PROPERTIES OF HEAT TREATED P/M ALLOY STEELS

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ABSTRACT

Further development of ferrous P/M technology into highly stressed applications will require the development of P/M steels with mechanical properties approaching those of cast or wrought products.

The P/M process offers many routes to improve mechanical properties through alloy design, increased density and high temperature sintering. The paper will present the results of a study into the effects of density and composition upon the microstructure and properties of quenched and tempered P/M alloy steels.

INTRODUCTION

The research work described in this paper was prompted by several customer requests for a P/M alloy steel of high apparent hardness, 45-50 HRC, and high density, 7.3 to 7.4 g/cm^{3}· Normally, such properties would be produced by a double pressing and sintering process. However, it was considered that the additional presintering and repressing operations would make the P/M route economically uncompetitive. The potential part also required some machining after sintering. The machining operations thus prevented further development of "sinter-hardening" systems previously described[m] that came close to meeting the property targets.

It was decided to explore the possibilities of attaining the property targets by single compaction and sintering followed by heat treatment to form tempered martensite of high hardness.

PRINCIPLES OF PROGRAM

The primary aims of the program were to attain the highest possible green, and hence sintered, density at commercially practical compaction pressures and to introduce alloys that produce high strength and hardness. Unfortunately, these requirements are contradictory. The hardness of martensites depends principally upon their carbon content(2~ with the exception of precipitation-hardening steels. Thus, the hardness requirement dictates a high carbon content. Unfortunately, high graphite contents reduce attainable green density~3'4'5~· In effect, the low specific gravity constituents in a premix, such as graphite, occupy space in the green compact that should be occupied by iron.

Ideally, these problems could be overcome through the use of liquid-phase sintering to increase density through shrinkage. However, the practical iron-phosphorous carbon systems do not develop high hardnesses. Iron-copper-graphite systems develop relatively high hardness but they tend to grow on sintering so as to reduce density and properties.

The program thus explored the properties of P/M steels produced from premixes, employing low alloy steel powders to which nickel and graphite were admixed as alloying elements.

Low Alloy Matrix

Two prealloyed steel powders, ~Ancorsteel® 4600V and Ancorstee185HP were employed as the premix base.

~Ancnrateel i.q a rAnisternal trademark of Hoeoaoaes CorDoration

I/4, DL.C I. II.~UIIII,,IU~IUUII UI I.UW /-~IlUy OLCCI rUVVU~IO

A4600V	0.55	0.18	1.85
A85HP	0.85	0.15	-

The nickel-molybdenum prealloy is widely used in the production of high strength heat treated P/M parts. However, the 0.85% molybdenum prealloy possesses significantly higher compressibility.

Nickel

Prealloyed nickel tends to reduce compressibility but nickel enhances strength and hardenability once dissolved in the matrix. Mixes were made with 2%-contained and 4%-contained nickel by a combination of prealloy and elemental additions. Nickel (both prealloyed and admixed) also tends to promote shrinkage during sintering and could provide some further density and property improvement.

Graphite

Graphite was admixed at 0.25, 0.50 and 0.75 wt.%. It was thought that the lowest level would promote increased green density. Higher levels would increase matrix hardness but reduce green density.

Carbon Potential

In view of the need to heat treat following sintering, the possibility of introducing carbon and nitrogen from the heat treatment atmosphere was explored with the 0.25% graphite materials. If successful, this carbonitriding treatment could significantly increase apparent hardness.

Lubricant Content

A lubricant content of 0.5% was employed. This was a compromise between the need for lubrication during compaction and ejection and the ideal of zero lubricant content for maximum green density.

The test materials were produced using the 2ANCORBOND°t6.7.m process to improve die fill and reduce both dusting and segregation. Areas deficient or rich in admixed nickel could reduce hardness compared to the overall matrix. The ANCORBOND process has also been shown to function efficiently in high density parts production.

EXpERIMENTAl,. pROCEDURE

A series of 500-pound test premixes was prepared using the ANCORBOND process. The premix compositions shown in Table II were designed to assess the influence of alloy steel matrix, nickel addition and graphite content upon the green density, sintered density, hardness and mechanical properties of the test materials.

The sintered chemistry of the test materials is shown in Table II.

The manganese, molybdenum and nickel contents were measured by optical emission spectrometry. Carbon content was determined by LECO carbon analyzer using samples from the heat treated test pieces.

Test Piece Preparation

The test pieces for determination of mechanical properties were pressed by Remington Powder Metal Products.

Tensile properties were measured using test pieces of 0.25-inch diameter, conforming to ASTM E8 for wrought steels, machined from sintered impact blanks. This test piece is located within the testing grips by machined threads. It almost eliminated the problems of gripping under load and premature failure observed with heat treated high strength P/M steels. The test method and data may be compared directly with that for wrought steels. Charpy impact testing was performed using un-notched test pieces as shown in ASTM E-23. Test pieces were compacted at pressures of 30, 40 and 50 tsi to determine the effect of density upon mechanical properties. Test piece densities were measured by the immersion technique, following MPIF Standard 42, 1985-6 edition on impregnated sections cut from the impact test pieces.

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Sinterina Conditions

Test pieces were sintered in a production pusher furnace with conditions indicated below:

Sintering Temperature:	2050°F
Time at Temperature:	45 minutes
Atmosphere:	80% nitrogen/20% DA
Dewpoint:	-25oC (-13°F)

Heat Treatment Conditions

The test pieces were heat treated using conditions indicated below, that have previously produced good combinations of strength and hardness in P/M nickel-molybdenum steels. The current program did not attempt to determine the effects of other austenitizing or

tempering conditions upon the materials tested.

Carbonitriding 1575OF 20
Minutes
Oil
Quenching
Endothermic with 3% Ammonia
0.90%
Oil at 150°F 350OF 2 Hours

Carbon Potential

The test pieces with 0.50 and 0.75% graphite were austenitized in atmospheres of 0.50 and 0.75% carbon content potentials, respectively, to maintain their carbon content. The materials with 0.25% graphite were carbonitrided at a carbon potential of 0.90%.

Testina

Tensile testing was performed using a Tinius Olsen testing machine at a crosshead speed of 0.025 in./min. The Charpy test pieces were broken on a Baldwin impact test machine. Hardness measurements were made using a Wilson hardness tester.

Austenitizing Temperature:	1575OF 30
Austenitizing Time:	Minutes
Atmosphere:	Endothermic
Carbon Potential:	0.50%, 0.75%
Quenchant:	Oil at 150°F
Tempering Temperature:	350OF 2
Tempering Time:	Hours

MetallograDhy

Sections for metallographic examination were cut from the tensile and impact test pieces compacted at 50 tsi. Quantitative metallography was conducted on selected test pieces to determine the distribution of microstructural phases using a point-count technique. The metallographic preparation and point-count procedure are described in Reference 9.

RESULTS

The aim of the program was to examine the influence of material design in achieving high heat treated hardness. A specific goal was to attain a heat treated hardness of 45-50 HRC in a single compacted material. The results, presented in Table III, show that the test materials developed hardnesses up to 48 HRC when compacted at 50 tsi.

Density-

The premix compositions, particularly those based upon the 0.85% molybdenum steel, attained high green density (Figure 1) and consequently high heat treated densities (Figure 2). For test materials employing the nickel-molybdenum prealloy, heat treated density increased from 6.6 g/cm^{a} when compacted at 30 tsi to 7.1 g/cm^{3} when compacted at 50 tsi. Test materials made with the 0.85% molybdenum prealloy possessed higher densities. Their heat treated density increased from 6.8 g/cm^{3} to 7.3 g/cm^{3} with increasing compaction pressure.

MetallooraDhy

The test materials possessed microstructures consisting largely of tempered martensite with discrete light etching areas. These austenitic nickel-rich areas appeared to increase in frequency with increasing nickel additions. They were almost completely absent (Table IV) in the nickel-molybdenum prealloy (Figure 3), but most frequent in the 0.85% molybdenum prealloy with a 4% nickel addition (Figure 4). At higher magnifications, the microstructures of materials containing 0.5% graphite consisted of uniform fine tempered martensite (Figures 5-8). The matrix of tempered martensite contained fine white etching retained austenite, between martensite needles, that may be more prevalent in the materials of higher nickel content (Figures 6 and 8) and of higher carbon content.

The carbonitrided materials possessed generally similar microstructures consisting of a tempered martensite matrix that contained discrete nickel-rich areas. However, the martensite in the core of the carbonitrided materials appeared more "lath"-like (Figure 9) than in the quenched and tempered materials. It is possible that the carbonitrided materials contained more retained austenite, particularly close to their surface (Figure 10). This surface layer may have contained some fine carbides.

The qualitative findings were partially confirmed by the results of the quantitative examination shown in Table IV for the quenched and tempered materials.

TABLE IV
Quantitative Metallography of Q & T Materials Compacted at 50 tsi

Nickel Addition (%)	0	0	2	2	2	2	4	4
Graphite (%)	0.5	0.75	0.5	0.75	0.5	0.75	0.5	0.75
Phase (%)								
Tempered Martensite	89.09	90,54	87.98	89.01	88.33	88.86	86.76	85.0
Nickel-Rich Austenite	0.66	0.71	2.27	2.74	2.42	2.64	4.24	6
Porosity	10.25	8.75	9.75	8.25	9.25	8.50	9.00	5.94
								9.00

The data indicate a progressive increase in the area of the nickel-rich austenite phase with increasing admixed nickel content. It is believed that these consist of a nickel-rich "core" surrounded by a region of iron-nickel-carbon retained austenite. The results do not include the very fine retained austenite in the martensite matrix.

Mechanical Prooertie~

The test materials developed excellent combinations of strength and hardness in the quenched and tempered condition (Figures 10, 11, 12). For the nickel-molybdenum prealloy (Figure 10), the highest tensile strengths were obtained with 0.5% graphite content increasing from approximately 120,000 psi when compacted at 30 tsi to approximately 185,000 psi when compacted at 50 tsi. Increasing graphite content increased hardness but reduced tensile strength at a given green compaction pressure. The maximum hardness of 46 HRC was obtained with material C that contained no admixed nickel.

The properties of the materials based upon the 0.85% molybdenum prealloy showed similar trends (Figure 11) but were superior to those of the nickel-molybdenum prealloy. The highest tensile strengths were developed in the materials containing 0.5% graphite. Increasing compaction pressure fi-om 30 to 50 tsi increased heat treated tensile strength from approximately 140 to approximately 200,000 psi while hardness increased from approximately 33 to approximately 43 HRC. Increasing graphite content from 0.5 to 0.75% increased hardness but reduced tensile strength at a given compaction pressure. In the molybdenum prealloy, the maximum hardness of 47.5 HRC was attained with addition of 2% nickel and 0.75% graphite but ultimate tensile strength was approximately 145,000 psi.

