21: SINTERED DENSITY OF 410L COMPACTED AT 50 tsi WITH VARIOUS LITHIUM STEARATE LEVELS AND SINTERED AT 1260°C FOR 30 MINUTES IN HYDROGEN

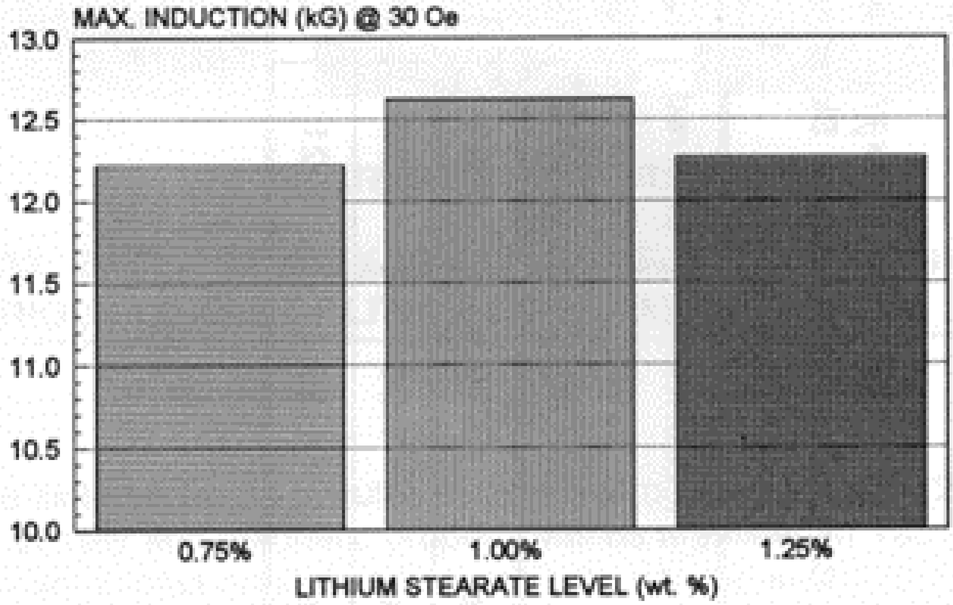

FIGURE 22: MAXIMUM PERMEABILITY OF 410L COMPACTED AT 50 tsi WITH VARIOUS LITHIUM STEARATE LEVELS AND SINTERED AT 1260°C FOR 30 MINUTES IN HYDROGEN

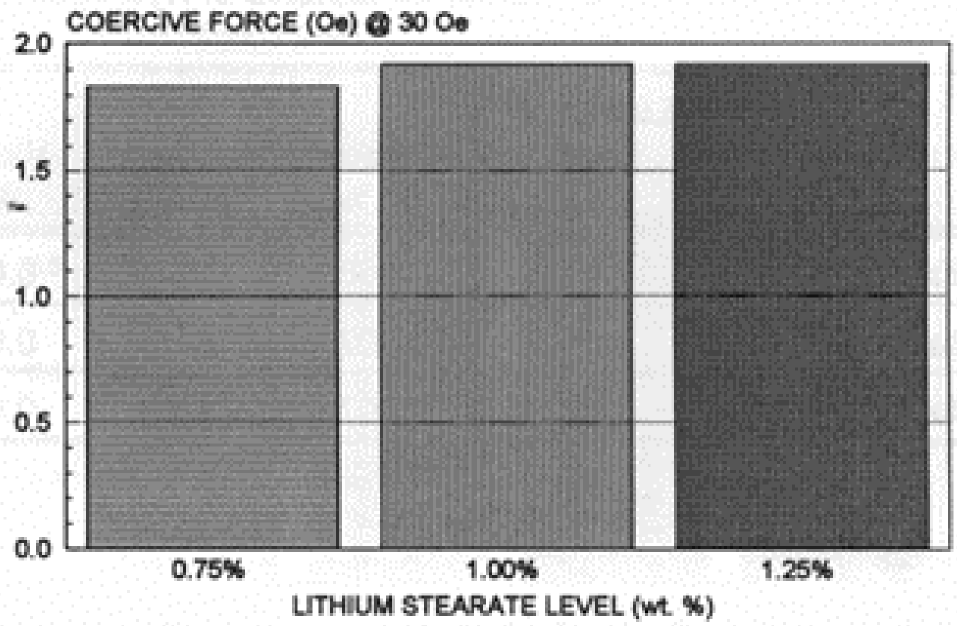

FIGURE 23: COERCIVE FORCE OF 410L COMPACTED AT 50 tsi WITH VARIOUS LITHIUM STEARATE LEVELS AND SINTERED AT 1260°C FOR 30 MINUTES IN HYDROGEN

