SINTER HARDENING LOW-ALLOY STEELS

Robert J. Causton
Hoeganaes Corporation
Riverton, NJ 08077

John J. Fulmer
Burgess-Norton Manufacturing Company
Geneva, IL 60134

Presented at the 1992 Powder Metallurgy World Congress
San Francisco, CA, June 21-26, 1992

ABSTRACT

The availability of prealloyed steel powders employing molybdenum as the major alloying element offers new levels of compressibility and mechanical properties.

When the prealloyed powders are combined with conventional P/M additives such as copper, nickel and graphite, it is possible to develop high strength martensitic microstructures directly from the sintering cycle.

The impact and tensile properties of copper, nickel, graphite premixes based upon the prealloyed molybdenum steels are compared under controlled cooled conditions.

The ability to balance tensile strength, toughness and hardness by control of alloy chemistry is illustrated.

INTRODUCTION

This paper presents the results of an investigation into the effects of copper and nickel additions upon the properties of low-alloy steel powder premixes. This investigation is part of a broader program to develop “High Performance” P/M materials and as such complements other recently published papers. (1) The aim of the work is develop tensile strengths in a single pressed compact that match, if not surpass, those previously obtained by double pressing techniques. If successful, such work offers P/M parts’ designers a significantly more efficient route to high strength/high performance P/M components.

PRINCIPLES OF PROGRAM

The strength of a porous P/M material depends upon many factors including:

The relative density or porosity level
The matrix strength
Microstructure

To investigate these factors, test materials were made from premixes of molybdenum prealloyed low-alloy steel powders that employed copper, nickel and graphite as alloying elements.

Molybdenum

Molybdenum was tested at two levels by using [1]Ancorsteel® 85HP and Ancorsteel 1 50H P, these steel powders contain 0.85 and 1.5% molybdenum, respectively. Molybdenum has very little solution hardening effect in iron, thus, it is possible to obtain high relative density by single compaction. However, molybdenum significantly increases hardenability once carbon is dissolved. Thus, it should be possible to develop high strength martensitic or bainitic microstructures on cooling from sintering temperature.

Copper and Nickel

The normal alloying additions in P/M materials are copper and nickel. Both tend to reduce compressibility if prealloyed but enhance strength and hardenability once dissolved during sintering. The program examined their combined effects upon final material properties.

Accelerated Cooling to Develop Martensite

Sintered P/M parts are often heat treated to develop a tempered martensitic micro-structure possessing high tensile strength. The alloy steel formed by solution of copper and nickel in the prealloyed matrix should improve the hardenability of the test materials. Rapidly cooling the compact from sintering temperature should develop high strength martensitic or bainitic microstructures. As described previously,(2) this may enable a separate heat treatment operation to be omitted given favorable part geometry. The program attempted to quantify the effects of copper and nickel with molybdenum upon the microstructure and hence the properties developed in the sintered materials.

The test materials were produced using the ANCORBOND® (3,4,5) process to suppress micro and macro segregation. Areas deficient in admixed copper, nickel or graphite could reduce strength compared to the overall matrix of the material.

EXPERIMENTAL PROCEDURE

A series of 500-pound test premixes was prepared using the

ANCORBOND process. The premix compositions, shown in Table I, were designed to assess the influence of alloy steel matrix, copper and nickel contents upon the properties of the final sintered material.

TABLE I
Premix Compositions

Material	Low-alloy Base	Copper (%)	Nickel (%)	Graphite (%)	Zinc Stearate (%)
A	Ancorsteel 85HP	0	2	0.5	0.5
B	Ancorsteel 85HP	1	2	0.5	0.5
C	Ancorsteel 85HP	0	4	0.5	0.5
D	Ancorsteel 85HP	1	4	0.5	0.5
E	Ancorsteel 150HP	0	2	0.5	0.5
F	Ancorsteel 150HP	1	2	0.5	0.5
G	Ancorsteel 150HP	0	4	0.5	0.5
H	Ancorsteel 150HP	1	4	0.5	0.5

Note:		
	Copper:	Alcan 8081
	Nickel:	Inco 123
	Graphite:	Asbury 3203
	Zinc Stearate:	Mallinckrodt “HiDense”

The sintered chemistry and basic sintered properties, measured following standard Hoeganaes test procedures, are shown in Tables II and III.

The copper, nickel and molybdenum contents were measured by optical emission spectroscopy. The sintered carbon content was determined by LECO carbon analysis.

These preliminary QC tests confirmed that the material compositions could develop high strength. There was evidence of the favorable interaction of copper and nickel upon transverse rupture strength and dimensional change.

TEST PIECE PREPARATION

Following these standard laboratory tests, the test pieces for determination of mechanical properties were pressed and sintered under industrial conditions at Burgess-Norton Manufacturing Company.

Tensile properties were measured using ASTM E 8 “Dog-bone” tensile test pieces. Charpy impact testing was performed using un-notched test pieces as shown in ASTM E 23. The 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 42,1985-1986 Edition, on impregnated sections cut from the impact and tensile test pieces.

Sintering

The basic sintering cycle is indicated below.

Sintering temperature:	2050°F
Atmosphere:	Endothermic with carbon potential control
Dewpoint:	32-35°F
Equilibration temperature:	1550°F
Sintering time:	20 minutes

TABLE II
Sintered Chemistry of Test Materials

Premix	Copper (%)	Nickel (%)	Molybdenum (%)	Sintered Carbon (%)
A	--	2.26	0.83	0.49
B	0.99	2.17	0.83	0.47
C	--	4.04	0.81	0.47
D	1.06	4.44	0.81	0.46
E	--	2.22	1.41	0.45
F	1.14	2.37	1.38	0.52
G	--	4.44	1.39	0.51
H	1.13	4.10	1.38	0.53

TABLE III
Properties of Test Premixes

Premix	A.D. (g/cm^3)	Flow (sec/50g)	Sintered Density (g/cm^3)	Dimen. Change (%)	TRS ($psi \times 10^3$)	Hardness (HRB)
A	3.16	26	7.01	-0.07	174.8	86
B	3.18	27	6.96	+0.10	193.5	91
C	3.25	26	7.05	-0.23	213.5	94
D	3.18	26	6.99	0.00	216.9	96
E	3.29	24	7.02	-0.08	178.6	85
F	3.27	26	6.96	+0.14	200.4	92
G	3.33	25	7.04	-0.20	225.3	96
H	3.30	25	7.00	0.00	235.4	98

Notes:
1. Test bars compacted to 7.0 g/cm^3 green density.
2. Sintering: 2050°F, 25% N_2/75% H_2, 30 minutes.
3. Dimensional change from die size.

The sintering furnace was equipped with a controlled cooling zone such that cooling from equilibration to room temperature could be accelerated. For the work quoted below, the mean cooling rate from 1550°F to 930°F was 70°F/minute.

The standard test pieces have limited cross section. They experience very high cooling rates under accelerated cooling conditions. A series of test pieces was prepared to simulate the effect of increased section size upon mechanical properties. This was achieved by placing the test pieces on one-half inch thick sintered sheets. All test pieces were tempered at 450°F for one hour.

Testing

Tensile testing was performed using an Instron testing machine with a cross head speed of 0.1 “/minute. The Charpy test pieces were broken on a Baldwin impact test machine. Hardness measurements were made using a Wilson hardness test machine.

Metallography

Sections for metallographic examination were cut from the tensile and impact test pieces compacted at 40 tsi. These were prepared according to procedures in Reference 6. Quantitative metallography was conducted to estimate the distribution of microstructural phases within the test pieces using a “point count” technique as described in Reference 9.

RESULTS

The properties of the sintered test pieces met the aims of the research program in that the test materials attained very high density and, consequently, very high tensile strength levels. The detailed results are given in Tables IV and V and illustrated briefly below.

Density

The premix compositions attained the first objective of the program. They developed high green densities (Figure 1) when compacted to standard green density test pieces at pressures of 30 to 50 tsi.

TABLE IV

Results of Quantitative Metallography of Test Materials Compacted at 40 tsi

	Accelerated Cooling Rate							
	0.85% Molybdenum Prealloy				**1.5% Molybdenum Prealloy**			
Phase	**2 Ni, 0 Cu**	**2 Ni, 1 Cu**	**4 Ni, 0 Cu**	**4 Ni, 1 Cu**	**2 Ni, 0 Cu**	**2 Ni, 1 Cu**	**4 Ni, 0 Cu**	**4 Ni, 1 Cu**
Temp. Martensite	77.0	75.0	75.0	74.8	82.3	83.0	78.8	79.3

Nickel-Rich	5.0	5.8	9.3	13.5	5.8	8.5	12.5	12.8
Bainite	0	7.3	1.5	3.3	0.3	0	0.5	0.3
Pearlite	9.8	3.5	5.0	0.3	3.0	2.0	1.8	0.8
Porosity	8.3	8.5	9.3	8.3	8.8	6.5	6.5	7.0

	Reduced Cooling Rate							
	0.85% Molybdenum Prealloy				**1.5% Molybdenum Prealloy**			
Phase	**2 Ni, 0 Cu**	**2 Ni, 1 Cu**	**4 Ni, 0 Cu**	**4 Ni, 1 Cu**	**2 Ni, 0 Cu**	**2 Ni, 1 Cu**	**4 Ni, 0 Cu**	**4 Ni, 1 Cu**
Temp. Martensite	44.8	51.5	64.5	60.5	51.8	64.0	67.5	69.0
Nickel-Rich	3.3	1.0	7.5	6.8	5.0	8.3	12.3	10.8
Bainite	2.0	0	2.5	0	1.5	1.3	1.0	0
Pearlite	43.3	39.5	17.0	28.3	31.5	16.5	11.0	15.8
Porosity	6.8	8.0	8.5	4.5	10.3	10.0	8.3	4.5

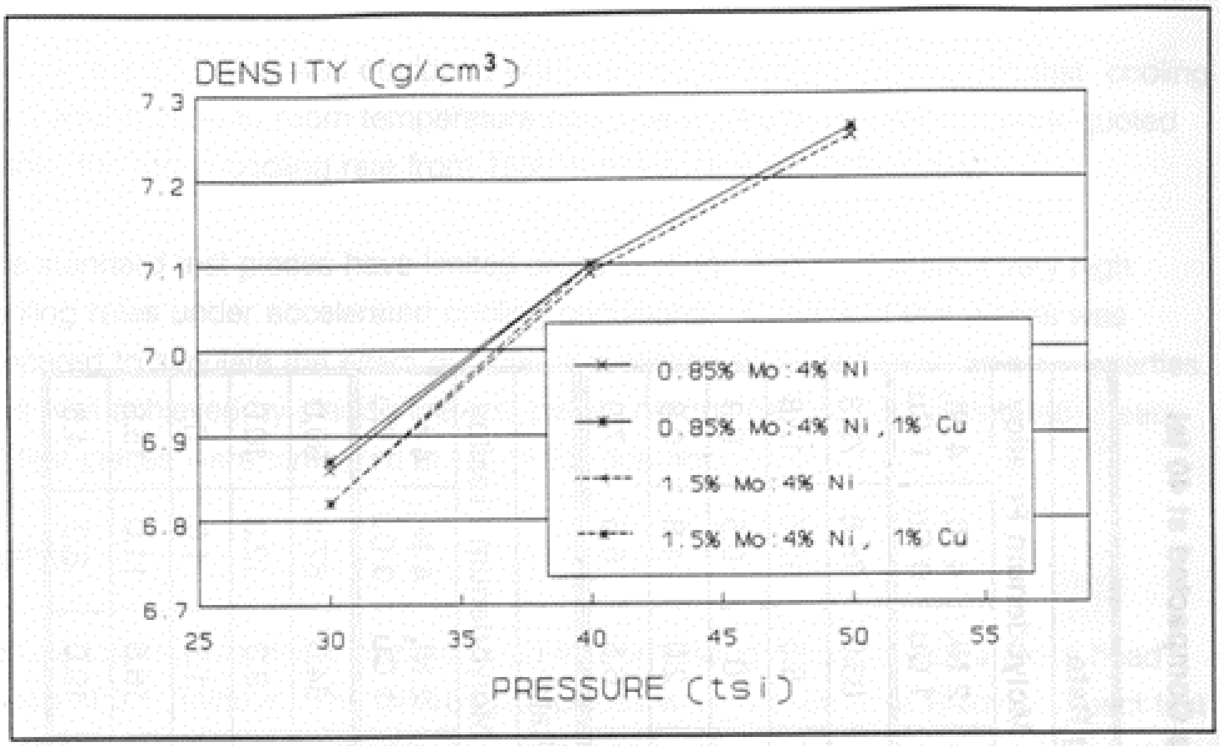

Figure 1: Compressibility of Test Materials

The high green densities translated into high sintered densities, Figure 2. This was especially noticeable in the case of the materials that contained only nickel additions. Slight shrinkage occurred on sintering to produce sintered densities approaching 7.3 g/cm^3.