The properties of the carbonitrided materials were between those of the 0.50% graphite and 0.75% graphite systems (Figure 12). At a compaction pressure of 30 tsi, the carbonitrided materials possessed hardnesses of approximately 35 HRC and tensile strengths of approximately 110,000 psi. Increasing compaction pressure to 50 tsi increased hardness to about 45 HRC and ultimate tensile strength to approximately 150,000 psi.

In the carbonitrided condition, the materials based upon the 0.85% molybdenum prealloy possessed superior properties to those based upon the nickel-molybdenum prealloy. For both prealloys, increasing nickel content from 2% to 4% increased the tensile strength at a given hardness level, but reduced the maximum hardness attained. The carbonitrided molybdenum prealloy containing 2% admixed nickel developed the maximum apparent hardness of approximately 47.5 HRC.

DISCUSSION

The review above indicates that the program attained its goal of achieving hardnesses in excess of 45 HRC in both quenched and tempered and carbonitrided conditions. Heat treated tensile strengths (in excess of 200,000 psi) above those of double pressed and sintered materials, were produced in the materials made with the 0.85% molybdenum prealloy by single compaction processing. The development program also confirmed the possibility of attaining high apparent hardness by carbonitriding sintered compacts of low carbon content. The program showed that the materials possessed a wide range of properties. The interaction of factors such as prealloy base, nickel content, graphite addition and density is discussed below.

Density

The results confirm that the hardness, ultimate tensile strength and impact energy of all materials increase with increasing density. The results showed clearly that the increased compressibility of the molybdenum prealloy produced compacts of higher green density (Figure 1). The test results confirmed that increasing graphite content from 0.25 to 0.75% reduced the maximum density attained (Figure 13) in both prealloys. The reduction in density at 50 tsi was most apparent in the materials made with the 0.85% molybdenum prealloy.

Increasing nickel content from 2 to 4% by admixing tends to increase green density slightly (Figure 13). Under the sintaring and heat treatment conditions used, increasing admixed nickel by 2% increased the final density of the 0.25% graphite, carbonltrided materials. This may be due to an increased content of retained austenite in the materials and slightly greater shrinkage on sintering. The lower green density of the higher graphite materials did not translate to consistently lower heat treated densities.

The final measured density of the heat treated test materials depended upon their composition, microstructure and porosity. In an attempt to clarify these factors, the "pore-free" density of impact test pieces compacted at 30 tsi was measured using a Micromeritics Pycnometer. The results, in Table V, indicate that the "pore-free" density of the heat treated test materials varied from 7.71 g/cm^3 to 7.79 g/cm^3.

The ~pore-fi'ee" densities measured by the pycnometer can be used to convert measured densities to relative densities, then to redraw compressibility curves. These curves of relative density versus compaction pressure (Figure 14) confirm the higher compressibility of the molybdenum prealloy that should produce improved properties.

They also show that admixed nickel increased relative density at 30 and 40 tsi but had no benefit at 50 tsi. Increasing graphite from 0.5 to 0.75% reduced measured density but had little effect on relative density. However, the carbonitrided materials developed higher relative density than the quenched and tempered materials.

The relative density of a P/M material strongly influences its properties. Ideally, the mechanical properties of the heat treated P/M steels should be compared at the same relative density to separate the effects of porosity from microstructure. The compressibility curves show that the test materials attained 90% relative densities at practicable compaction pressures. For the materials tested, a measured density of 7.0 g/cm^3 is reasonably close to 90% relative density (Table VI) and was used to compare properties.

TABLE VI: Calculated 90% Relative Density of Heat Treated Materials

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0.25	6.97	6.97	6.98	7.01
0.50	6.96	6.96	6.99	7.01
0.75	6.94	6.95	6.98	7.01

It is considered that errors from this assumption should be close to experimental error for the density levels and properties measured in the development program.

Hardness

The aim of the program, to achieve heat treated hardness in excess of 45 HRC was attained. The results showed that high hardness could be attained at high carbon content, particularly in the 0.85% molybdenum steels and by carbonitriding. The hardnesses of the test materials was determined by density, compaction pressure and prealloy base as discussed below.

Hardness Quenched and Temoered Materi~ls

The apparent hardness of the test materials is determined largely by graphite content and sintered density (Figure 15). This could be anticipated given their similar microstructures.

When compared at a fixed compaction pressure of 40 tsi, the higher compressibility of the 0.85% molybdenum prealloy increases apparent hardness by approximately 3 HRC. When compacted at 40 tsi, increasing graphite increases the hardness of the 2% nickel materials by 5 HRC but has less effect in the 4% nickel materials (Table VII).

Increasing nickel content from 2 to 4% had little effect upon materials with 0.5% graphite content but reduced the hardness of materials with 0.75% graphite in both prealloys.

It appears from the microstructure that much of the increased nickel content is present in nickel-rich areas and may also produce an increased retained austenite content. The negative effects of increased nickel content upon quenched and tempered microstructure and hardness are more apparent when the materials are compared at a fixed density of 7.0 g/cm^3 (Table VIII).

TABLE VIII
Effect of Composition on Hardness (HRC) at 7.0 g/cm$^{=}$

Nickel-Molybdenum Prealloy

Molybdenum Prealloy

ilililiNilCl(elililCOh!eht!ili(%)!iiiiii

			0.75	
0.50	37.3	36.5		
			38.3	35.4
0.75	42.9	40.6	42.0	39.4
0.50				

This removes the generally beneficial effects of admixed nicke} on density. It is clear that increasing nickel content from 2 to 4% reduces the hardness of quenched and tempered alloys at both graphite contents. This is very noticeable in the 0.85% molybdenum prealloy, in which all nickel was admixed and is presumably more difficult to dissolve. When compared at fixed density, it appears that the 2% nickel alloys attain similar hardness whether the nickel is prealloyed or admixed. Thus, in commercial parts production, the 0.85% prealloy plus 2% nickel would prove superior due to its significantly higher density at equivalent compaction pressure.

Hardness of Carbonitrided Materials

The carbonitriding process produced materials of high apparent hardness. Hardness increased with increasing density (Figure 16) from approximately 35 HRC at 6.7 g/cm^{a} to 46 HRC at 7.3 g/cm$^{a\cdot}$ The apparent hardness of the carbonitrided materials was influenced by both the low alloy base powder and admixed nickel content.

When compared at fixed compaction pressure, the materials based upon the molybdenum prealloy possessed higher hardnesses than the equivalent material made with the nickel-molybdenum prealloy. Increasing nickel content from 2 to 4% reduced the apparent hardness of the carbonitrided materials slightly (Table IX).

The relative effects of alloying elements, upon properties of the carbonitrided materials at a density of 7.0 g/cm^{3,} were somewhat different from the quenched and tempered alloys.

The data indicate that when compared at fixed density, the carbonitrided nickel-molybdenum prealloys possess slightly higher apparent hardness than the molybdenum prealloys (Table X). Increasing nickel content from 2 to 4% reduces apparent hardness.

TABLE X
Effect of Composition on Hardness (HRC) of Carbonitrided Materials at 7.0 g/cm^3

2	43.5	42.6
4	41.1	38.8

Comoarison of Carbonitrided and Quenched and Tempered Hardness

The results indicate that carbonitriding test pieces prepared from materials with 0.25% graphite addition produced apparent hardness equivalent to quenching and tempering of the 0.75% graphite materials. Thus, the aim of developing high hardness in a material of iow sintered carbon content was achieved (Table XI).

TABLE Xl
Hardness (HRC) of Carbonitrided and Quenched and Tempered Materials

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	i~i~ii~i~i	
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~i~i~i~i
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30	**35.5**	**34.0**	**38.5**	**38,5**
40	42.0	41.0	44.5	44.5
50	46.5	45.5	47.5	48.0

This process route may offer advantages in the production of complex parts. The relatively low sintered hardness of the 0.25% graphite materials should make secondary operations such as coining or machining prior to heat treatment somewhat easier.

The impact energy of the test materials is almost completely determined by density (Figure 17) increasing from approximately 6 ft-lbf at a density of 6.6 g/cm^3 to approximately 16 ft-lbf at approximately 7.3 g/cm^3.

Overall, the higher compressibility of the molybdenum prealloy increases impact energy slightly, especially in the quenched and tempered 2% nickel materials. Surprisingly, increasing graphite content slightly increases the impact energy of the test materials. Increasing nickel content also increases impact energy, at 40 tsi compaction pressure (Table XII). This appears to be due to its beneficial effects upon density.

TABLE XlI

Effect of Composition on Impact Energy (ft-lbf) at 40 tsi

Nickel-Mol 'bdenum Prealloy

i iiiiiiiii !i !iii
iii !i iii iii iii

iii iii i~i~ ii i~ii ii~ii
iii iii

0.50	9	12
0.75	10	12

Molybdenum Prealloy

0.50	11 I 13 E	
0.75	12I	13

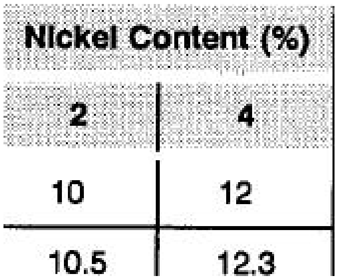
The increase in rompact energy may reflect a slight increase in toughness due to the greater plasticity of the softer nickel-rich areas in the 4% nickel materials. This possibility may be supported when the impact energies are compared at fixed density (Table XIII), where it may be seen that increasing nickel content increases the impact energy of the nickel-molybdenum materials slightly.

TABLE XllI

Effect of Composition on Impact Energy (ft-lbf) at 7.0 g/cm^3

Nickel-Mol, rbdenum Prealloy

iiiiiiiii~!~iii ii



Nickel Content (%)	
2	4
10	12
10.5	12.3

ii~iiiiiiiili iii

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0,50	
0.75	

Molybdenum Prealloy

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iiiiiiiiiiilililililiiiiiiiiilililililili ii iii ii i ii i ii

0,50	10.4	11
0.75	11	12

The carbonitriding process may slightly reduce the impact energy of the test materials. The impact energies of the carbonitrided materials lie slightly below the trend line (Figure 18) for the quenched and tempered materials. Although the overall trend of increasing density increasing impact energy still dominates impact properties.

Ultimate Tensile Strength of Quenched and Tempered Materials

The test materials, particularly those with 0.5% graphite, developed high ultimate tensile strengths that were determined largely by carbon content and sintered density (Figure 19).

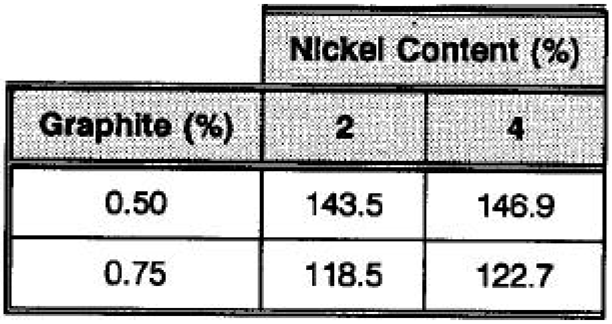
The materials with 0.5% graphite developed higher strengths. Ultimate tensile strength increased from approximately 115,000 psi at 6.6 g/cm3 to approximately 200,000 psi at densities of 7.3 g/cm^3. The strengths of the heat treated materials with 0.75% graphite increased from approximately 120,000 psi at a density of 6.6 g/cm^3 to approximately 160,000 psi at a density of 7.25 g/cm^3.