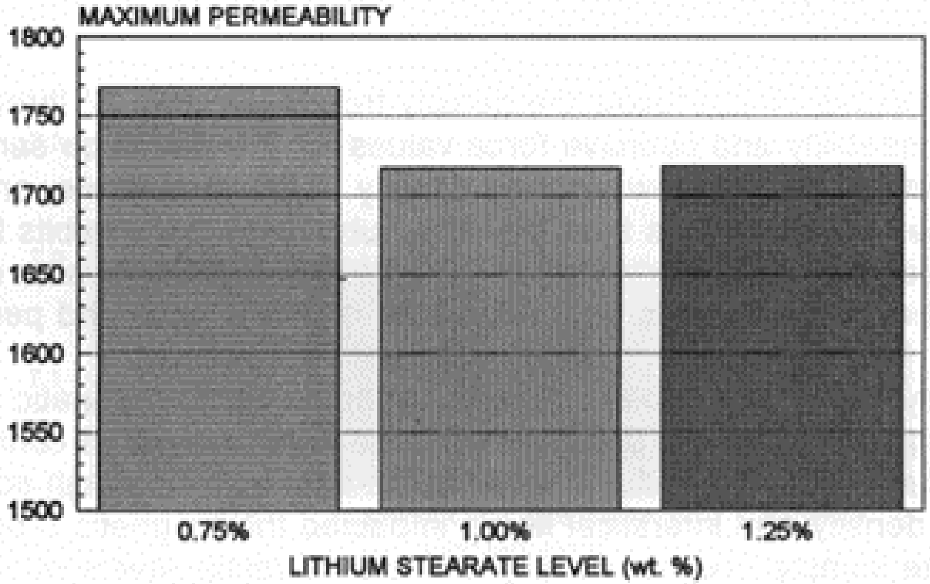

FIGURE 24: MAXIMUM PERMEABILITY OF 410L COMPACTED AT 50 tsi WITH VARIOUS LITHIUM STEARATE LEVELS AND SINTERED AT 1260°C FOR 30 MINUTES IN HYDROGEN

TABLE XI
Sintered Chemistry Results for Ancor 410L Compacted at 50 tsi and Sintered at 1260°C for 30 Minutes In Hydrogen

Lubricant Type	Lubricant Level	Carbon Wt.%	Oxygen Wt.%	Nitrogen Wt.%
Lithium Stearate	0.75	0.006	0.14	0.0058
Lithium Stearate	1.00	0.007	0.16	0.0060
Lithium Stearate	1.25	0.007	0.16	0.0067

Effect of Lubricant Type

As a means of studying the effects of lubricant type on magnetic properties, samples of 41 OL were mixed with 1% each of lithium stearate, Acrawax, zinc stearate, and Kenolube and compacted at 50 tsi. Green density measurements are illustrated in Figure 25. Lithium stearate affords the highest green density while the others are essentially equivalent. After being sintered at 1260°C (2300°F) in pure hydrogen for 30 minutes, sintered density and magnetic properties were determined for each of the samples

(Table XII). Sintered density values continue to indicate the superiority of lithium stearate for maximized density (Figure 26). However, the Kenolube sintered density is worth noting because of its significantly lower value in relation to the Acrawax and zinc stearate (which, though lower than lithium stearate, remain on an even level).

Magnetic test results do not follow the density trends (Figures 27 through 29). The maximum permeability and coercive force values for the Kenolube sample are the best, in spite of its relatively low sintered density. Lithium stearate, on the other hand, achieved higher density values than the other lube types but exhibits the worst magnetic properties. The Acrawax and zinc stearate demonstrate similar magnetic performance, with the former exhibiting slightly better coercive force and permeability.

Chemical analysis listed in Table XIII explains the excellent magnetic properties of the Kenolube sample. Low levels of oxygen, nitrogen and carbon all contribute to the enhancement of magnetic properties. However, it appears as though some factor other than sintered density and interstitial levels impacted the magnetic properties of the lithium stearate sample. Higher density and low interstitial levels would seem to imply correspondingly good magnetic properties but this clearly is not the case with the lithium stearate sample.