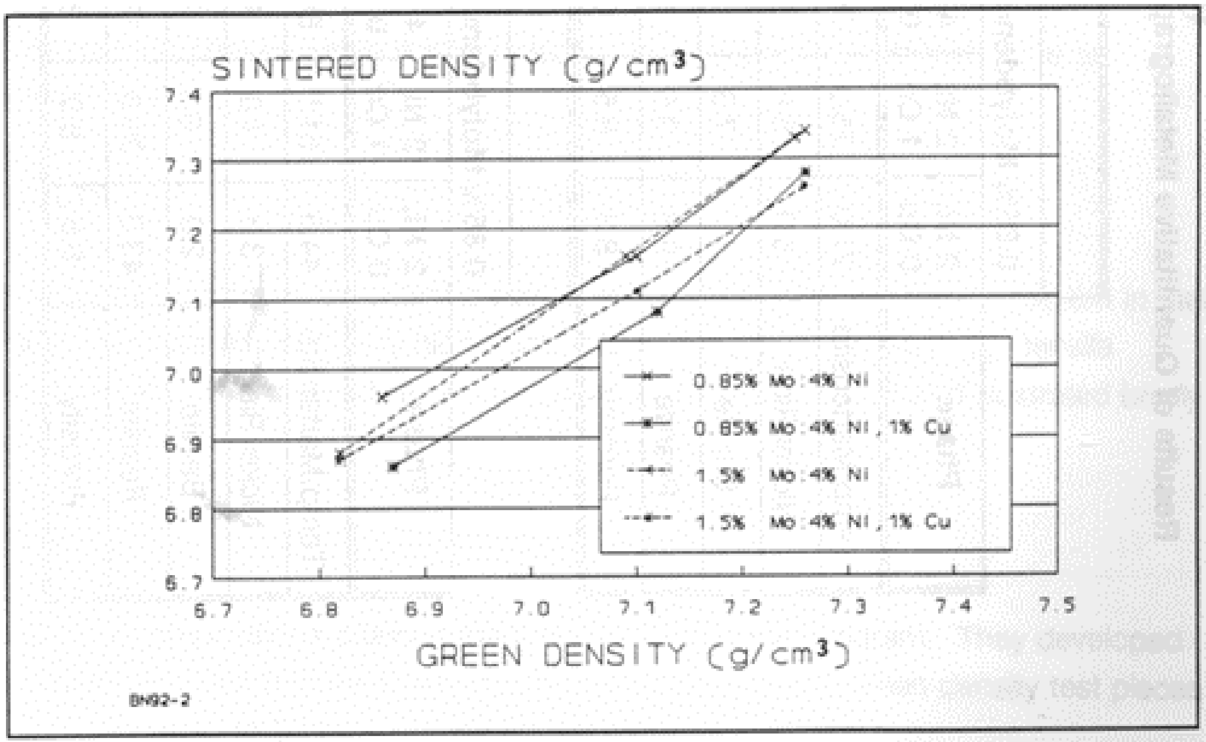

Figure 2: Sintered Density of Test Materials

METALLOGRAPHY

Qualitative Examination

The microstructures of the test materials were strongly influenced by cooling rate and composition. Examples of the range of microstructures produced are shown for materials based upon the 0.85% molybdenum prealloy. The materials experiencing accelerated cooling rates possessed largely martensitic microstructures (Figure 3) with smaller amounts of nickel-rich areas, bainite and pearlite.

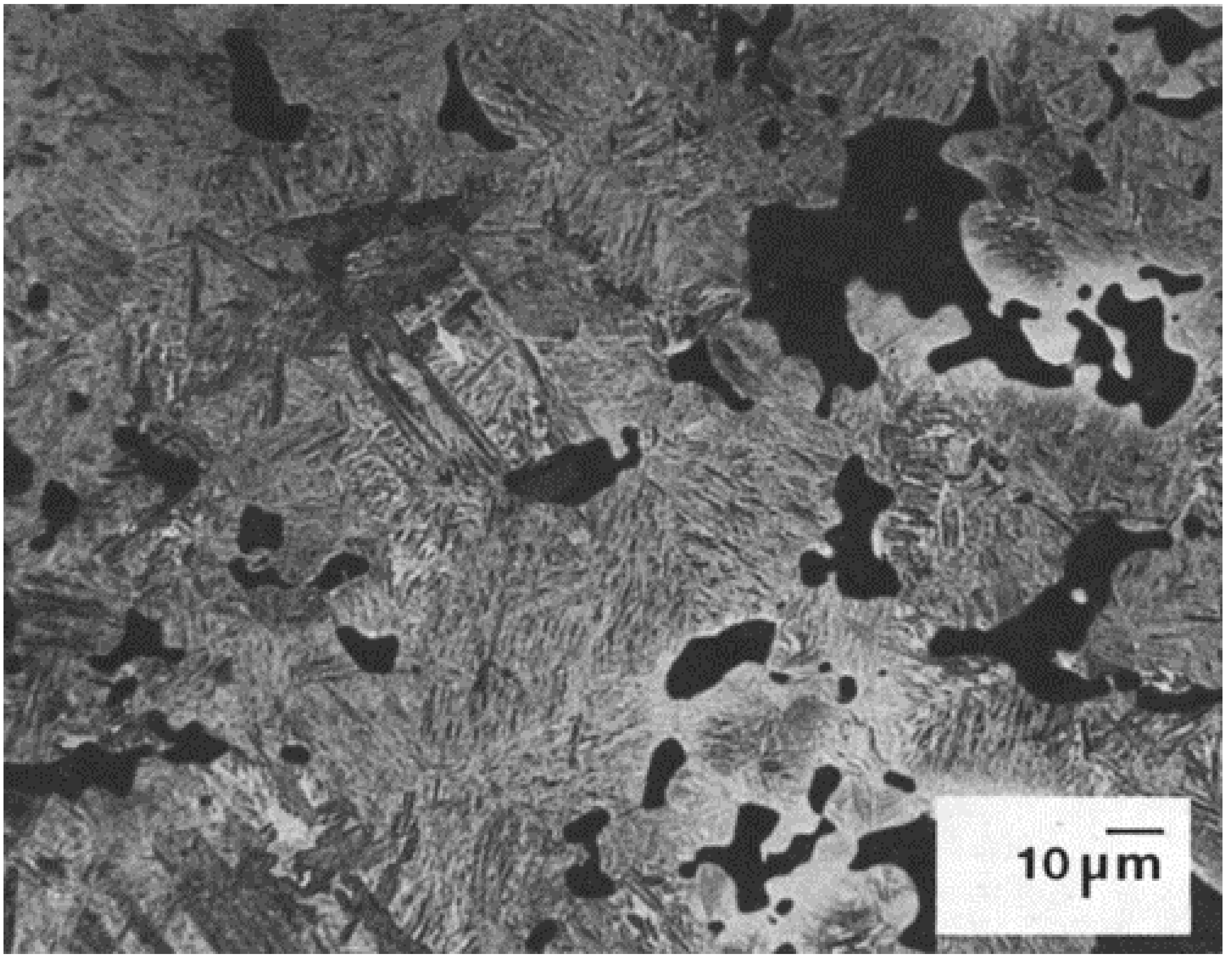

Figure 3: Microstructure of material B following accelerated cooling from the sintering temperature. Etched with a combination of 2% nital/4% picral. Original magnification 750X.

The microstructures of the test pieces that experienced reduced cooling rates (Figures 4 to 7) consisted of tempered martensite and pearlite plus quantities of nickel-rich areas and bainite.

Quantitative Examination

The qualitative findings were confirmed by the quantitative metallography with results shown in Table IV and illustrated in Figures 8 and 9.

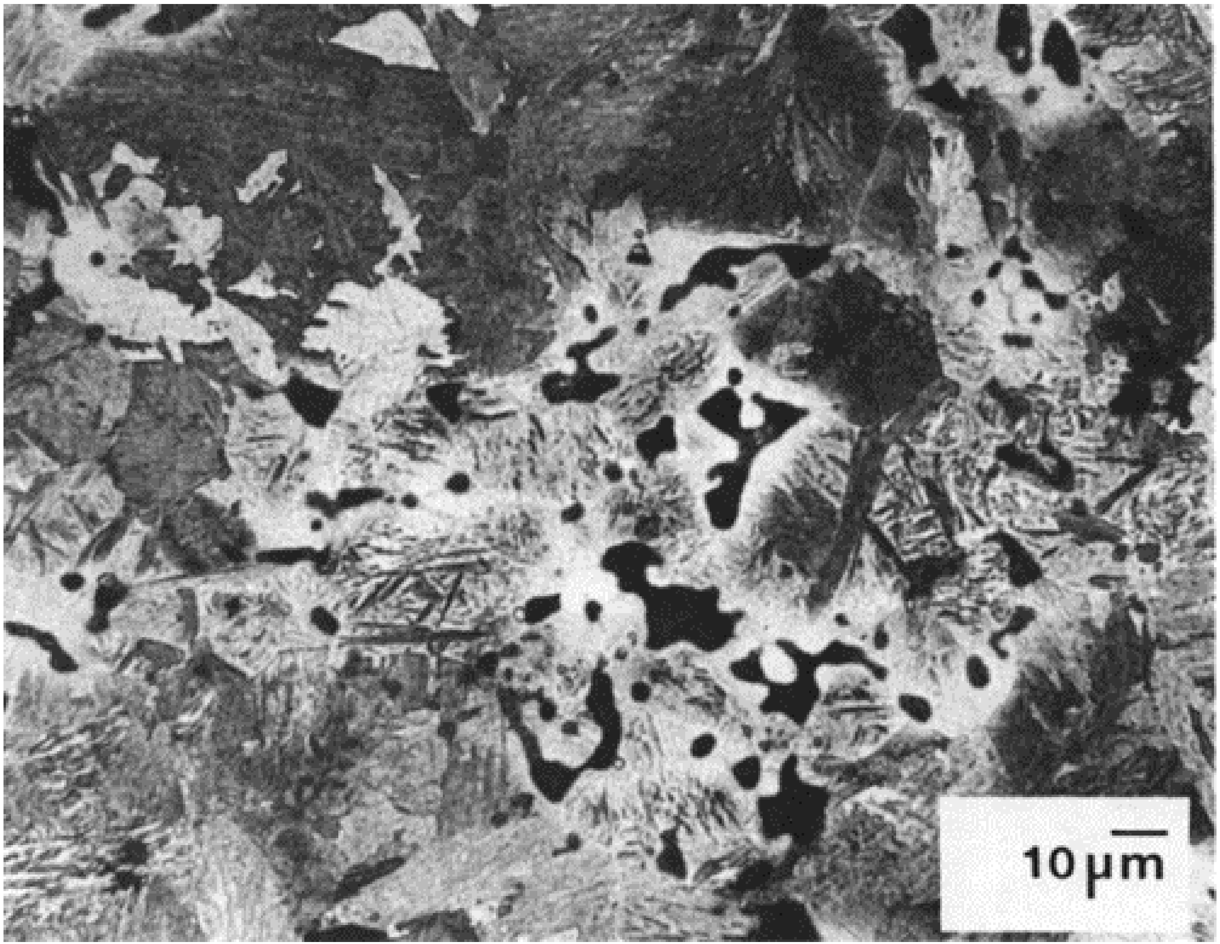

Figure 4: Microstructure of material A produced at reduced cooling rate from the sintering temperature. Etched with a combination of 2% nital/4% picral. Original magnification 750X.