It is believed that the 0.75% graphite materials, especially those using the nickel-molybdenum prealloy, were relatively brittle. At high density levels, some of the test pieces failed within the locating threads rather than within the gauge length. This may be due to the higher particle hardness and possibly the presence of fine carbides.

When compared at a fixed compaction pressure of 40 tsi, the higher compressibility of the 0.85% molybdenum prealloy produced higher density and higher strengths (Table XlV).

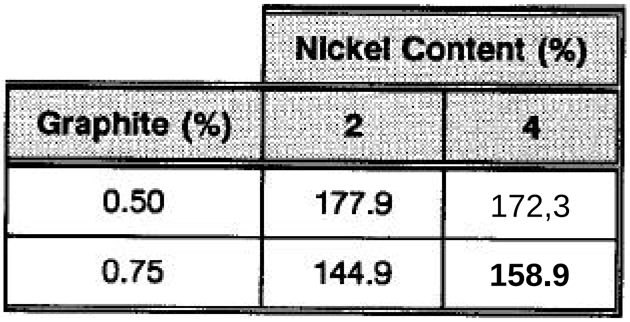
TABLE XlV

Ultimate Tensile Strength (1000 psi) of Test Materials at 40 tsl



	Nickel Content (%)	
Graphite (%)	**2**	**4**
0.50	143.5	146.9
0.75	118.5	122.7

Nickel-Molybdenum Prealloy



	Nickel Content (%)	
Graphite (%)	**2**	**4**
0.50	177.9	172,3
0.75	144.9	**158.9**

Molybdenum **Prealloy**

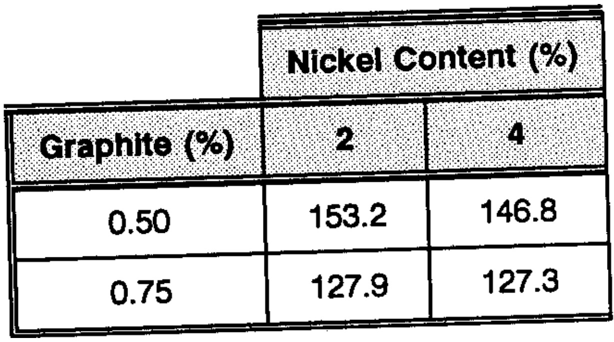
The results show clearly the lower strengths of the 0.75% graphite materials. They also show that increasing nickel content from 2 to 4% did not significantly affect ultimate tensile strength except for the molybdenum prealloy with 0.75% graphite. This may be due to its higher density at 40 tsi.

Comparing properties at a fixed density of 7.0 g/cm^3 confirms that increasing graphite content reduces ultimate tensile strength. At fixed density, it appears that adding an additional 2% nickel reduces the ultimate tensile strength of the materials with 0.5% graphite, but increases the ultimate tensile strength of the 0.85% molybdenum material with 0.75% graphite content (Table XV).

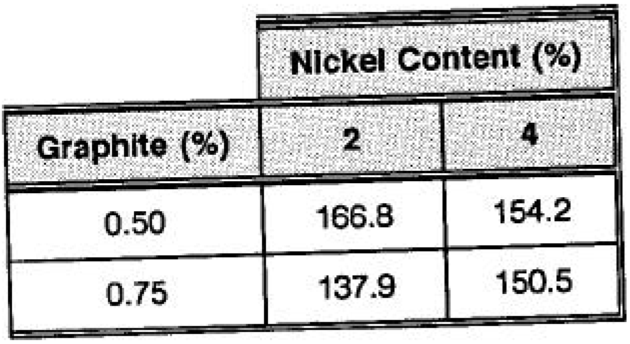
TABLE XV

Ultimate Tensile Strength (1000 psi) of Test Materials at 7.0 g/cm^3 Nickel-Molybdenum Prealloy Molybdenum Prealloy

Metallography did not reveal any single clear reason for this. It appears that increasing nickel additions may improve properties by accelerating sintering and densification rather than by modifying microstructures of the quenched and tempered materials.



	Nickel Content (%)	
Graphite (%)	2	4
0.50	153.2	146.8
0.75	127.9	127.3



	Nickel Content (%)	
Graphite (%)	2	4
0.50	166.8	154.2
0.75	137.9	150.5

I,)ltimate Tensile Strenoth of Carbonitrided Material,~

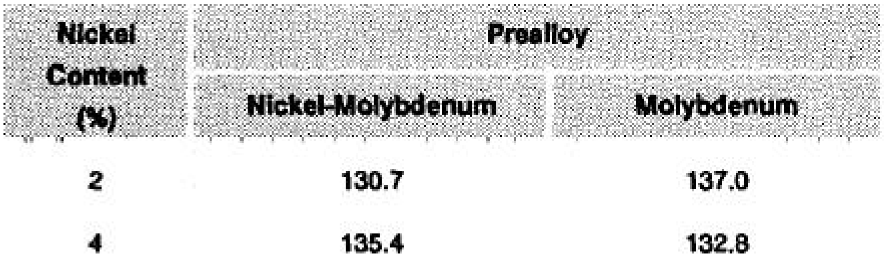
The tensile properties of the carbonitrided materials were determined by their sintered density (Figure 20). The ultimate tensile strength increased from approximately 105,000 psi at a density of 6.6 g/cm^3 to approximately 160,000 psi at a density of 7.3 g/cm^3.

When compared at a compaction pressure of 40 tsi (Table XVI), the improved compressibility of the molybdenum prealloy produces carbonitrided materials with higher tensile strength.

This increase may show the effect of nickel on densification in compaction and sintering. The ultimate tensile strengths of the carbonltrided materials are almost independent of composition when compared at a fixed density of 7.0 g/cm^3 (Table XVII).

TABLE XVII

UltlmMe Tensile Strength (1000 psi) of Carbonitrided Materials at 7.0 **g/cm^3**



Nickel Content (%)	Prealloy	
	Nickel-Molybdenum	Molybdenum
2	130.7	137.0
4	135.4	132.8

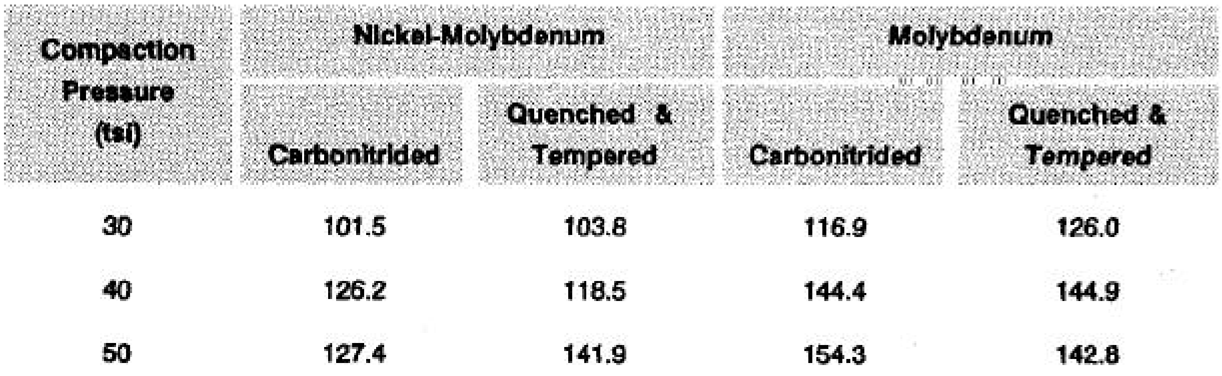
The increased density of the molybdenum prealloy produced a significant increase in the maximum ultimate tensile strength. It also appeared to assist in formation of a "case" of superior hardness at the test piece surface.

Com-oarison of Carbonitrided and Quenched and Temoered Materials

The design of the carbonitrided materials was intended to achieve high greendensity, by reducing graphite content, then to develop increased strength and hardness by introducing carbon and nitrogen from the furnace atmosphere during the carbonitriding process. The test results show that the ultimate tensile strength of the carbonitrided materials of 2% nickel content compare closely with quenched and tempered *materials* of 0.75% graphite content (Table XVIll).

TABLE XVIII

Comparison of Ultimate Tensile Strength (1000 psi) of Carbonltrided Materials with 2% Nickel



Compaction Pressure (tsi)	Nickel-Molybdenum		Molybdenum	
	Carbonitrided	Quenched & Tempered	Carbonitrided	Quenched & Tempered
30	101.5	103.8	116.9	126.0
40	126.2	118.5	144.4	144.9
50	127.4	141.9	154.3	142.8

COMPARISON WITH EXISTING P/M MATERIAa $

The test materials developed very high combinations of strength and hardness following single compaction processing. The property levels achieved in the materials made with the molybdenum prealloy exceed those of the heat treated nickel-molybdenum steels and also high density heat treated P/M nickel steels such as FN-0205HT or FN-0405HT.

The test data indicate that the hardness of the molybdenum prealloy with 2% nickel significantly exceeds that of the FN-0205HT and FN-0405HT (Figure 21) as represented in MPIF Standard 35, even when the latter are processed to high density levels by double pressing and sintering.

Similarly, the molybdenum prealloy with a 2% nickel content attains tensile strengths of 200,000 psi by single compaction. These values exceed those attained with FN-0405HT (Figure 22) even when processed by double pressing and sintering.

The current work shows that the quenched and tempered properties of the 0.85% molybdenum steel generally exceed those of the nickel-molybdenum steel. The combination of the ANCORBOND process plus the molybdenum prealloy produced a maximum tensile strength exceeding 200,000 psi at a density of 7.25 g/cm^3 by single compaction processing (Table XIX). This compares favorably with an ultimate tensile strength of 173,000 psi at a density of 7.25 g/cm^3 quoted in the literature for a double-pressed and double-sintered nickel-molybdenum prealloy™.

TABLE XIX
Comparison of ANCORBOND Processed P/M Molybdenum Steel with DPDS Nickel-Molybdenum Steel

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FL-4605HT	7.25	35	173,250	DPDS
Mo 2%Ni 0.5% Graphite	7.29	44	204,000	ANCORBOND

CONCLUSIONS

The high compressibility of the molybdenum prealloy enables materials to be developed that possess heat treated properties typical of double pressed and sintered materials but by single compaction processing.

Materials were developed that possess apparent hardness of 45-47 HRC in the quenched and tempered condition with ultimate tensile strengths in excess of 180,000 psi.

A carbonitriding process can be used to produce high apparent hardness, 45-48 HRC on materials of low sintered carbon content. Because of their low sintered carbon content, these materials should possess lower sintered hardness, hence better machinability than materials of higher sintered carbon content.