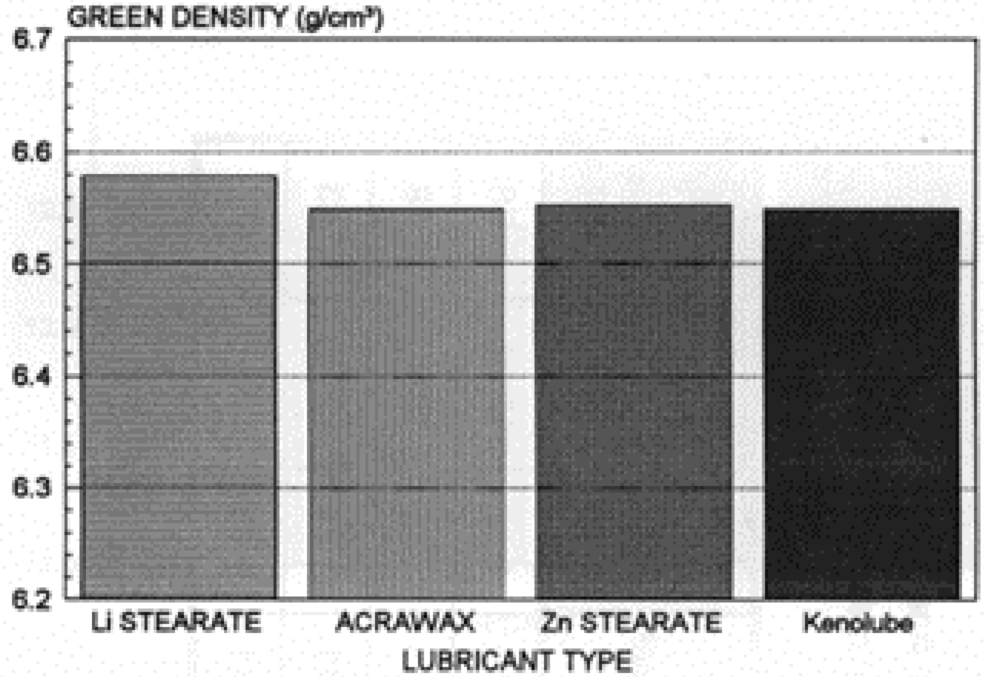

FIGURE 25: GREEN DENSITY OF 410L COMPACTED AT 50 tsi WITH 1% OF VARIOUS LUBRICANT TYPES

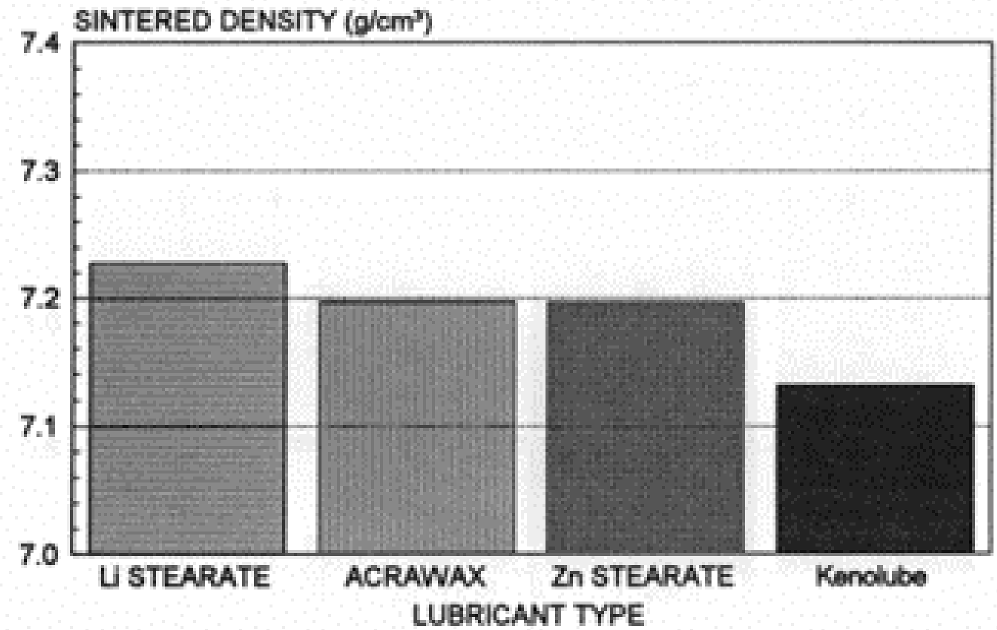

FIGURE 26: SINTERED DENSITY OF 410L COMPACTED AT 50 tsi WITH 1% OF VARIOUS LUBRICANT TYPES AND SINTERED AT 1260°C FOR 30 MINUTES IN HYDROGEN