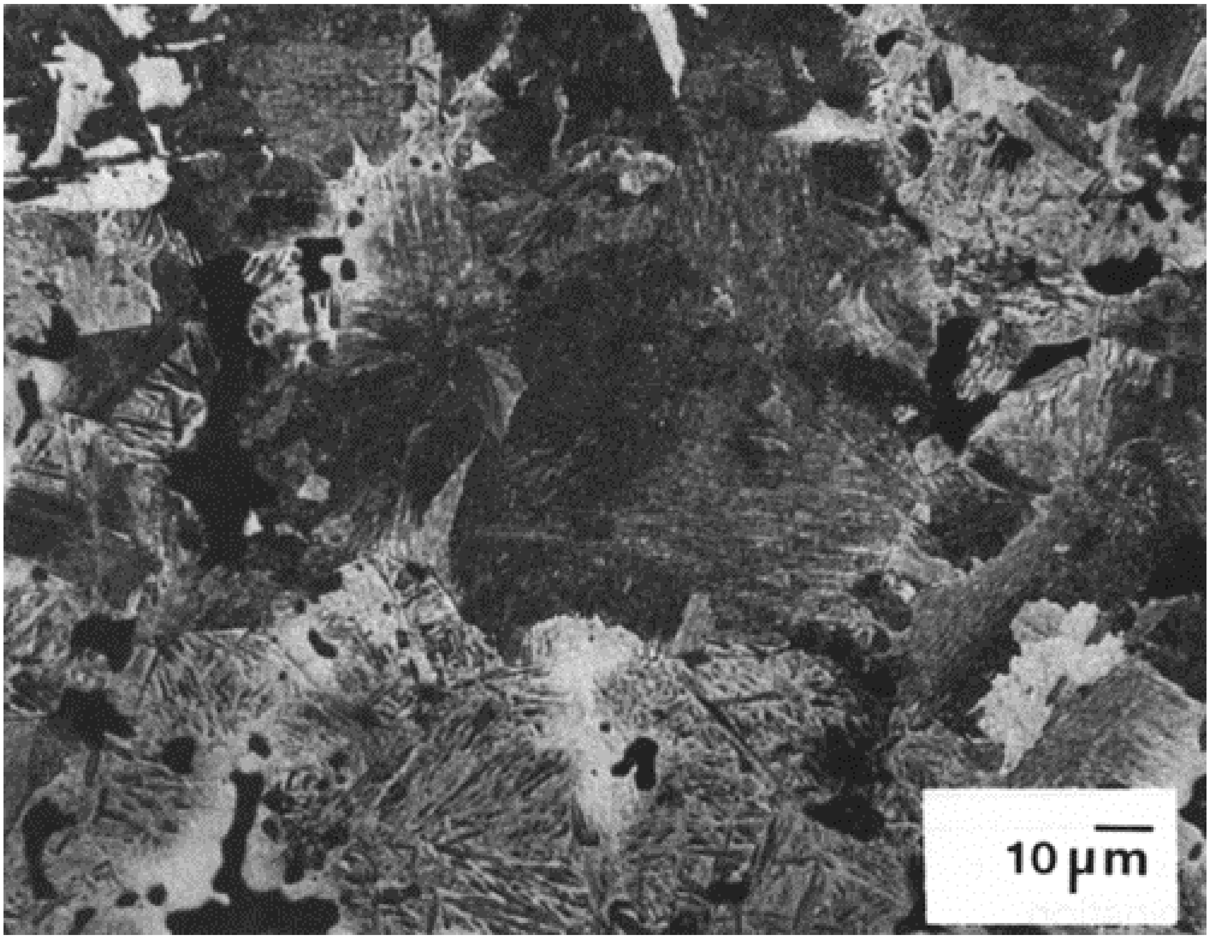

Figure 5: Microstructure of material B produced at reduced cooling rate from the sintering temperature. Etched with a combination of 2% nital/4% picral. Original magnification 750X.

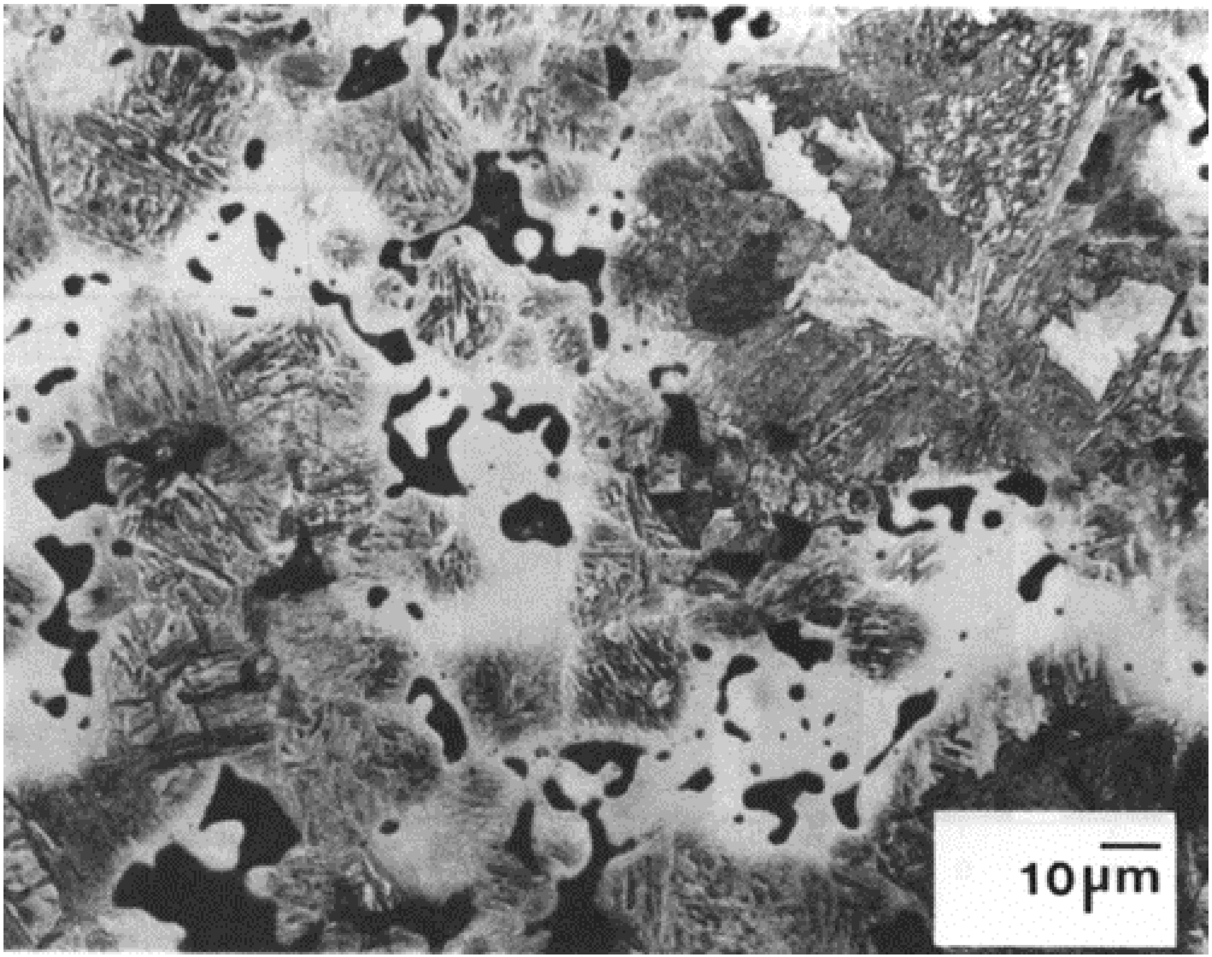

Figure 6: Microstructure of material C produced at reduced cooling rate from the sintering temperature. Etched with a combination of 2% nital/4% picral. Original magnification 750X.