The test materials, especially those based on the molybdenum prealloy, attained maximum ultimate tensile strength at 0.5% graphite, but maximum hardness at 0.75% graphite.

Increasing nickel content from 2 to 4% by admixing to the molybdenum prealloy did not greatly improve the properties of the quenched and tempered materials. It did improve the ultimate tensile strength of the carbonitrided materials.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of Remington Powder Metal Products and Hoeganaes Corporation. They would like to thank the staff of Remington Powdered Metal Products and, in particular, B. Dodson and S. Bridges for their assistance in producing and processing the test specimens. They are particularly grateful for the cooperation of the following Hoeganaes personnel: Messrs. R. Fitzpatrick and C. Gamble for measurement of mechanical properties along with T. Murphy, G. Golin and S. Kolwicz for metailography.

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TABLE II
Material Compositions

	Premix Composition				Sintered Chemistry			
Material	Low Alloy Base	Nickel Addition (%)	Graphite (%)	Zinc Stearate (%)	Nickel (%)	Molybdenum (%)	Manganese (%)	Carbon* (%)
A	A4600V	0	0.25	0.50	1.84	0.56	0.22	0.44
B	A4600V	0	0.50	0.50	1.80	0.55	0.21	0.51
C	A4600V	0	0.75	0.50	1.80	0.55	0.21	0.74
D	A4600V	2	0.25	0.50	3.73	0.54	0.21	0.46
E	A4600V	2	0.50	0.50	3.75	0.55	0.21	0.51
F	A4600V	2	0.75	0.50	3.76	0.55	0.21	0.74
G	A85HP	2	0.25	0.50	2.14	0.79	0.11	0.47
H	A85HP	2	0.50	0.50	2.10	0.79	0.12	0.51
J	A85HP	2	0.75	0.50	2.11	0.79	0.12	0.74
K	A85HP	4	0.25	0.50	4.23	0.80	0.09	0.44
L	A85HP	4	0.50	0.50	4.19	0.79	0.10	0.50
M	A85HP	4	0.75	0.75	4.12	0.79	0.11	0.77

Nickel:	Inco 123
Graphite:	Asbury 3203
Zinc Stearate:	Mallinckrodt Hi-Dense

* Carbon content following heat treatment

TABLE III
Properties of Test Materials with Nickel-Molybdenum Prealloy

Material	Nickel Addition (%)	Graphite (%)	Compaction Pressure (tsi)	Density (g/cm³)	TRS (1000 psi)	0.2% Yield Stress (1000 psi)	UTS (1000 psi)	Elongation (%)	Impact (ft-lbf)	Hardness (HRC)
A	0	0.25	30	6.58	125.2	91.8	101.5	1.0	5	35.5
	0	0.25	40	6.94	162.0	114.0	126.2	1.1	7.5	42.0
	0	0.25	50	7.10	194.1	119.3	137.4	1.1	8	46.5
B	0	0.50	30	6.63	159.3	109.4	114.8	1.0	6	28.0
	0	0.50	40	6.96	204.6	131.4	143.5	1.1	9	36.0
	0	0.50	50	7.12	241.7	153.0	181.3	1.6	13	41.5
C	0	0.75	30	6.60	134.2	95.0	103.8	1.1	6	34.0
	0	0.75	40	6.91	184.5	105.5	118.5	1.0	10	41.0
	0	0.75	50	7.13	199.0	129.6	141.9	1.0	11	45.5
D	2	0.25	30	6.74	144.3	102.5	117.4	1.2	7	33.0
	2	0.25	40	7.01	206.2	114.1	136.3	1.4	10	41.0
	2	0.25	50	7.27	226.2	123.3	146.2	1.3	12	44.5
E	2	0.50	30	6.67	174.1	105.4	128.0	1.3	8	28.5
	2	0.50	40	7.00	234.1	120.6	146.9	1.3	12	36.5
	2	0.50	50	7.12	279.9	147.3	193.3	1.8	14	40.5
F	2	0.75	30	6.69	162.4	83.3	125.8	1.3	7	32.5
	2	0.75	40	6.97	195.9	82.3	122.7	1.3	12	39.0
	2	0.75	50	7.16	235.3	104.3	155.3	1.4	14	44.0

TABLE III

Heat Treated Properties of Test Materials with Molybdenum Prealloy

Material	Nickel Addition (%)	Graphite (%)	Compaction Pressure (tsi)	Density (g/cm^3)	TRS (1000 psi)	0.2% Yield Stress (1000 psi)	UTS (1000 psi)	Elongation (%)	Impact (ft-lbf)	Hardness (HRC)
G	2	0.25	30	6.81	147.7	105.2	116.9	1.0	7	38.5
	2	0.25	40	7.08	204.7	130.2	144.4	1.1	9	44.5
	2	0.25	50	7.27	223.4	132.5	154.3	1.2	10	47.5
H	2	0.50	30	6.85	200.4	124.5	143.4	1.2	9	34.0
	2	0.50	40	7.07	231.1	145.7	177.9	1.5	11	40.0
	2	0.50	50	7.29	282.3	155.9	203.7	1.8	16	44.0
J	2	0.75	30	6.83	185.0	103.5	126.0	1.2	10	38.5
	2	0.75	40	7.11	227.5	108.0	144.9	1.2	12	44.5
	2	0.75	50	7.24	228.9	129.7	142.8	1.0	13	48.0
K	4	0.25	30	6.93	172.7	103.8	127.1	1.3	9	37.0
	4	0.25	40	7.18	222.9	124.6	148.5	1.3	12	43.0
	4	0.25	50	7.37	260.4	133.8	165.5	1.5	13	45.5
L	4	0.50	30	6.92	206.6	108.1	144.3	1.5	10	33.0
	4	0.50	40	7.15	252.8	131.6	172.3	1.6	13	39.5
	4	0.50	50	7.30	297.9	140.5	191.8	1.7	15	42.0
M	4	0.75	30	6.92	197.7	86.0	146.0	1.6	11	37.0
	4	0.75	40	7.15	236.5	94.5	158.3	1.4	13	42.5
	4	0.75	50	7.25	264.5	100.2	163.0	1.3	17	45.5

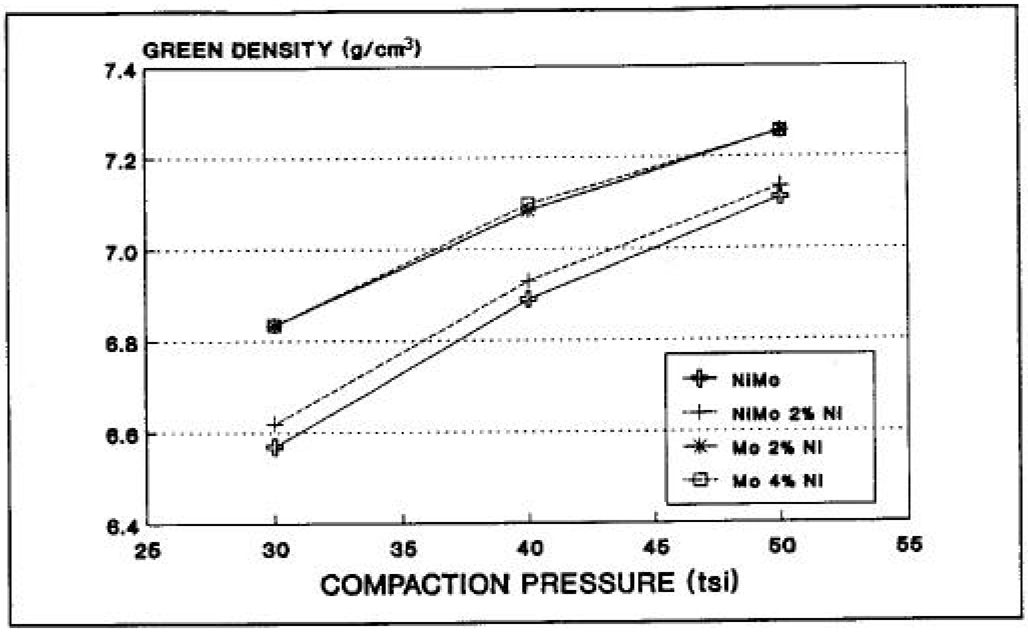

Figure 1: Effect of Composition on Green Density of Test Materials with 0.5% Graphite.

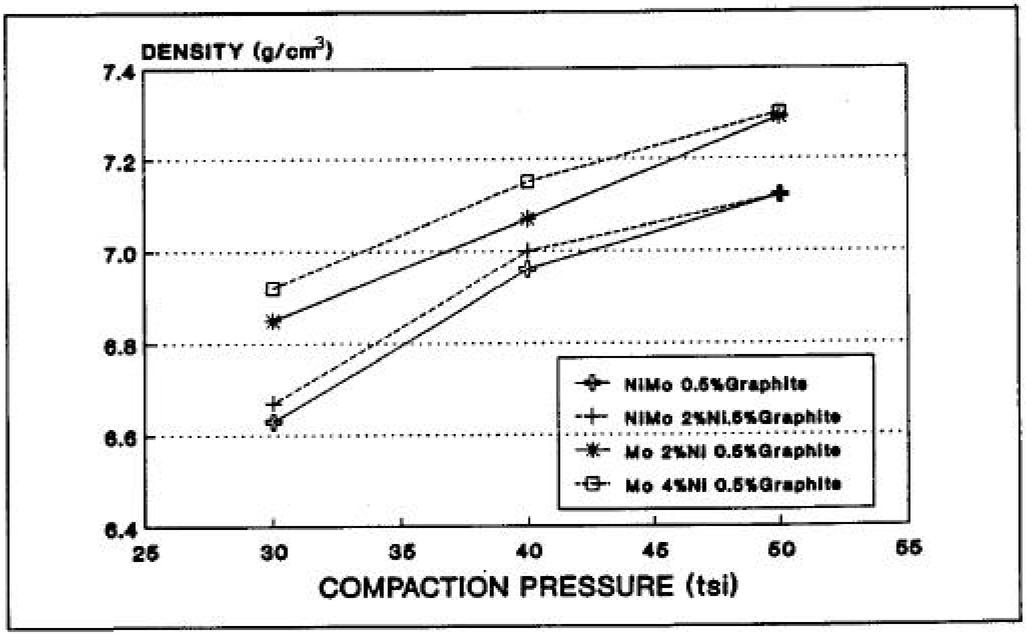

Figure 2: Effect of Composition on Quenched & Tempered Density of Test Materials

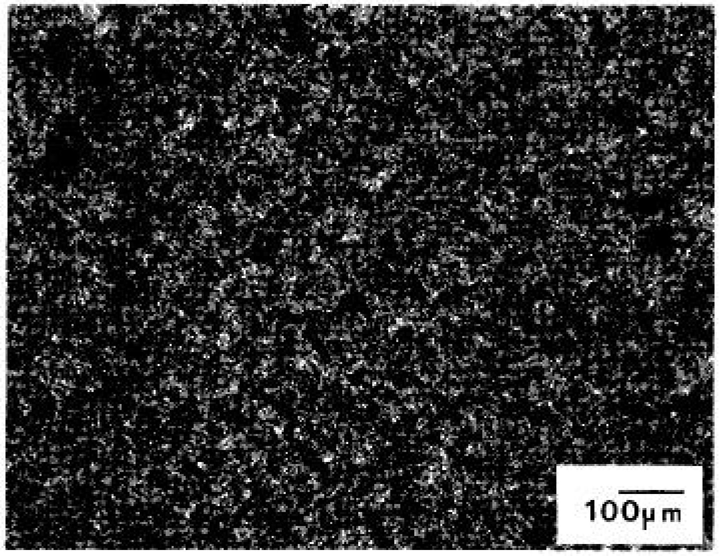

Figure 3: Microstructure of Quenched and Tempered Material B, NiMo prealloy, 0.5% graphite. Etched with a combination of 2% nital/4% picral. Original magnification 100X.