TABLE XII
Sintered Densities and Magnetic Properties of Ancor 410L Compacted at 50 tsi and Sintered at 1260°C for 30 Minutes in Hydrogen

Lubricant Type	Sintered Density (g/cm^3)	H_{c-15} (Oe)	B_{max-15} (kG)	B_{r-15} (kG)	μ_{max}	H_{c-30} (Oe)	B_{max-30} (kG)	B_{r-30} (kG)
Lithium Stearate	7.23	1.92	10.86	6.83	1717	1.92	12.62	6.98
Acrawax	7.20	1.75	10.99	7.14	1983	1.75	12.43	7.18
Zinc Stearate	7.20	1.79	11.07	7.16	1941	1.81	12.96	7.43
Kenolube	7.13	1.70	11.99	7.39	2111	1.71	12.96	7.60

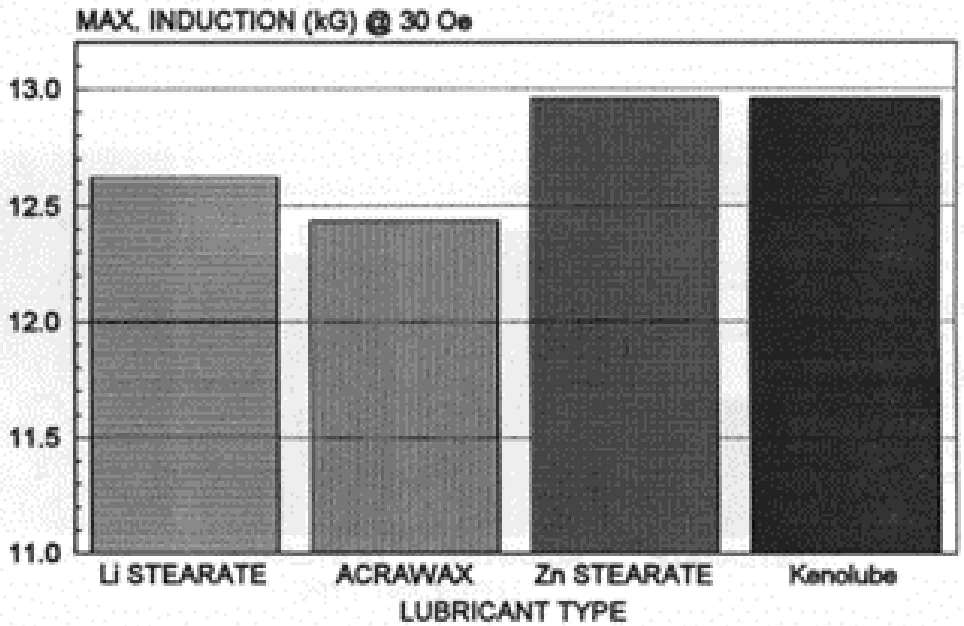

FIGURE 27: MAXIMUM INDUCTION FOR 410L COMPACTED AT 50 tsi WITH 1% OF VARIOUS LUBRICANTS AND SINTERED AT 1260°C FOR 30 MINUTES IN HYDROGEN