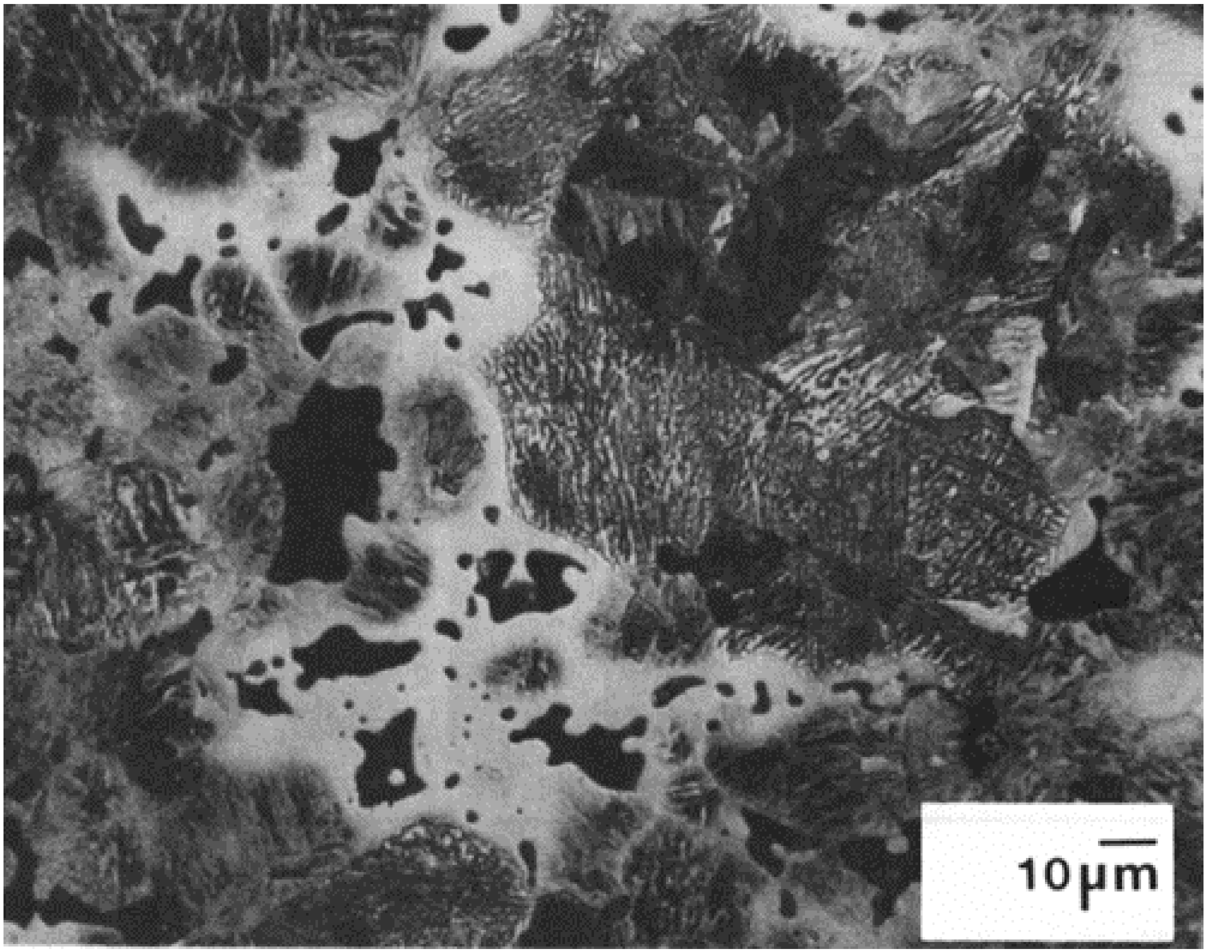

Figure 7: Microstructure of material D produced at reduced cooling rate from the sintering temperature. Etched with a combination of 2% nital/4% picral. Original magnification 750X.

The results confirm that the accelerated cooling rate produced test materials possessing largely martensitic microstructures (Figure 8). The reduced cooling rate, simulating increased section size, reduced the martensite content and increased the amount of pearlite (Figure 9).

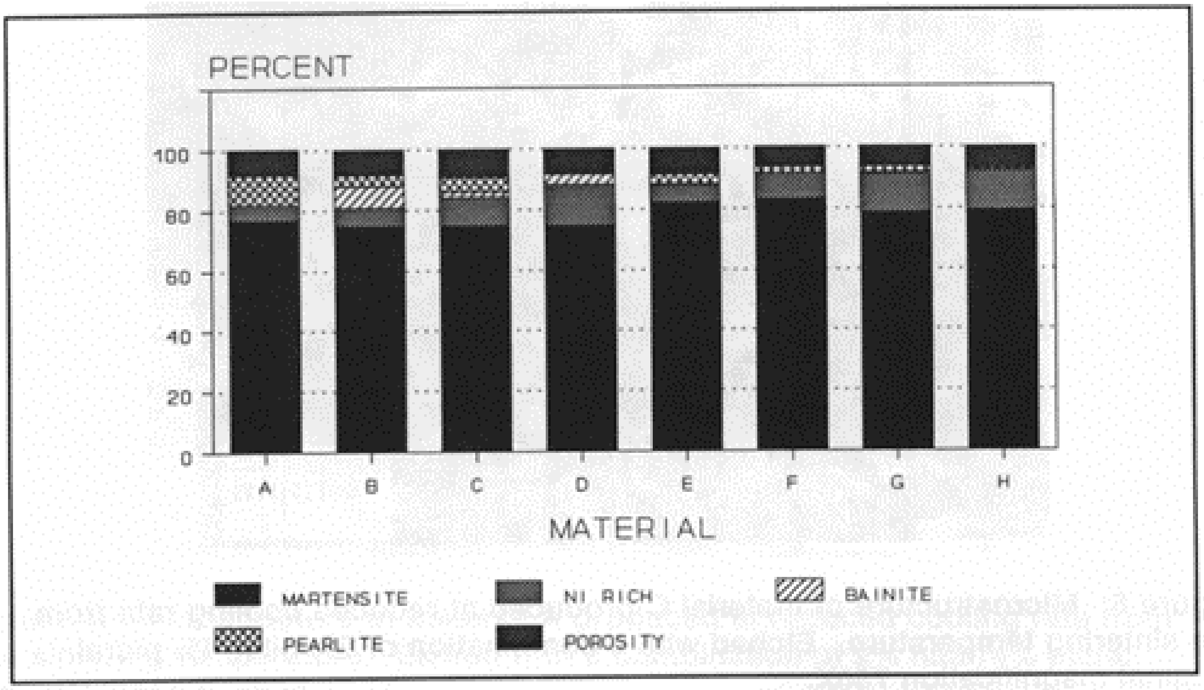

Figure 8: Microstructure of Test Materials Experiencing Accelerated Cooling Rate

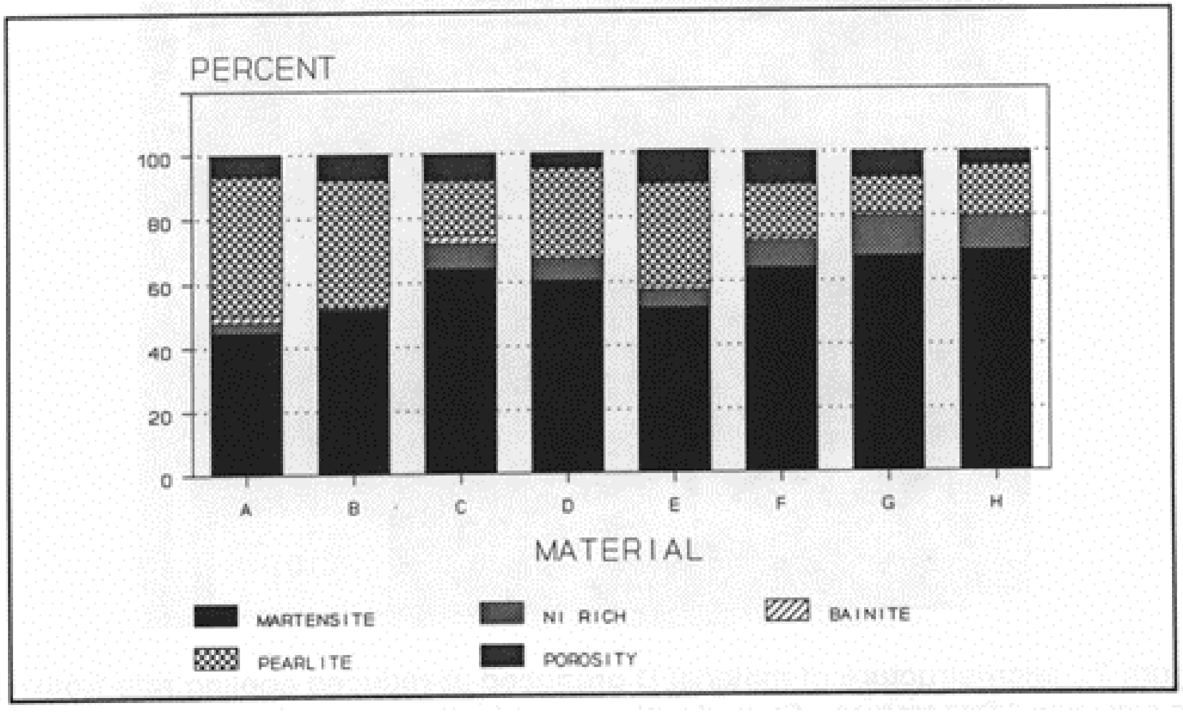

Figure 9: Microstructure of Test Materials Experiencing Reduced Cooling Rate

The quantitative data indicate that the proportion of nickel-rich areas increases with increasing nickel content under both cooling conditions. The quantitative data confirm that the microstructures have very low bainite contents with the exception of the material containing 2% nickel and 1% copper made with the 0.85% molybdenum prealloy.

Tensile Strength

The mechanical properties of the test materials are given in Table V and discussed subsequently. The properties of materials experiencing accelerated cooling are illustrated below to indicate overall trends.

The materials developed high tensile strengths, illustrated in Figures 10 and 11 for the 0.85% and 1.5% molybdenum prealloys, respectively.

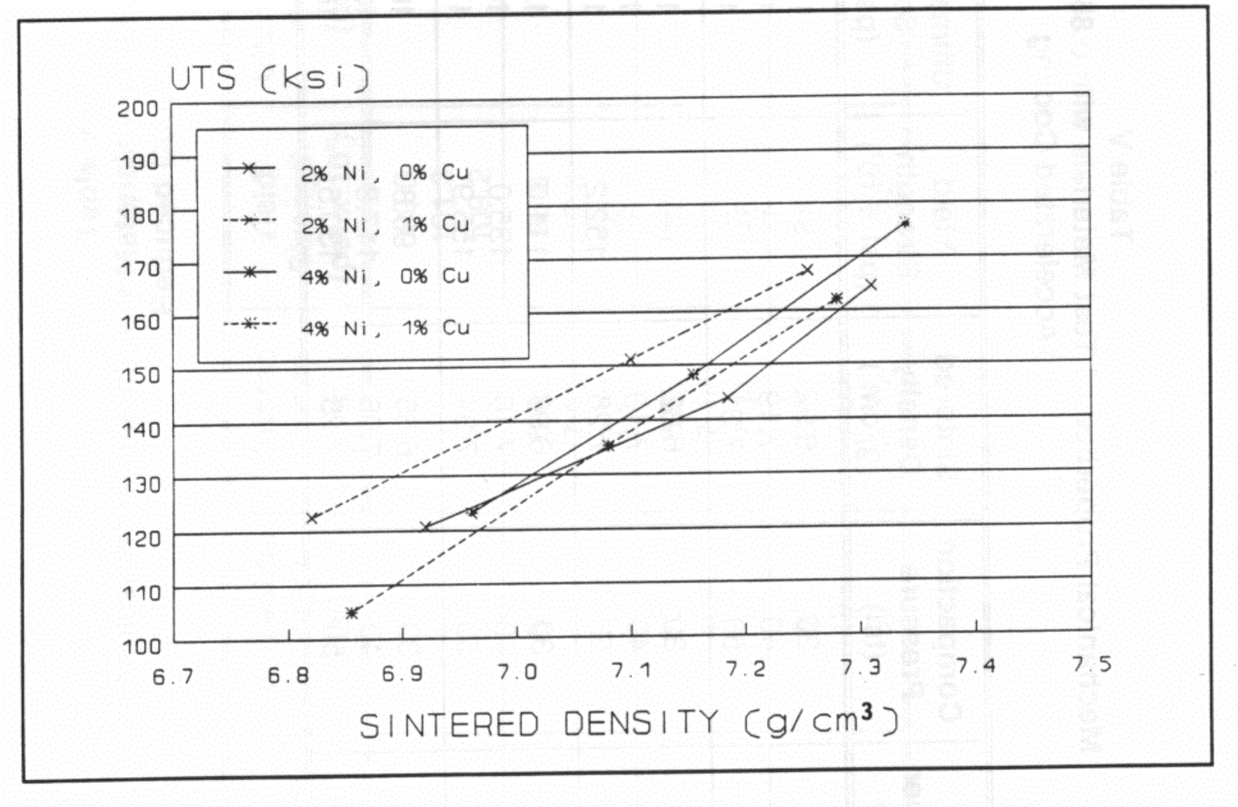

Figure 10: Effect of Accelerated Cooling Upon UTS of Test Materials with 0.85% Mo Prealloy