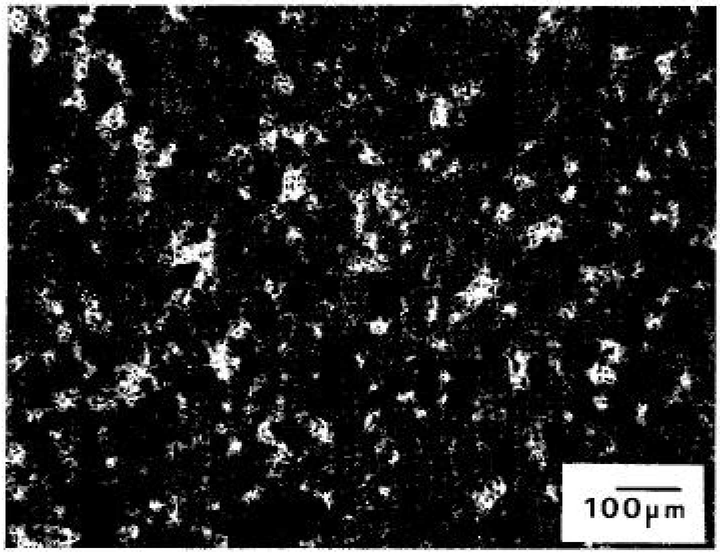

Figure 4: Microstructure of Quenched and Tempered Material L, Mo prealloy, 4% nickel, 0.5% graphite. Etched with a combination of 2% nital/4% picral. Original magnification 100X.

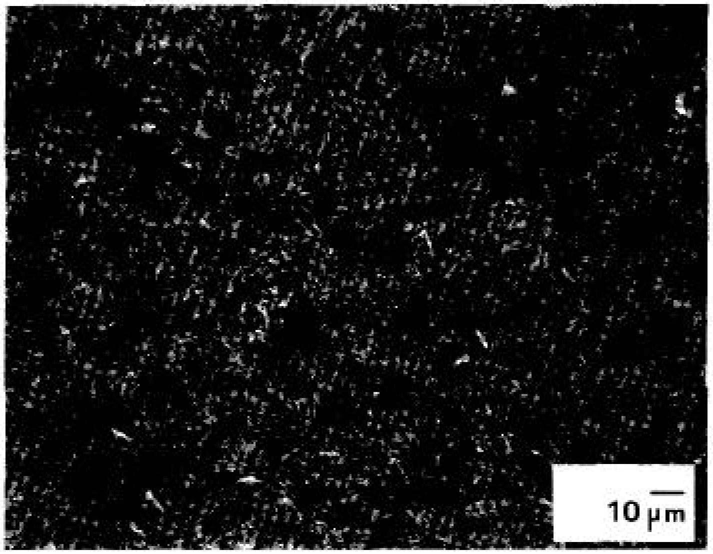

Figure 5: Microstructure of Quenched and Tempered Material B, NiMo prealloy, 0.5% graphite. Etched with a combination of 2% nital/4% picral. Original magnification 500X.

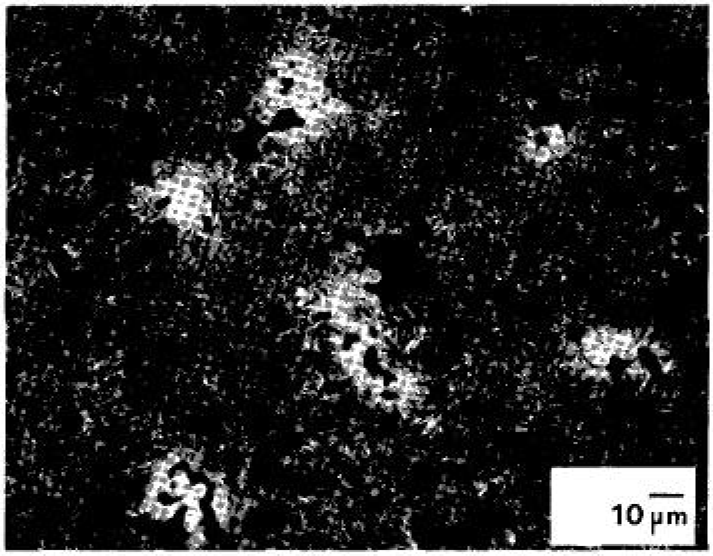

Figure 6: Microstructure of Quenched and Tempered Material E, NiMo prealloy, 2% nickel, 0.5% graphite. Etched with a combination of 2% nital/4% picral. Original magnification 500X.

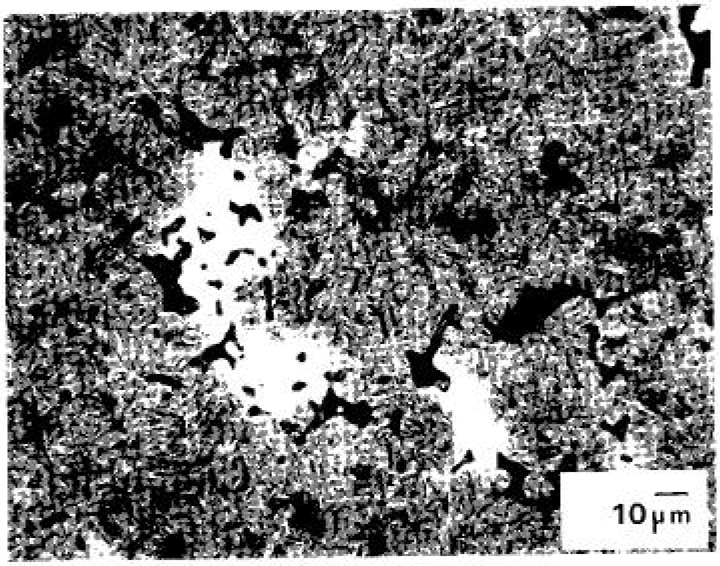

Figure 7: Microstructure of Quenched and Tempered Material H, Mo prealloy, 2% nickel, 0.5% graphite. Etched with a combination of 2% nital/4% picral. Original magnification 500X.

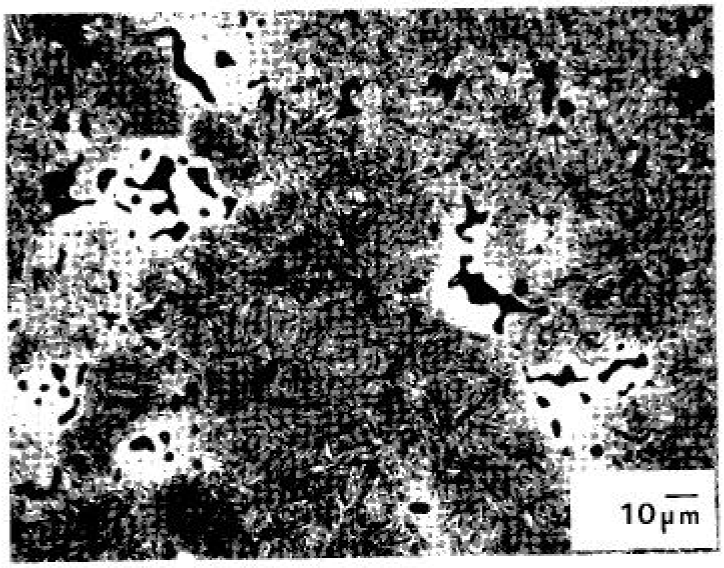

Figure 8: Microstructure of Quenched and Tempered material L, Mo prealloy, 4% nickel, 0.5% graphite. Etched with a combination of 2% nital/4% picral. Original magnification 500X.

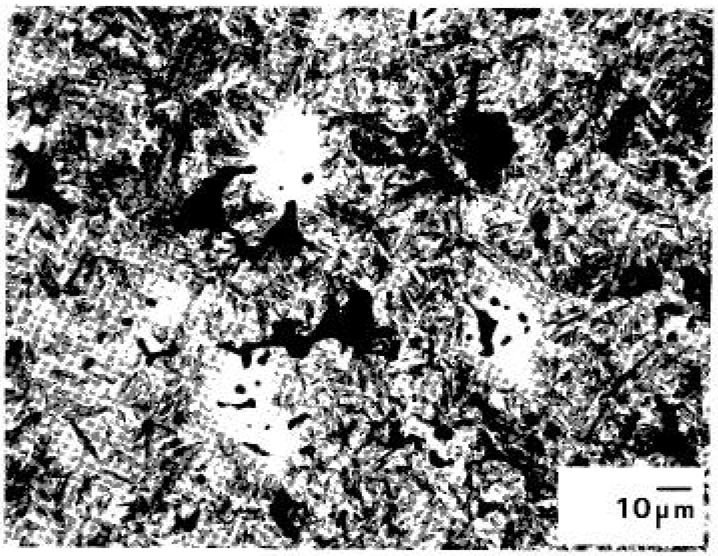

Figure 9: Core Microstructure of Carbonitrided Material D, NiMo prealloy, 2% nickel, 0.25% graphite. Etched with a combination of 2% nital/4% picral. Original magnification 500X.

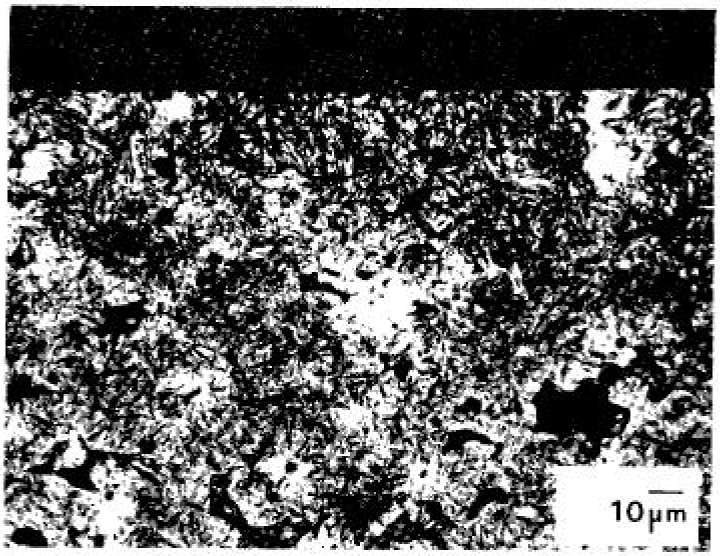

Figure 10: Surface Microstructure of Carbonitrided Material D, NiMo prealloy, 2% nickel, 0.25% graphite. Etched with a combination of 2% nital/4% picral. Original magnification 500X.