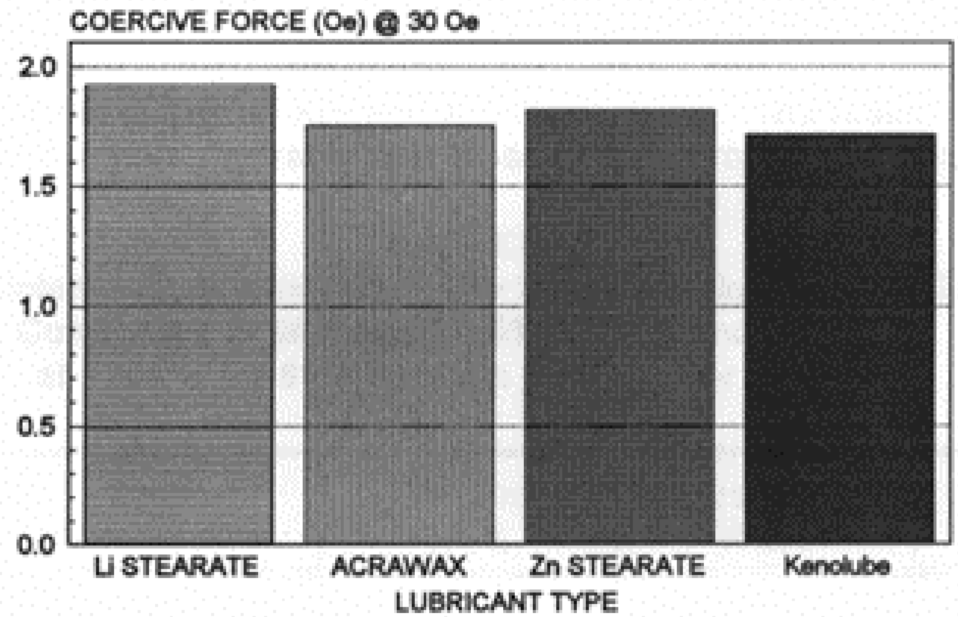

FIGURE 28: COERCIVE FORCE FOR 410L COMPACTED AT 50 tsi WITH 1% OF VARIOUS LUBRICANT TYPES AND SINTERED AT 1260°C FOR 30 MINUTES IN HYDROGEN

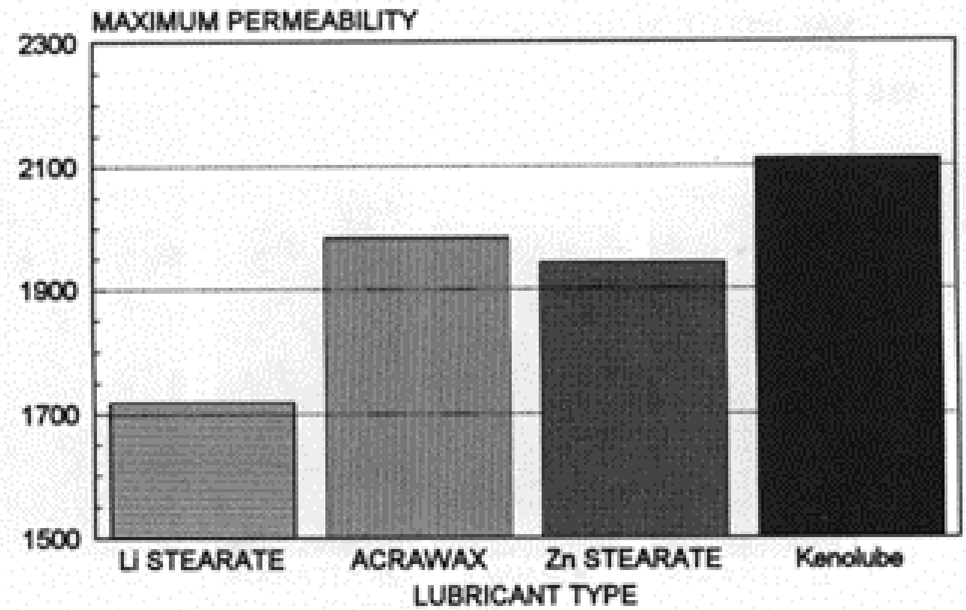

FIGURE 29: MAXIMUM PERMEABILITY OF 410L COMPACTED AT 50 tsi WITH 1% OF VARIOUS LUBRICANT TYPES AND SINTERED AT 1260°C FOR 30 MINUTES IN HYDROGEN

TABLE XIII
Sintered Chemistry Results for Ancor 410L Compacted at 50 tsi with 1% of Various Lubricants and Sintered at 1260°C for 30 Minutes in Hydrogen

Lubricant Type	Carbon Wt.%	Oxygen Wt.%	Nitrogen Wt.%
Lithium Stearate	0.007	0.16	0.0066
Acrawax	0.005	0.14	0.0072
Zinc Stearate	0.010	0.18	0.0070
Kenolube	0.006	0.13	0.0054

DISCUSSION

Many of the chemical analyses provided in this document exhibit interstitial levels that might be somewhat higher than expected. It must be noted, however, that no special considerations were taken in the de-lube, hot zone, and cooling cycles to ensure extraordinary results. Rather, the materials were processed according to acceptable, economically viable practice for achieving high density stainless steel parts with necessary magnetic performance.