TABLE V
Mechanical Properties of Test Materials with 0.85% Molybdenum Prealloy Accelerated Cooling

Nickel (%)	Copper (%)	Compaction Pressure (tsi)	Sintered Density (g/cm^3)	Yield Strength (psi x 10^3)	Ultimate Tensile Strength (psi x 10^3)	Elongation (%)	Impact (ft•lbf)	Hardness (HRC)
2	0	30	6.92	--	120.75	0.7	7	22.9
		40	7.19	--	143.9	0.7	10	28.1

		50	7.31	--	164.5	0.9	12	30.7
2	1	30	6.82	--	122.7	0.8	7	24.1
		40	7.10	--	151.1	1.0	10	30.3
		50	7.26	152.2	167.5	1.0	13	33.0
4	0	30	6.96	111.0	123.2	0.9	8	23.0
		40	7.16	135.0	148.2	1.0	11	28.4
		50	7.34	155.9	176.1	1.8	14	32.4
4	1	30	6.86	104.9	104.9	0.9	9	24.4
		40	7.08	135.3	135.3	1.1	11	28.1
		50	7.28	162.0	162.0	1.2	13	32.8

TABLE V

Mechanical Properties of Test Materials with 0.85% Molybdenum Prealloy Reduced Cooling

Nickel (%)	Copper (%)	Compaction Pressure (tsi)	Sintered Density (g/cm^3)	Yield Strength (psi x 10^3)	Ultimate Tensile Strength (psi x 10^3)	Elongation (%)	Impact (ft•lbf)	Hardness (HRC)
2	0	30	6.92	89.0	105.3	1.0	7	13.6
		40	7.19	101.3	121.9	1.3	10	18.8
		50	7.31	109.2	131.8	1.3	12	18.6
2	1	30	6.82	96.8	111.7	1.0	7	19.4
		40	7.10	117.8	135.8	1.1	10	22.6
		50	7.26	123.0	148.0	1.2	14	26.2
4	0	30	6.96	102.3	114.9	0.9	8	19.4
		40	7.16	111.9	141.4	1.4	12	26.1
		50	7.34	146.3	162.4	1.1	14	27.4
4	1	30	6.86	87.7	104.7	0.9	9	17.1
		40	7.08	111.1	135.9	1.3	12	20.7
		50	7.28	126.4	143.9	1.0	15	26.1

TABLE V

Mechanical Properties of Test Materials with 1.50% Molybdenum Prealloy Accelerated Cooling

Nickel (%)	Copper (%)	Compaction Pressure (tsi)	Sintered Density (g/cm^3)	Yield Strength (psi x 10^3)	Ultimate Tensile Strength (psi x 10^3)	Elongation (%)	Impact (ft•lbf)	Hardness (HRC)
2	0	30	6.86	--	110.6	0.6	6	25.3
		40	7.12	--	145.8	0.7	9	30.3
		50	7.32	--	180.2	1.0	12	35.5
2	1	30	6.83	108.7	118.0	0.8	7	25.2
		40	7.10	133.5	151.4	1.0	11	30.2
		50	7.25	--	156.5	1.1	13	33.8
4	0	30	6.88	113.0	124.1	0.9	7	24.3
		40	7.16	139.6	163.4	1.2	11	29.9
		50	7.33	165.3	187.9	1.5	13	34.9
4	1	30	6.87	93.8	104.5	0.9	8	23.6

		40	7.11	119.7	135.8	1.1	12	29.8
		50	7.26	142.1	166.4	1.7	13	32.1

TABLE V
Mechanical Properties of Test Materials with 1.50% Molybdenum Prealloy Reduced Cooling

Nickel (%)	Copper (%)	Compaction Pressure (tsi)	Sintered Density (g/cm^3)	Yield Strength (psi x 10^3)	Ultimate Tensile Strength (psi x 10^3)	Elongation (%)	Impact (ft•lbf)	Hardness (HRC)
2	0	30	6.86	--	101.0	0.7	6	20.1
		40	7.12	116.9	134.8	0.8	10	24.3
		50	7.32	141.9	161.1	1.1	11	29.6
2	1	30	6.83	103.9	110.4	0.8	7	20.9
		40	7.10	126.2	143.6	1.0	8	27.3
		50	7.25	128.4	142.8	1.1	12	27.3
4	0	30	6.88	104.9	118.5	0.9	7	23.3
		40	7.16	129.3	151.8	1.1	12	27.9
		50	7.33	146.5	174.6	1.6	13	34.7
4	1	30	6.87	--	104.0	1.0	8	21.4
		40	7.11	112.7	130.1	1.1	12	25.8
		50	7.26	128.6	154.6	1.6	14	30.3

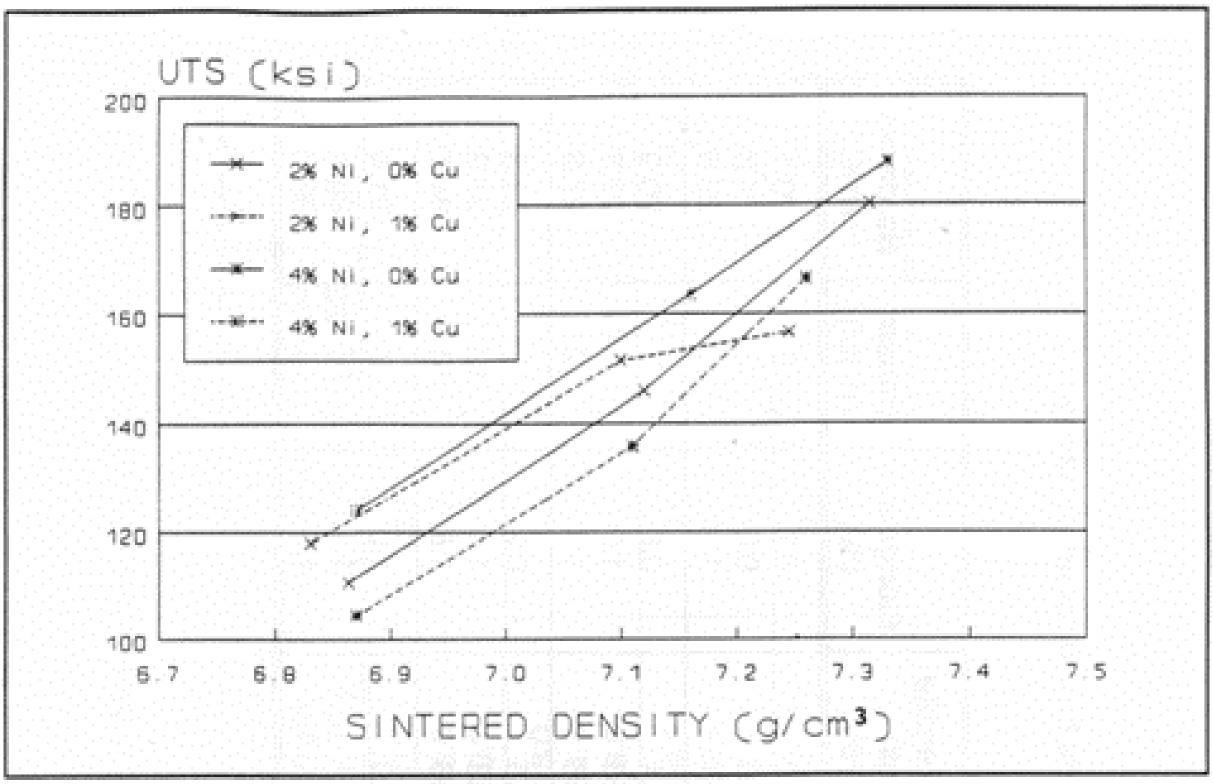

Figure 11: Effect of Accelerated Cooling Upon UTS of Test

Materials with 1.5% Mo Prealloy

For the materials based upon the 0.85% molybdenum prealloy, tensile strength varied from approximately 110,000 psi, at sintered densities of approximately 6.9 g/cm^3, to over 160,000 psi for materials with sintered densities approaching 7.3 g/cm^3. Similar trends were observed for materials based upon the 1.5% molybdenum prealloy where an ultimate tensile strength in excess of 180,000 psi was obtained in material G containing 4% admixed nickel.

However, the strength data indicate clear interactions between copper and nickel contents and tensile properties. These are discussed in further below.

Impact

The impact energies, following accelerated cooling, are summarized in Figures 12 and 13 for materials based upon the 0.85 and 1.5% molybdenum prealloys, respectively. For both systems, impact strength increases with increasing density.

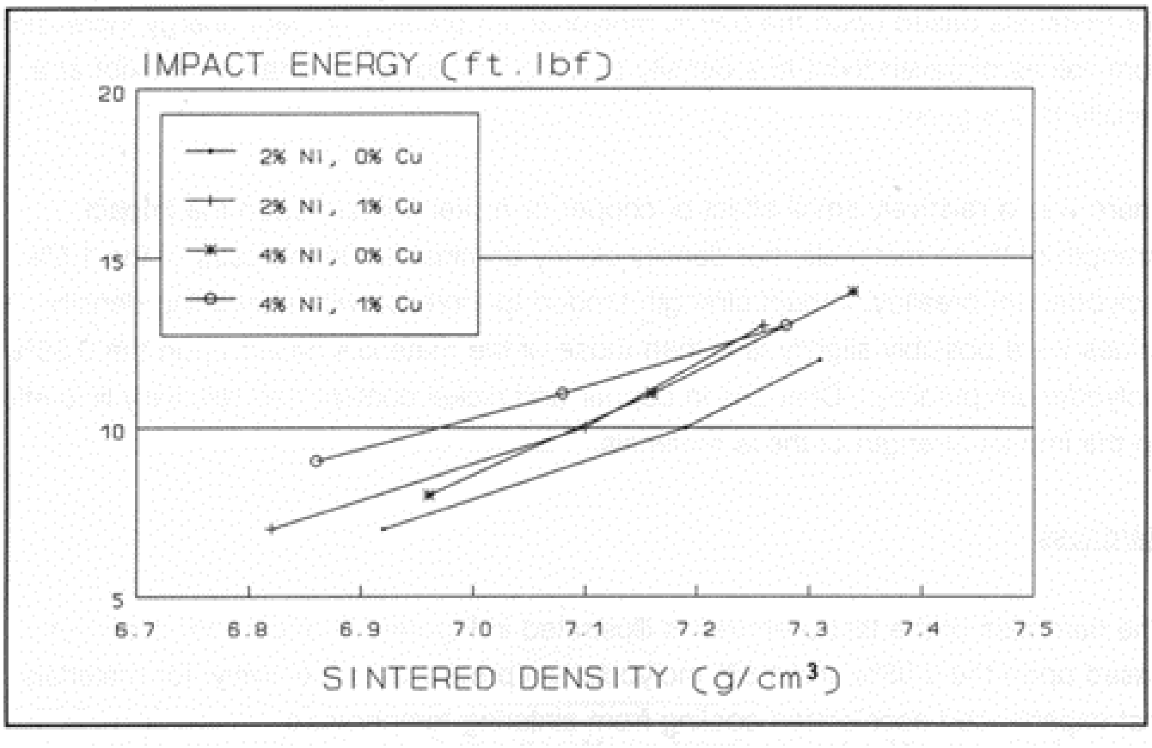

Figure 12: Effect of Accelerated Cooling Upon Impact Energy of 0.85% Mo Test Materials