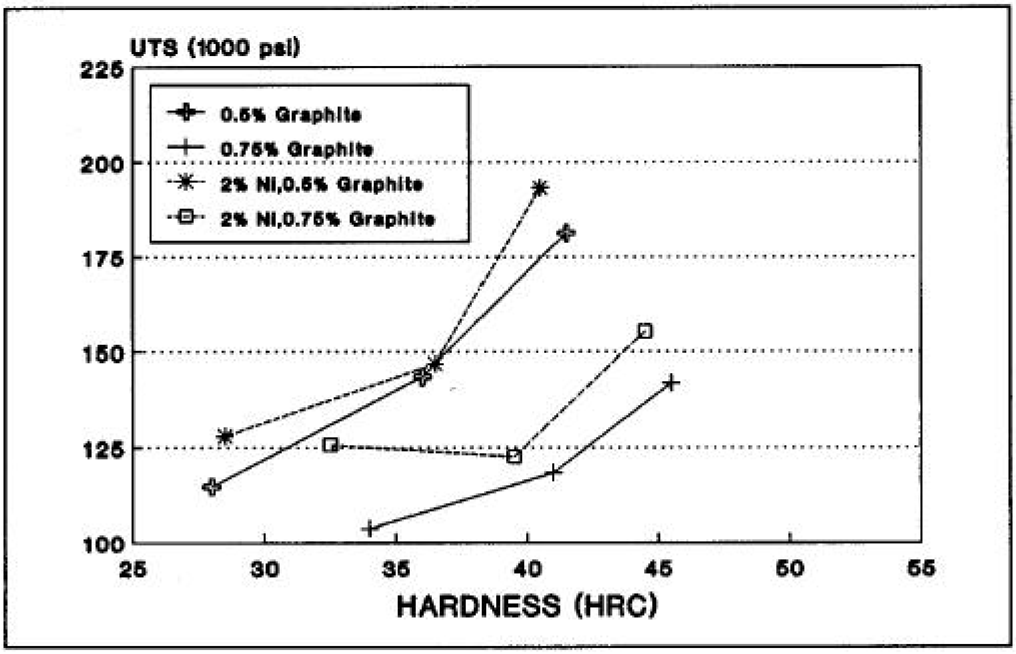

Figure 10: Ultimate Tensile Strength versus Hardness of Quenched and Tempered Nickel-Molybdenum Prealloy

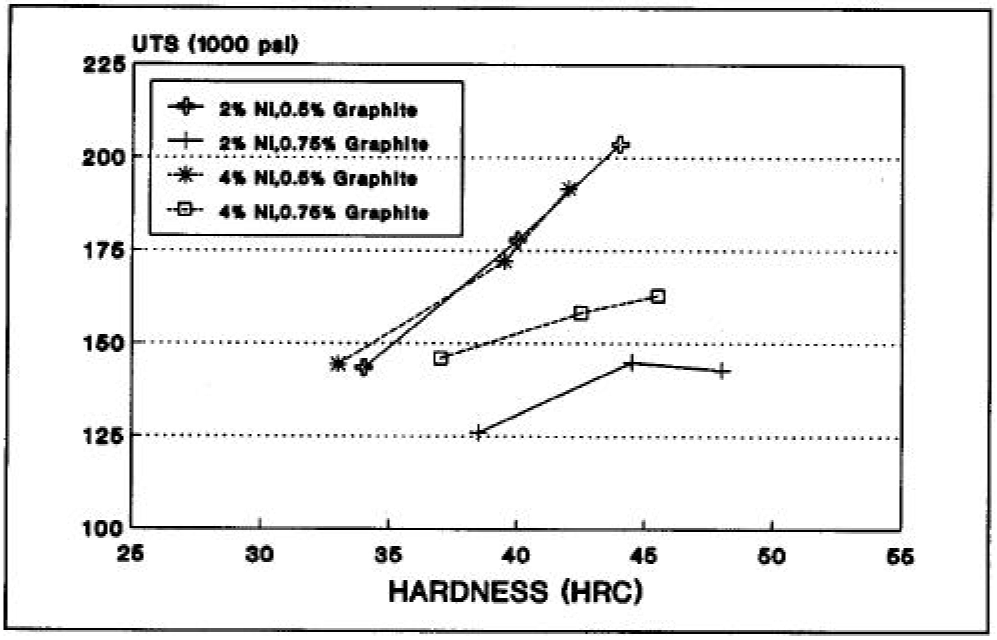

Figure 11: Ultimate Tensile Strength versus Hardness of Quenched and Tempered Molybdenum Prealloy

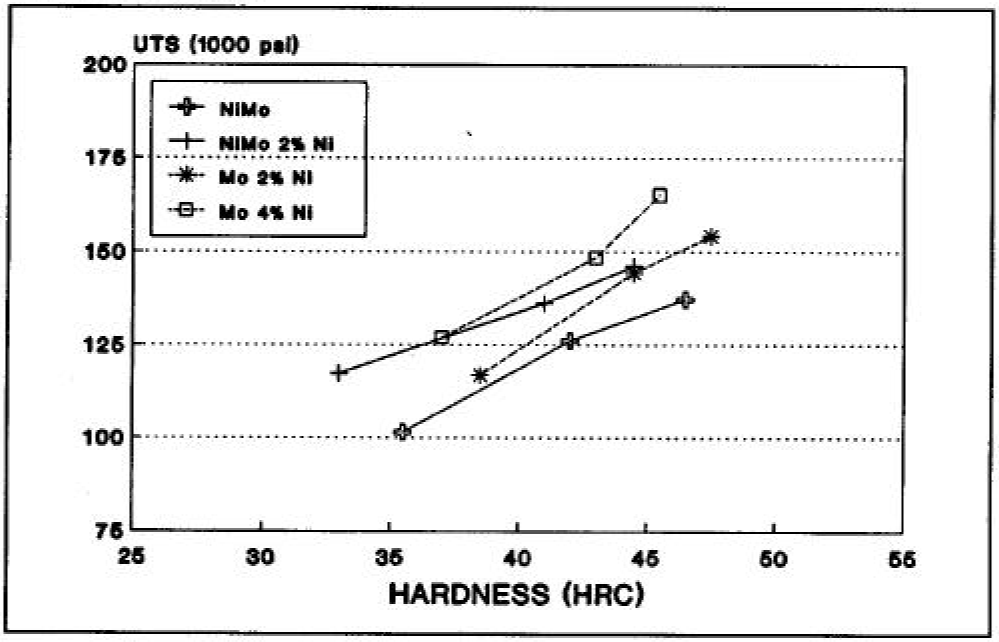

Figure 12: Ultimate Tensile Strength versus Hardness of Carbonitrided Materials

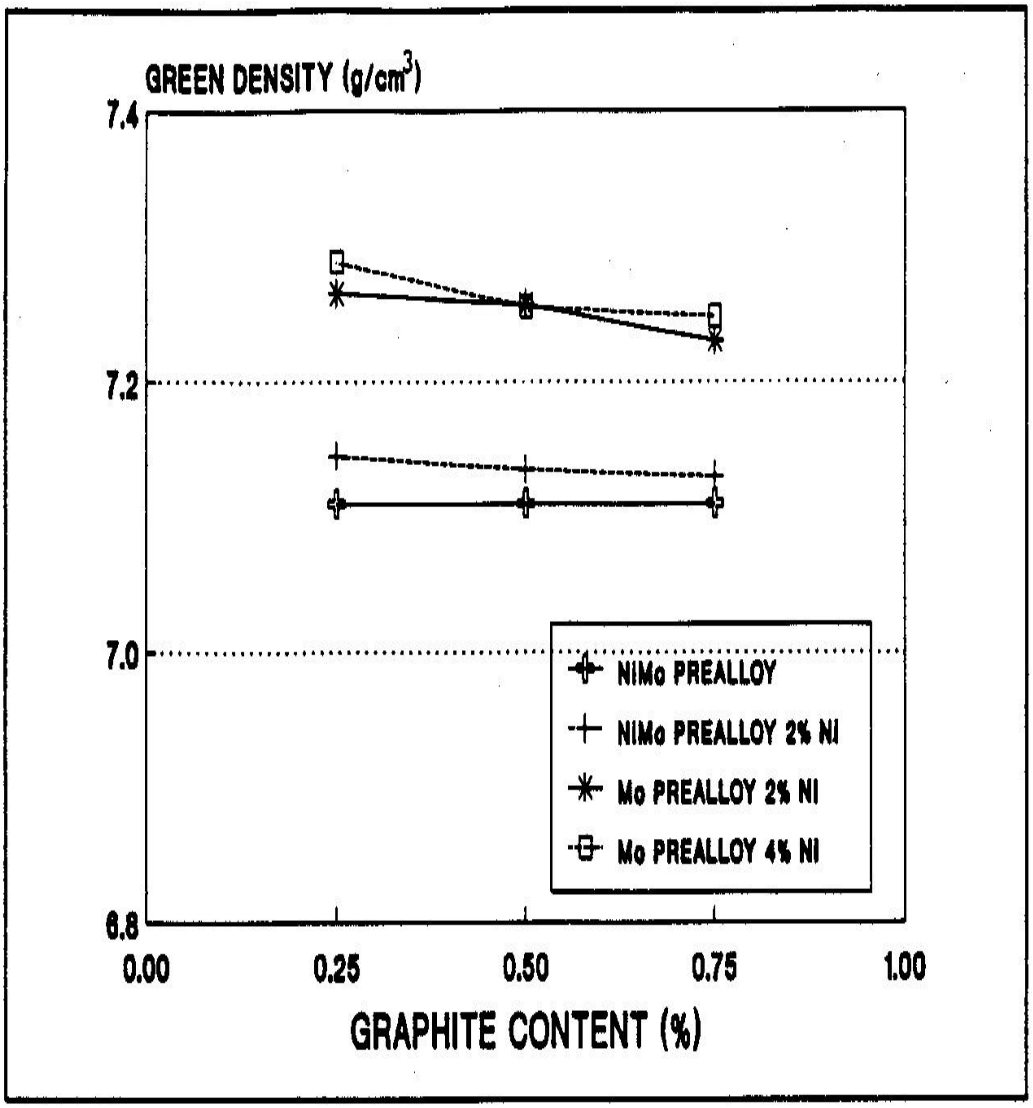

Figure 13: Effect of Graphite Content Upon Green Density at 50 tsi

TABLE V: Pycnometric Densities (g/cm^3) of Test Materials

	Nickel-Molybdenum Prealloy		0.85% Molybdenum Prealloy	
Graphite (%)	2% Nickel	4% Nickel	2% Nickel	4% Nickel
0.25	7.75	7.75	7.74	7.79
0.50	7.74	7.74	7.77	7.79
0.75	7.71	7.73	7.76	7.77