As a point of reference, a recent round robin study was conducted in an effort to prepare an ASTM P/M ferritic stainless steel specification. Three powder suppliers provided samples of 410L and 434L and several stainless steel parts fabricators manufactured magnetic specimens in order to establish typical capability levels for mechanical, chemical and magnetic properties. Mean values for chemistry levels and magnetic properties are listed in Tables XIV and XV, respectively. The results generated in the present study compare favorably with those from the round robin study.

Table XIV
Mean Sintered Chemistry Results for Various Stainless Steel Grades Compacted at 50 tsi with 0.5% PM100 and Sintered at 1260°C for 60 Minutes in Hydrogen or Vacuum

Powder Grade	Powder Manufacturer	Carbon Wt.%	Oxygen Wt.%	Nitrogen Wt.%
410L	A	0.0116	0.1719	0.0262
410L	B	0.0095	0.3119	0.0331
410L	C	0.0573	0.2398	0.0154
434	A	0.0058	0.2117	0.0257
434	C	0.0138	0.2736	0.1149

Table XV
Mean Magnetic Property Results for Various Stainless Steel Grades Compacted at 50 tsi with 0.5% PM100 and Sintered at 1260°C for 60 Minutes In Hydrogen or Vacuum

Powder Grade	Powder Manufacturer	B_{max-15} (kG)	B_{r-15} (kG)	μ_{max}	H_{c-15} (Oe)
410L	A	10.800	8.900	2100	2.0
410L	B	10.000	8.100	1400	2.9
410L	C	10.700	8.800	1800	2.2
434	A	9.700	8.000	1700	2.1
434	C	9.900	8.100	1700	2.1

In the current study, all hydrogen sintered test specimens are of sufficient magnetism to meet and exceed the requirements of the ABS tone wheel. Separate de-lube in air, use of higher hydrogen flow rates, and faster cooling rates could have had a substantial effect on lowering carbon, oxygen and nitrogen levels and thereby improving magnetic properties. However, the intent of this study was to analyze the real world capability with respect to magnetic performance by simulating the P/M work place.

Regarding material selection, the major factors not addressed in this study were corrosion resistance and physical properties. Obviously, there is need for a similar study in these areas, especially as P/M ferritic stainless steels receive further consideration for applications demanding corrosion resistance such as automotive engine sensors. It is entirely conceivable that more highly alloyed materials, such as 430L and 434L, could supplant 410L in some applications on the basis of corrosion resistance.

The results generated by the study suggest that 400-series powder metallurgy stainless steel grades can provide excellent magnetic properties if good processing practices are utilized. The results approach coercive force and maximum permeability values for iron parts processed in traditional manners. Although the price of stainless steel is higher than that of iron or iron-phosphorus alloys, part costs must be balanced versus performance requirements. The extra corrosion resistance afforded by the stainless steels may be required by a specific part application. It is also evident from the study that more cost effective processing routes can yield acceptable magnetic properties as long as the requirements of the application are well defined and understood. As mentioned above, no attempt has been made by this study to evaluate the effect on physical or corrosion properties that the more cost effective processing approach may have.

CONCLUSIONS

This study provides some answers and suggests some key areas of concern regarding the processing of P/M 400-series stainless steels for magnetic applications. It also identifies areas requiring further examination, providing targets for future research of the subject.

The following may be concluded from the study:

1) There is a definite relationship between part density and maximum induction. Higher densities impart higher induction values.

2) Carbon, nitrogen and oxygen have a detrimental effect on structure-related magnetic properties such as coercive force and permeability.

3) 410L exhibits superior processability and magnetic performance and therefore is the preferred ferritic P/M alloy for magnetic applications requiring corrosion resistance.

4) Increasing the sintering cycle time improves magnetic

properties, especially permeability, through increased part density and minimizing detrimental interstitial constituents.

5) Increasing the sintering temperature improves magnetic properties in the same manner as does a longer sintering cycle. Sintering at 1120°C (2050°F) produces exceptionally poor magnetic properties.

6) Nitrogen-containing atmospheres produce parts with unacceptably low magnetic properties. Of the sintering atmospheres selected for this study, only pure hydrogen is recommended for magnetic applications.

7) Saturation induction is a function of alloy content and density while permeability and coercive force are affected primarily by structure and purity.

8) Varying the lubricant content between 0.75% and 1.25% does not substantially affect magnetic properties.

9) Lithium stearate affords higher density levels to 410L but has a detrimental effect on magnetic properties.

10) Kenolube has a positive impact on structure-related magnetic properties though it does not facilitate high part density.

ACKNOWLEDGMENTS

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