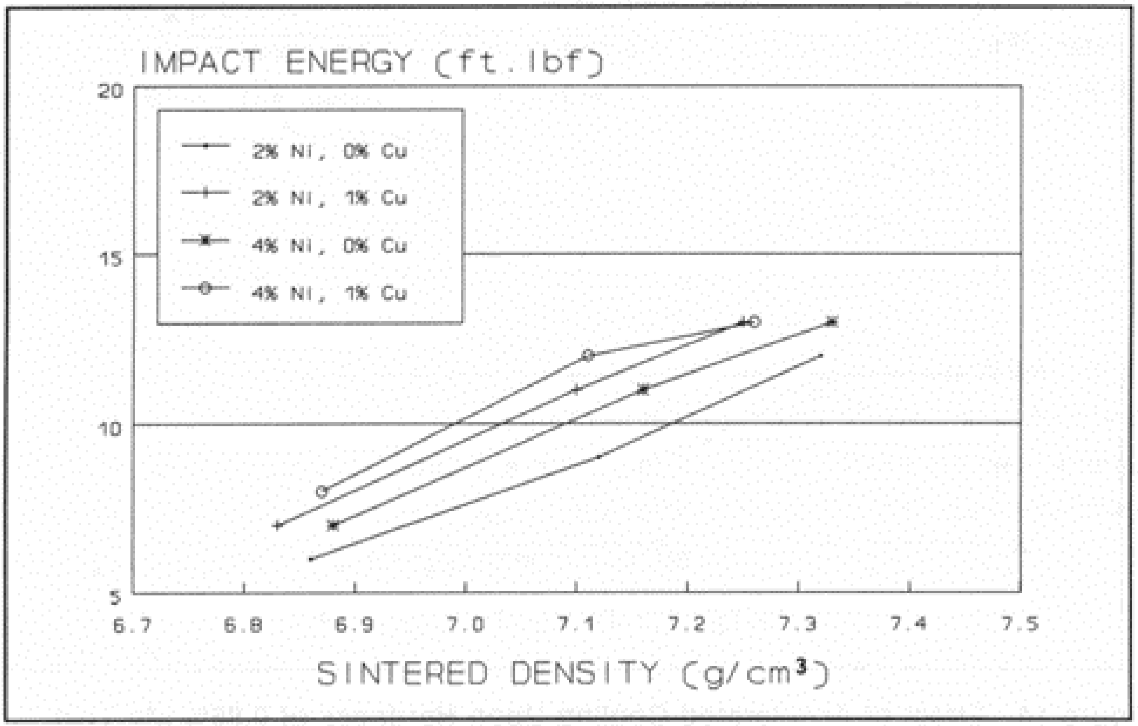

Figure 13: Effect of Accelerated Cooling Upon Impact Energy of 1.5% Mo Test Materials

For materials based upon the 0.85% molybdenum prealloy, impact energy increased from values of seven ft•lbf at a density of 6.8 g/cm^3 to approximately 14 ft•lbf at a density of 7.3 g/cm^3.

There was a relatively small effect of copper or nickel content upon the impact strength of these materials, but density clearly dominates. In the case of the 1.5% molybdenum prealloy, impact strength tended to increase with increasing density. The values were possibly slightly less than those of the materials based upon the 0.85% molybdenum prealloy. Changes in copper and nickel content had relatively little effect on the impact strength of these materials.

Hardness

The hardness of the test premixes is illustrated in Figures 14 and 15 for premixes based upon the 0.85% and 1.5% molybdenum prealloys, respectively, for materials that experienced accelerated cooling from sintering temperature.

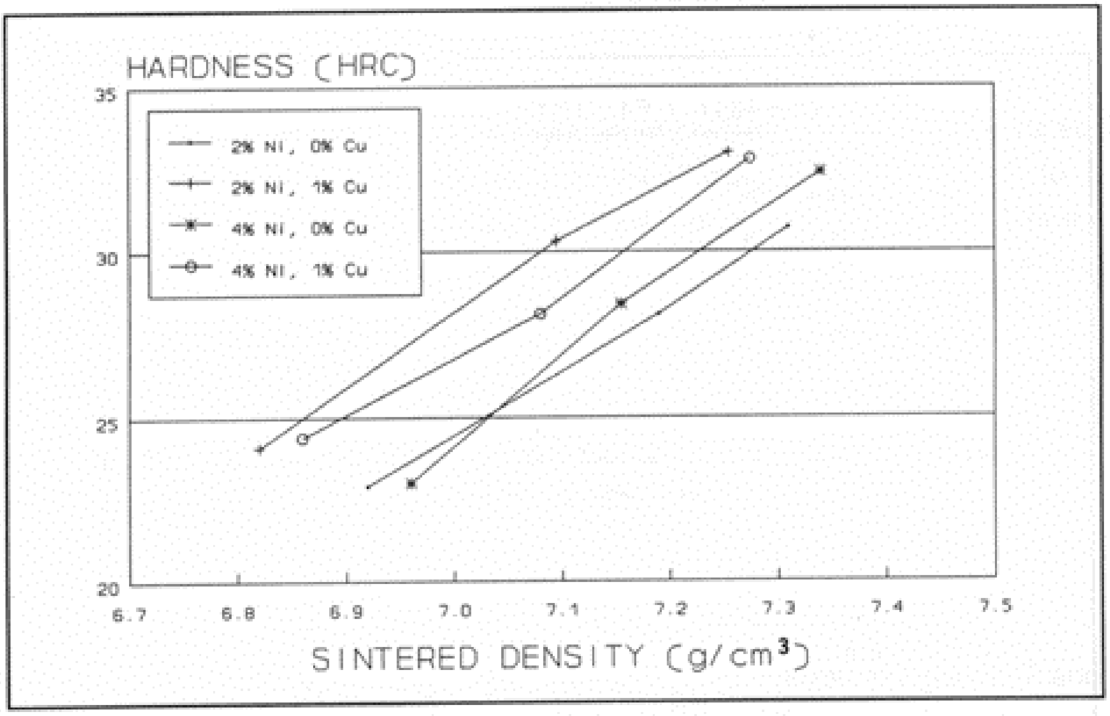

Figure 14: Effect of Accelerated Cooling Upon Hardness of 0.85% Mo Test Materials

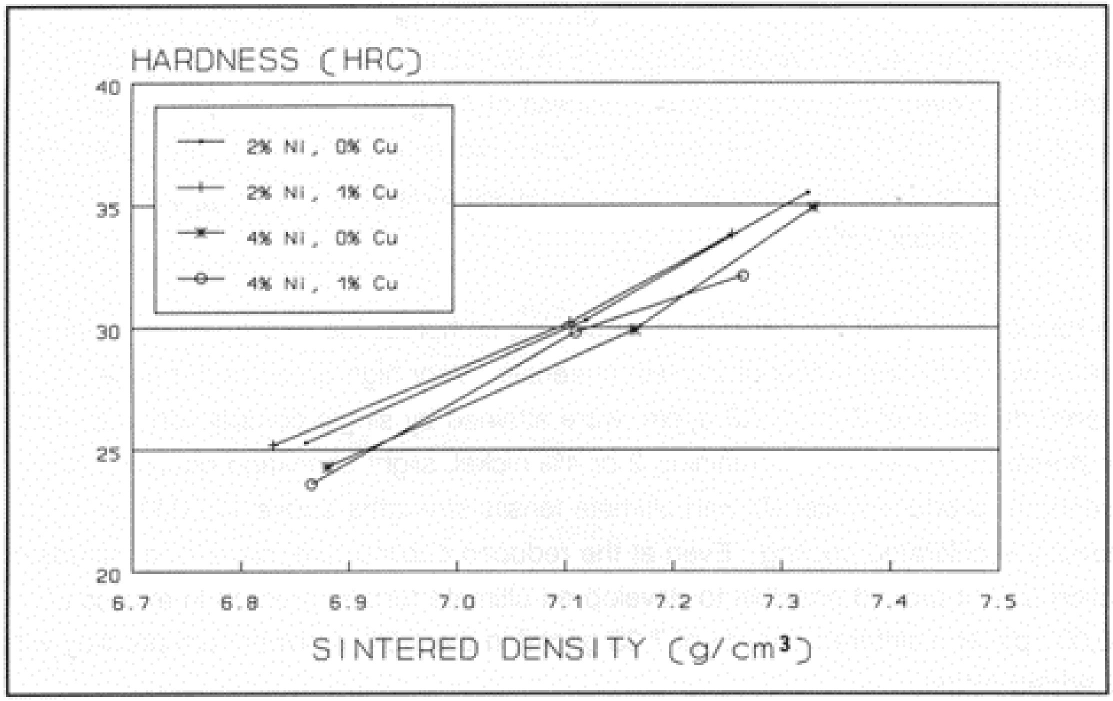

Figure 15: Effect of Accelerated Cooling Upon Hardness of 1.5% Mo Test Materials

The processing produced some variation in hardness between tensile and impact test pieces. For convenience, the hardness plotted is the mean of 15 to 25 determinations per test condition. The materials developed relatively high hardness levels from 15 to 35 HRC depending on density and composition.

For those materials based on the 0.85% molybdenum prealloy, hardness increases with increasing density from approximately 22 HRC at 6.8 g/cm^3 to high values of 33 HRC at 7.3 g/cm^3. The materials based upon the 1.5% molybdenum prealloy generally attain higher hardnesses than the equivalent material based upon the 0.85% molybdenum prealloy. Hardness increases from approximately 23 HRC at a density of 6.8 g/cm^3 to approximately 35 HRC at a density of 7.3 g/cm^3. There are clear interactions between the matrix compositions, and the relative additions of copper and nickel content upon hardness that are discussed further below.

DISCUSSION

The results above illustrate that the program attained its goals. By control of composition, processing and microstructure, materials were developed that attained properties comparable to those of double pressed, double sintered P/M materials but by single compaction processing. When compacted at 50 tsi, the low-alloy nickel, graphite materials achieved sintered densities in excess of 7.3 g/cm^3 with ultimate tensile strengths of 180,000 psi. The low-alloy copper, nickel, graphite materials possessed slightly lower sintered densities and ultimate tensile strengths of 7.25 g/cm^3 and 185,000 psi, respectively.

The results confirmed the benefits of employing compressible molybdenum prealloyed steel powders for the matrix of the test materials. Very high green and, hence, sintered densities of 7.25 to 7.3 g/cm^3 were attained by single compaction in production presses. In materials containing 2 or 4% nickel, slight shrinkage occurred on sintering to produce materials with ultimate tensile strengths above 175,000 psi following accelerated cooling. Even at the reduced cooling rate, simulating increased section size, it proved possible to develop an ultimate tensile strength in excess of 170,000 psi at a sintered density of 7.33 g/cm^3 in the 1.5% molybdenum prealloy with 4% added nickel.

Alternatively, by controlled additions of copper and nickel, materials were produced that achieved ultimate tensile strength above 160,000 psi at sintered densities of 7.2 g/cm^3, following accelerated cooling that show less size change in sintering.