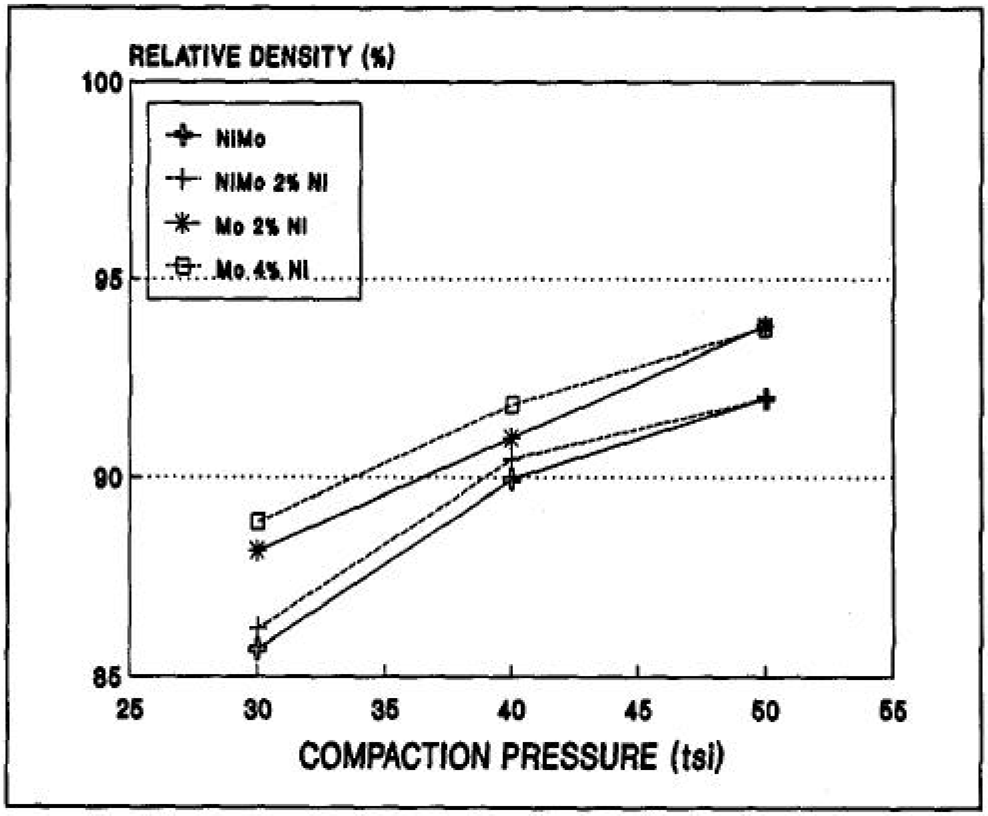

Figure 14: Effect of Composition Upon Relative Density of Test Materials with 0.5% Graphite Content

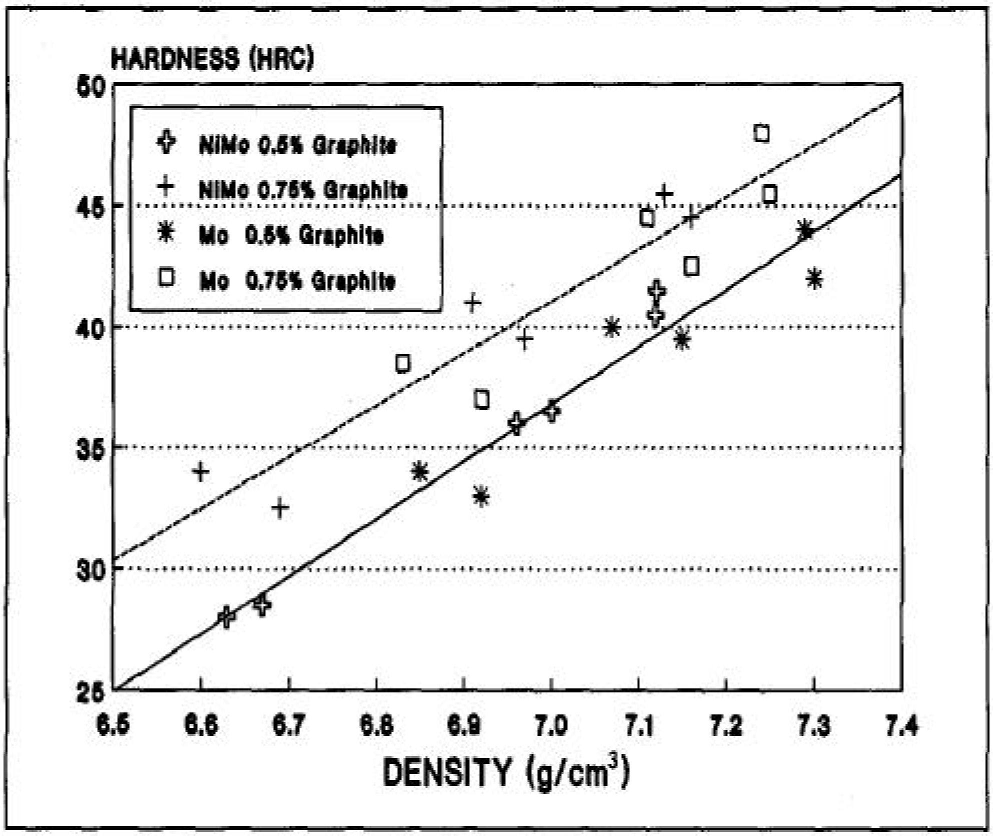

Figure 15: Effect of Density Upon Quenched and Tempered Hardness of Test Materials

TABLE VII

Effect of Composition on Hardness (HRC) at 40 tsi

Nickel-Molybdenum Prealloy

	Nickel Content (%)	
Graphite (%)	2	4
0.50	36.0	36.5
0.75	41.0	39.5

Molybdenum Prealloy

	Nickel Content (%)	
Graphite (%)	2	4
0.50	40.0	39.5
0.75	44.5	42.5

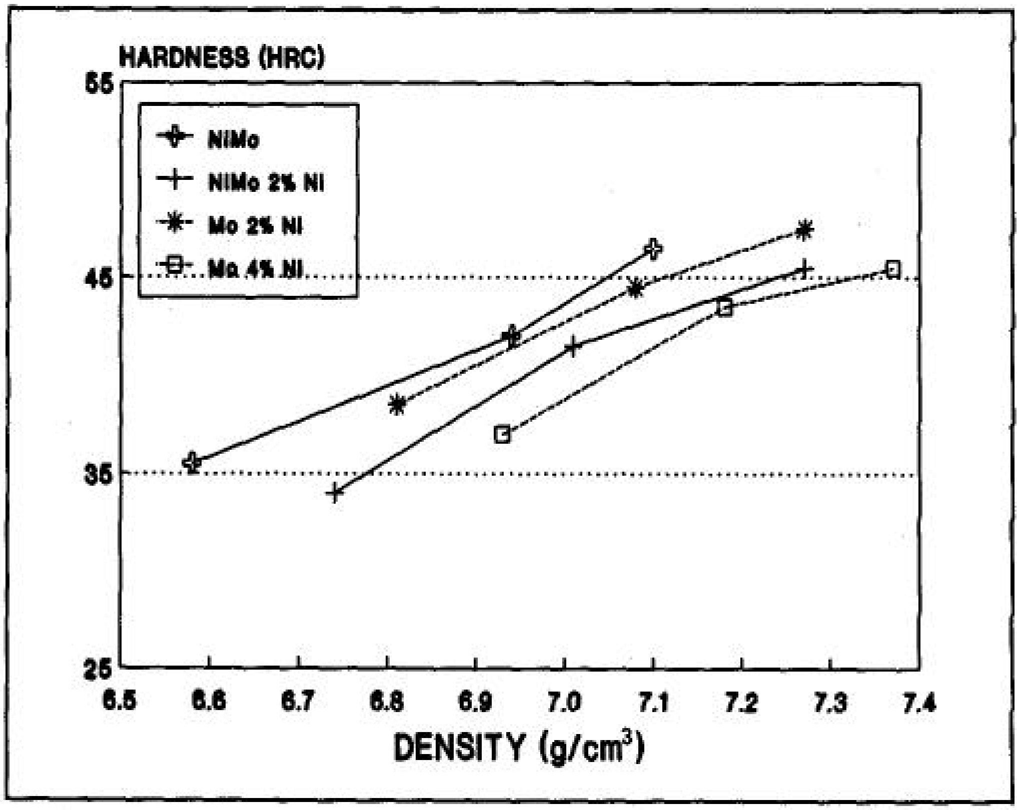

Figure 16: Hardness versus Density of Carbonitrided Test Materials

TABLE IX

Effect of Composition on Hardness (HRC) of Carbonitrided Materials at 40 tsi

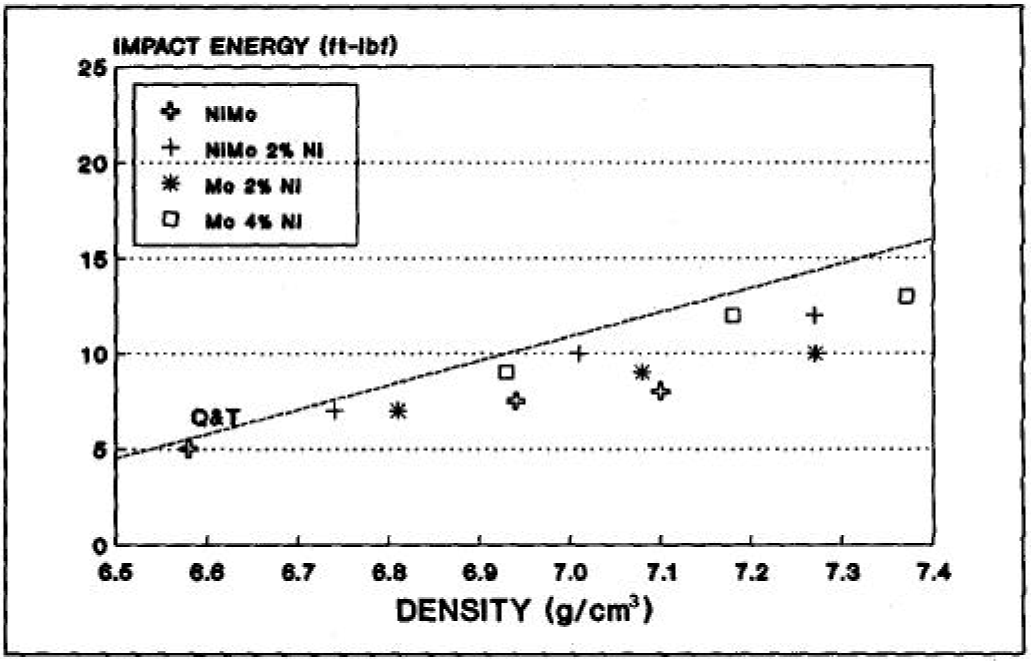

Figure 18: Effect of Density Upon Impact Energy of Carbonitrided Test Materials

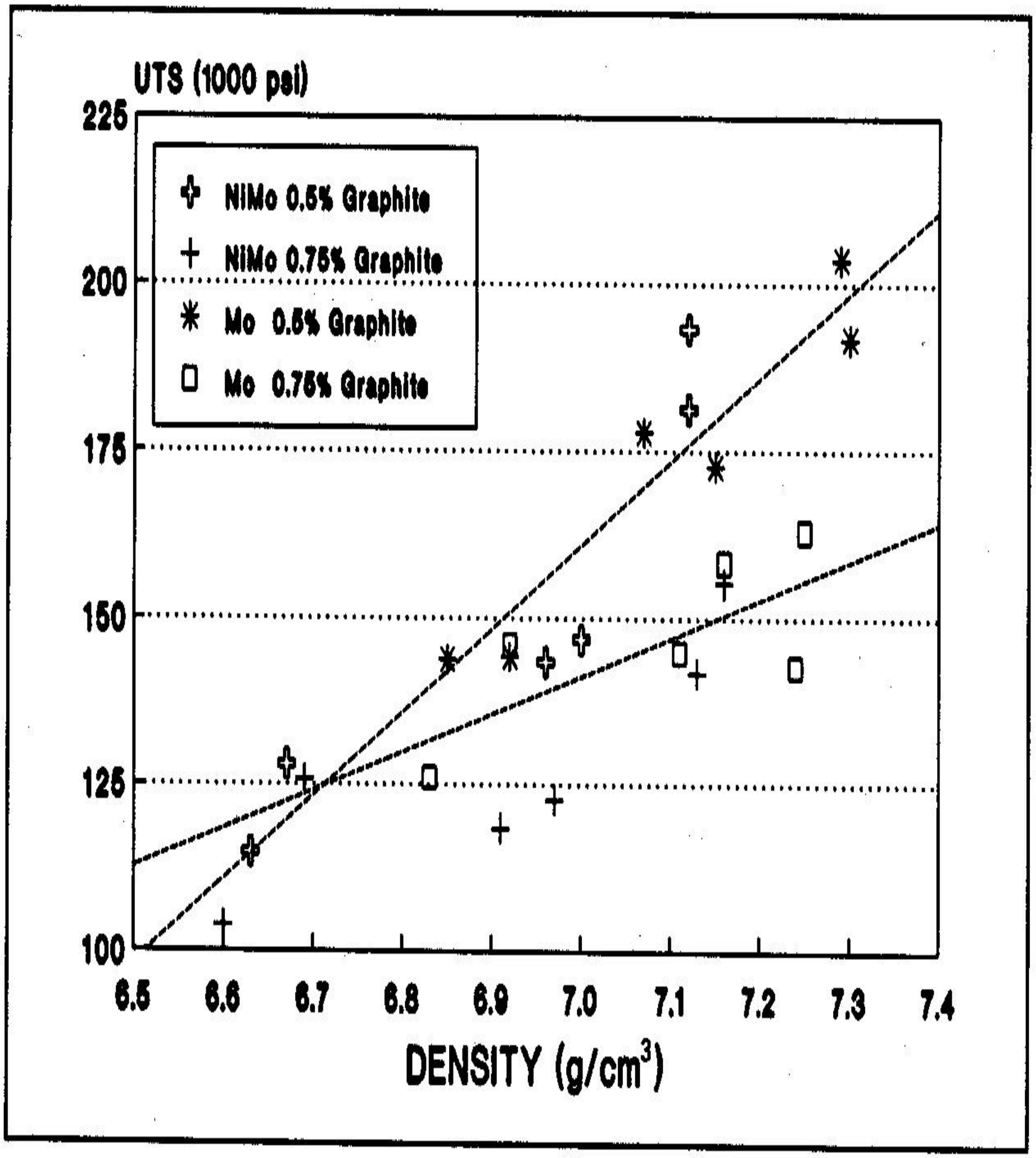

Figure 19: Effect of Density Upon Ultimate Tensile Strength of Quenched and Tempered Test Materials

TABLE XVI

Ultimate Tensile Strength (1000 psi) of Carbonitrided Materials at 40 tsi

Nickel Content (%)	Prealloy	
	Nickel-Molybdenum	Molybdenum
2	126.2	144.2
4	136.3	148.5

Increasing nickel addition increases the ultimate tensile strength of the nickel-molybdenum prealloy but has little effect on the molybdenum prealloy.

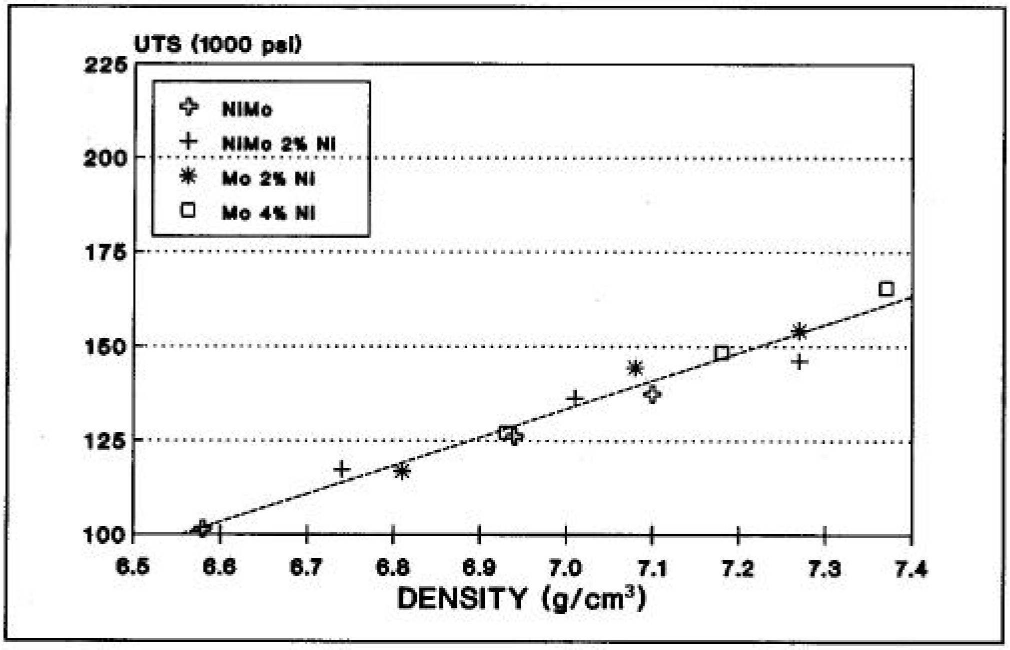

Figure 20: Ultimate Tensile Strength versus Density of Carbonitrided Test Materials

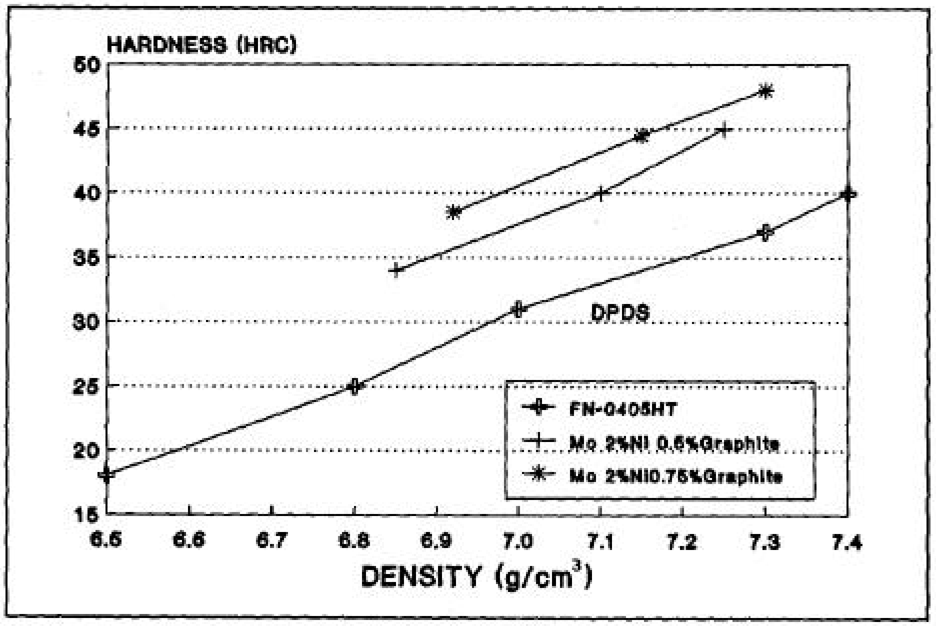

Figure 21: Hardness of Quenched and Tempered P/M Nickel Steels

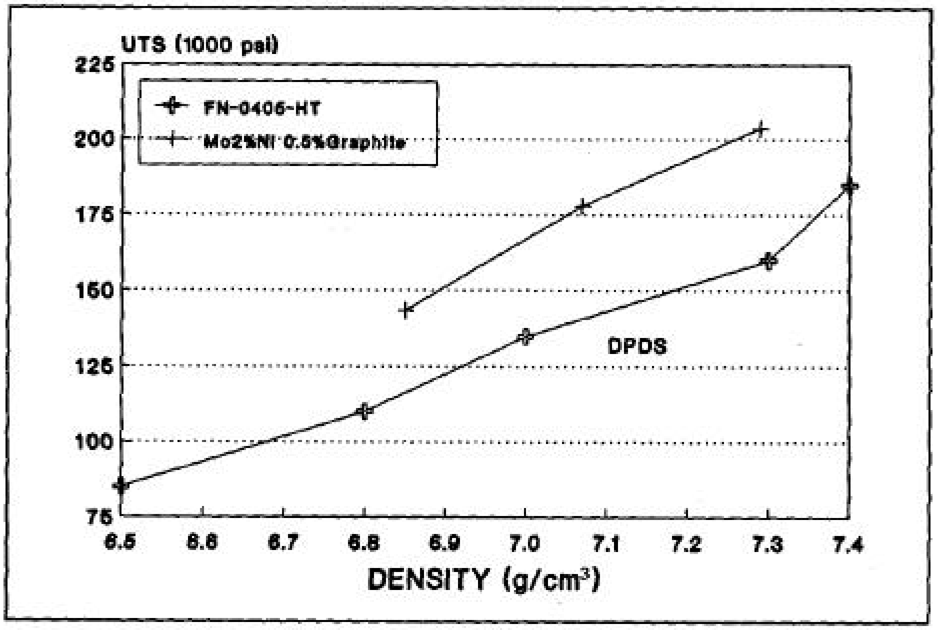

Figure 22: Ultimate Tensile Strength of Heat Treated P/M Nickel Steels