The results indicate interactions of composition and processing in controlling the microstructure and hence properties of the test materials. Certain of these were anticipated, such as the beneficial effects of molybdenum in improving the hardenability and strength of materials processed at lower cooling rates. Others were not anticipated, particularly the apparent adverse influence of copper on the properties of materials with higher nickel content. These are discussed below with reference to the original themes of:

relative density
microstructure
matrix

Relative Density

The results confirm that all materials' properties, UTS, impact energy and hardness increased with increasing sintered density. It appears that increasing the molybdenum content of the prealloy powder slightly reduces green density (Figures 1 and 2), particularly at lower compaction pressures. The effect is much less significant at higher compaction pressures.

It is possible that the higher molybdenum content slightly favors shrinkage on sintering. The sintered densities of test pieces of equivalent composition are almost identical (Figure 2), although the green densities of materials made with the 1.5% molybdenum prealloy are lower than those of their 0.85% molybdenum equivalent.

As is common in ferrous P/M, adding nickel to the test pieces favored shrinkage on sintering. Adding 1% copper to the test materials favored growth from die size on sintering. Thus, dimensional change on sintering can be used to increase sintered density and properties.

Microstructure

The metallography indicated that the materials possessed microstructures consisting of tempered martensite, pearlite, nickel-rich areas and small quantities of bainite (Figures 3 - 7). Overall, reducing the cooling rate suppressed martensite formation and increased pearlite contents (Figure 16). The lower cooling rate reduced the mean tempered martensite content of the test materials from 78% to 59%.

The tempered martensite content of the accelerated cooled materials was relatively consistent. It varied only from 75% to 83% indicating that the cooling rate was sufficiently rapid to form martensite independently of alloy content in the materials tested. Thus, under accelerated cooling, increasing the molybdenum content of the prealloy from 0.85% to 1.5% produces a small increase in the mean tempered martensite content from 75.5%

to 81%. At the reduced cooling rate, simulating increased section size, increasing the molybdenum content from 0.85% to 1.5% increases the mean tempered martensite content of the test materials more significantly from 55 to 63%.

Increasing nickel content from 2-4% has much less consistent effects. Under accelerated cooling, increasing nickel content has no significant effect upon the tempered martensite content of the materials made with the 0.85% molybdenum prealloy. Increased nickel may slightly reduce the tempered martensite content of materials made with the 1.5% Mo prealloy. There appears to be an interaction between the effects of copper and nickel content at the lower cooling rate.

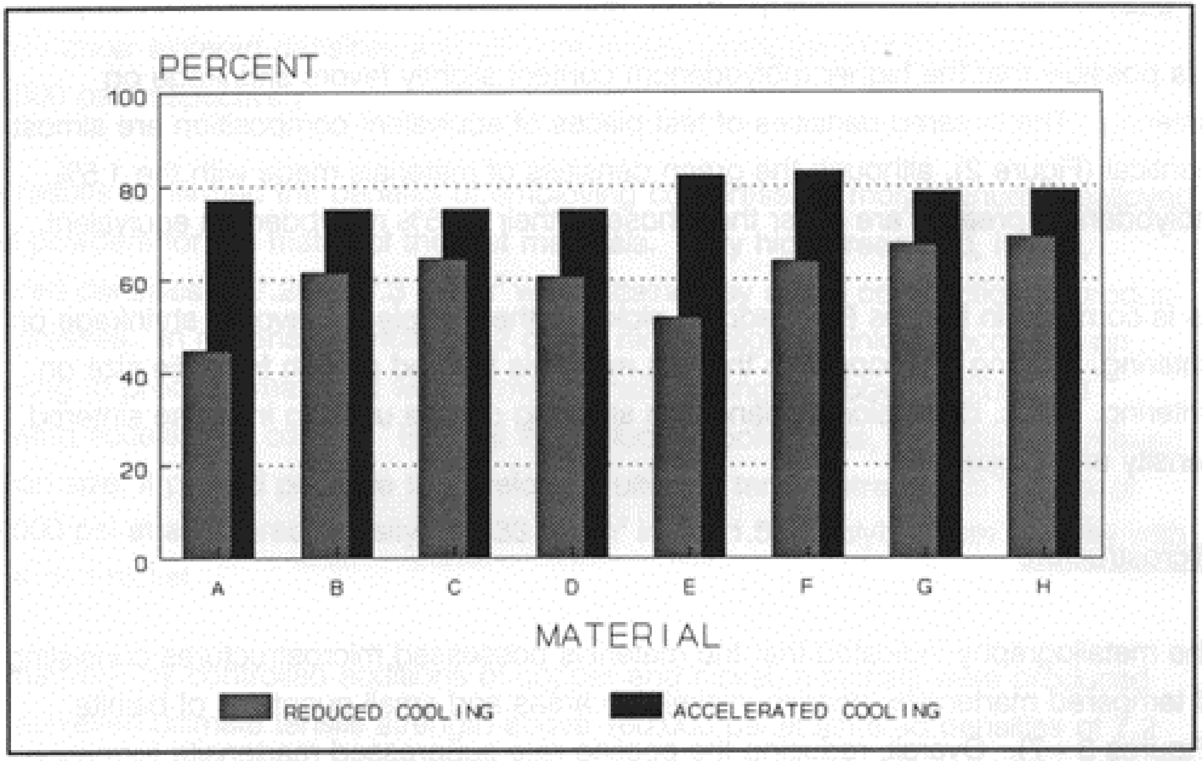

Figure 16: Effect of Cooling Rate Upon Tempered Martensite Content of Test Materials

In copper-free materials, increasing nickel content from 2 to 4% increases the tempered martensite content of slowly cooled materials from 48% to 66%. In the presence of 1% copper, increasing nickel from 2% to 4%, increases mean tempered martensite content from 57% to 66%.

Adding 1% copper to improve hardenability at the lower cooling rate is only effective at the 2% nickel level where the mean tempered martensite content increased from 48% to 58%. It is possible that this is due to formation of a stable copper and nickel-rich phase at higher copper and nickel contents. The proportion of nickel-rich areas increases significantly in the 4% nickel and 4% nickel, 1% copper materials (Table IV). Given the mutual solid solubility of copper and nickel, it is possible that these areas contain both copper and nickel. The presence of dissolved nickel in copper would raise the melting point of the copper to delay solution of copper in the matrix. The alloys, particularly copper, contained in the nickel-rich areas would reduce the concentration of alloy dissolved in the iron matrix at the end of sintering. Hence, the contribution of copper and nickel to strength and hardenability improvements would be less than anticipated from the chemical composition.

Mechanical Properties

The effects of changing microstructure are apparent in the mechanical properties of the test materials. When compacted at 40 tsi, both ultimate tensile strength (Figure 17) and hardness (Figure 18) increase with increasing tempered martensite content for all test materials under accelerated and reduced cooling rates. The impact strength of the test materials is largely independent of process conditions and microstructure but is dominated by porosity.

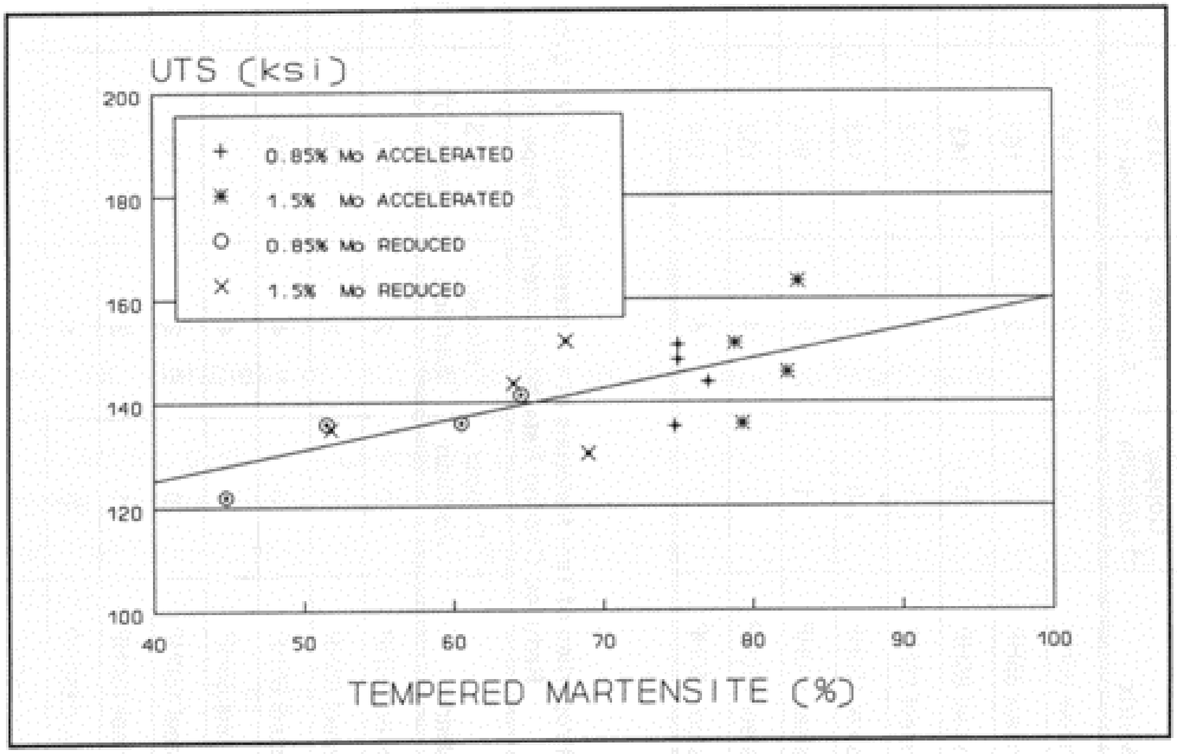

Figure 17: UTS of Test Materials versus Tempered Martensite

Increasing density improves the mechanical properties of the test materials. Thus, the effects of process conditions and composition are discussed using property values estimated at a sintered density of 7.1 g/cm^3 (Table VI) by interpolation from the curves of sintered properties versus sintered density.

Given the quantitative link between mechanical properties and tempered martensite content established by quantitative metallography, the interactions between chemical composition, cooling rate and ultimate tensile strength becomes more understandable in terms of basic metallurgical principles.

TABLE VI
Properties of Test Materials at a Sintered Density of 7.1 g/cm^3
Accelerated Cooling Rate from Sintering Temperature

Material	Matrix	Copper Addition	Nickel Addition	UTS (psi x 103)	Impact (ft•lbf)	Hardness HRC
A	Ancorsteel 85HP	0	2	136	9	26.2
B	Ancorsteel 85HP	1	2	152	10	30.3
C	Ancorsteel 85HP	0	4	143	10	26.8
D	Ancorsteel 85HP	1	4	138	11	28.5
E	Ancorsteel 150HP	0	2	143	9	29.8
F	Ancorsteel 150HP	1	2	151	11	30.2
G	Ancorsteel 150HP	0	4	152	10	28.6
H	Ancorsteel 150HP	1	4	134	12	29.5

TABLE VI
Properties of Test Materials at a Sintered Density of 7.1 g/cm^3
Reduced Cooling Rate from Sintering Temperature

Material	Matrix	Copper Addition	Nickel Addition	UTS (psi x 103)	Impact (ft•lbf)	Hardness HRC
A	Ancorsteel 85HP	0	2	117	9	17.1
B	Ancorsteel 85HP	1	2	136	10	22.8
C	Ancorsteel 85HP	0	4	133	11	24.0
D	Ancorsteel 85HP	1	4	137	12	21.0
E	Ancorsteel 150HP	0	2	133	10	24.0
F	Ancorsteel 150HP	1	2	143	11	27.2
G	Ancorsteel 150HP	0	4	144	11	26.9
H	Ancorsteel	1	4	129	11	25.6

	150HP					

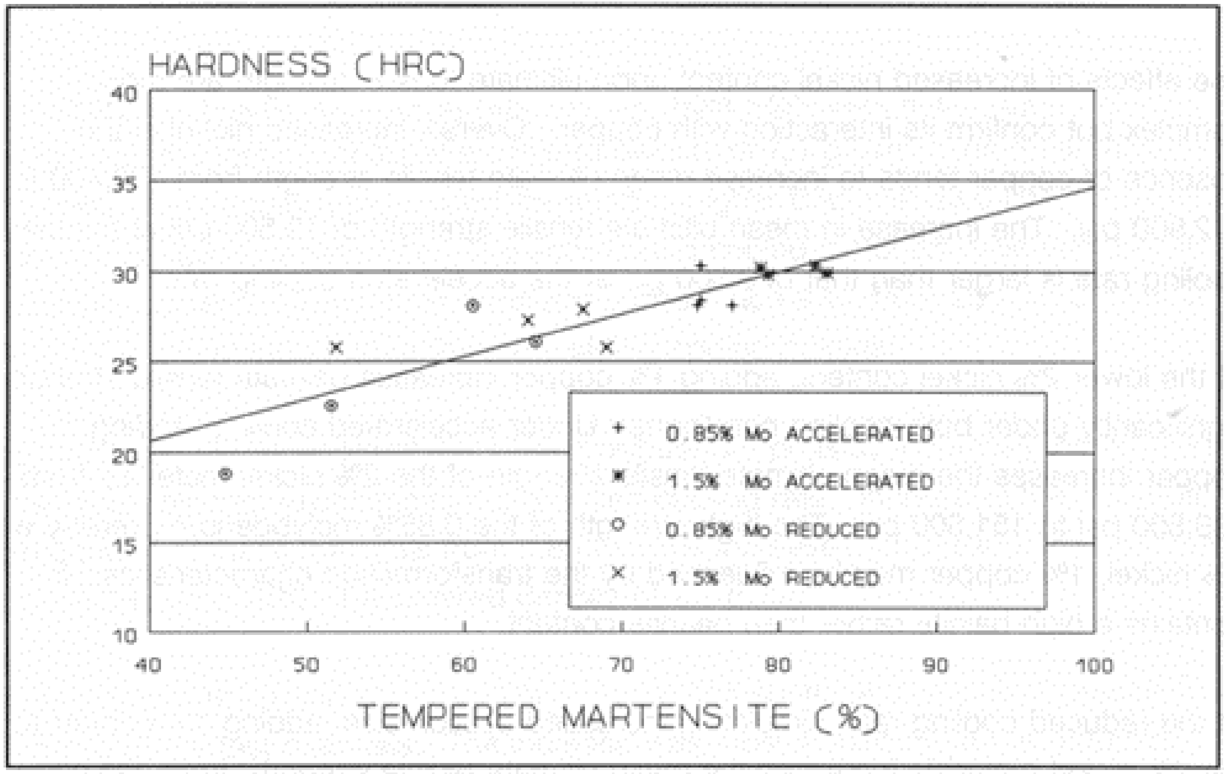

Figure 18: Hardness of Test Materials versus Tempered Martensite

Those factors, such as accelerated cooling, that increase tempered martensite content increase ultimate tensile strength and hardness. Those factors, such as nickel-rich areas, that reduce tempered martensite content reduce ultimate tensile strength and hardness.

Ultimate Tensile Strength

The major factor in controlling ultimate tensile strength, except porosity, is cooling rate. At a sintered density of 7.1 g/cm^3, the mean ultimate tensile strength, 143,800 psi, of accelerated cooled materials is higher than that, 138,000 psi, of materials experiencing the lower cooling rate.

The metallography indicated that the accelerated cooling rate was sufficient to promote almost complete martensite formation independently of composition. The mean ultimate tensile strength of materials based on the 0.85 and 1.5% molybdenum prealloy, 142,200 and 145,500 psi, respectively, are almost identical. The increased hardenability of the 1.5% molybdenum prealloy is more apparent at the lower cooling rate. Increasing molybdenum content increases the mean ultimate tensile strength of the materials experiencing the lower cooling rate from 130,700 to 137,200 psi.

The effects of increased nickel content upon ultimate tensile strength are more complex but confirm its interaction with copper. Overall, increased nickel in the absence of copper tends to increase mean ultimate tensile strength from 132,400 to 142,900 psi. The increase in mean ultimate tensile strength of 13,500 psi at the lower cooling rate is larger than that of 8,500 psi at the accelerated cooling rate.

At the lower 2% nickel content, adding 1% copper increases ultimate tensile strength significantly under both cooling conditions. Under accelerated cooling, adding 1% copper increases the mean ultimate tensile strength of the 2% nickel materials from 139,800 psi to 151,500 psi. The high strength of the 0.85% molybdenum prealloy with 2% nickel, 1% copper may be influenced by the transformation characteristics. It contains a high bainite rather than pearlite content.

At the reduced cooling rate, simulating increased section size, adding 1% copper to the 2% nickel materials increases the mean ultimate tensile strength from 125,000 psi to 139,400 psi.

In contrast, adding 1% copper to the 4% nickel material tends to reduce ultimate tensile strength, particularly in the higher molybdenum materials. The result confirms the metallography. The copper and nickel tend to form a stable solid solution discrete from the matrix such that the strengthening effects of increased copper and nickel are less than anticipated from the chemical composition alone. It is possible that longer sintering times or higher sintering temperatures could increase solution of copper and nickel in the ferrous matrix as discussed in Reference 1.

Hardness

The effects of processing and composition upon the hardness of the test pieces are very similar to their effects upon ultimate tensile strength . As indicated by the metallography and illustrated in Figure 19, increasing tempered martensite content favors increasing hardness. Thus, those factors that favor increased martensite content increased cooling rate, increasing molybdenum, increasing nickel in the absence of copper, and adding 1% copper to 2% nickel materials increase the hardness of the test materials. Factors such as reduced cooling rate, increased section size and the addition of 1% copper to 4% nickel materials that reduce martensite content reduce hardness.

As indicated in Figure 20, cooling rate has the most significant effect upon the hardness of the test materials at a sintered density of 7.1 g/cm^3. The mean hardness, 28.7 HRC of the accelerated cooled materials is higher than that 23.6 HRC of materials experiencing lower cooling rate. The accelerated cooled materials have very similar martensite contents. Thus, their hardness varies much less, from 26.2 HRC to 30.3 HRC at 7.1 g/cm^3 than that of the more slowly cooled materials.

The increased hardenability of the 1.5% molybdenum prealloy increases the hardness of the materials that experienced the reduced cooling rate. Increasing the molybdenum content of these materials from 0.85 to 1.5% increases the mean hardness from 21.2 HRC to 25.9 HRC at a sintered density of 7.1 g/cm^3.

Increasing the nickel content, from 2% to 4%, in the absence of copper increased the hardness of the test materials. The increase was most significant at the reduced cooling rate, where the mean hardness of the test materials at a density of 7.0 g/cm^3 increased from 20.5 HRC to 25.5 HRC with increased nickel content.

There is a similar interaction between the effects of copper and nickel upon hardness to that observed upon tensile strength. The effects are most apparent at the reduced cooling rate where there is much more variation in martensite content and hardness. At the 2% nickel level, adding 1% copper increases the mean hardness of the slowly cooled materials from 20.5 to 25 HRC. In contrast, introducing 1% copper slightly reduces the mean hardness of the 4% nickel materials from 25.4 HRC to 23.3 HRC, at a sintered density of 7.1 g/cm^3.

The data show that by combining these factors correctly, it should be possible to develop sinter-hardening compositions from the test materials. The 27 HRC hardness of the 1.5% molybdenum prealloy with 2% nickel and 1% copper at the reduced cooling rate compares favorably with the values of 26 to 30 HRC obtained in the accelerated cooled materials.

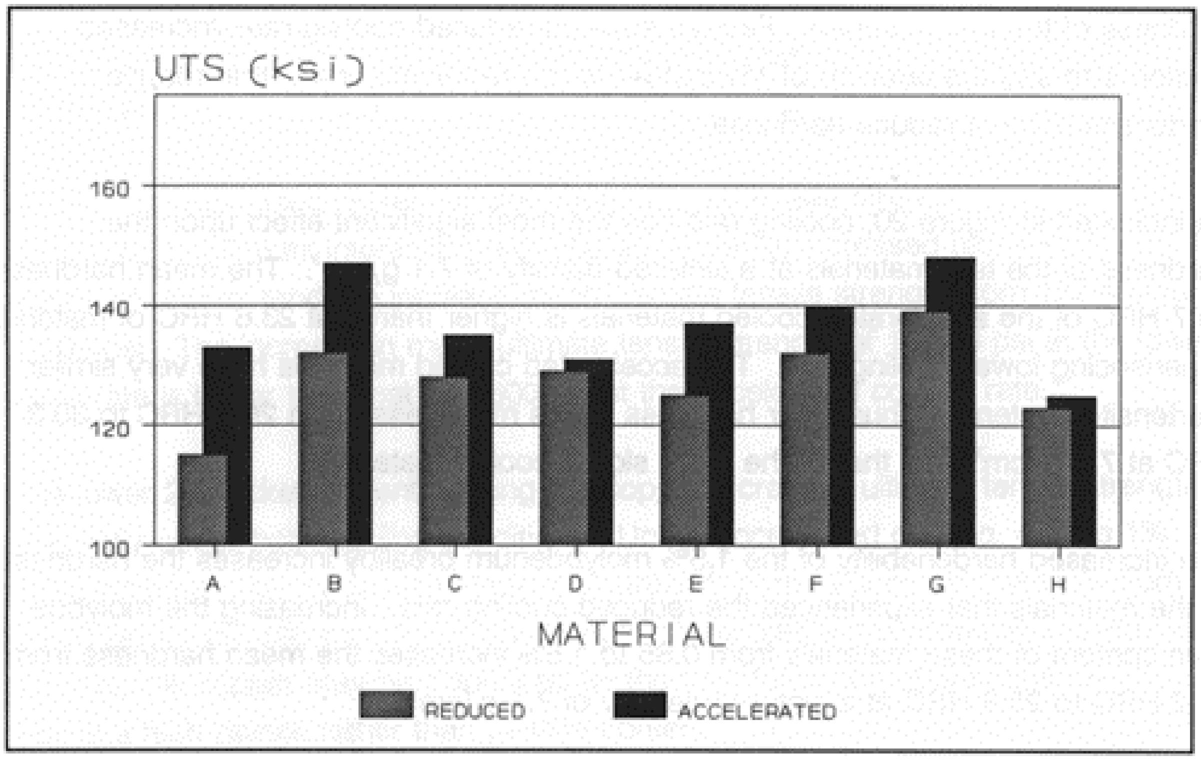

Figure 19: Effect of Cooling Rate Upon UTS of Test Materials, 7.1 g/cm^3

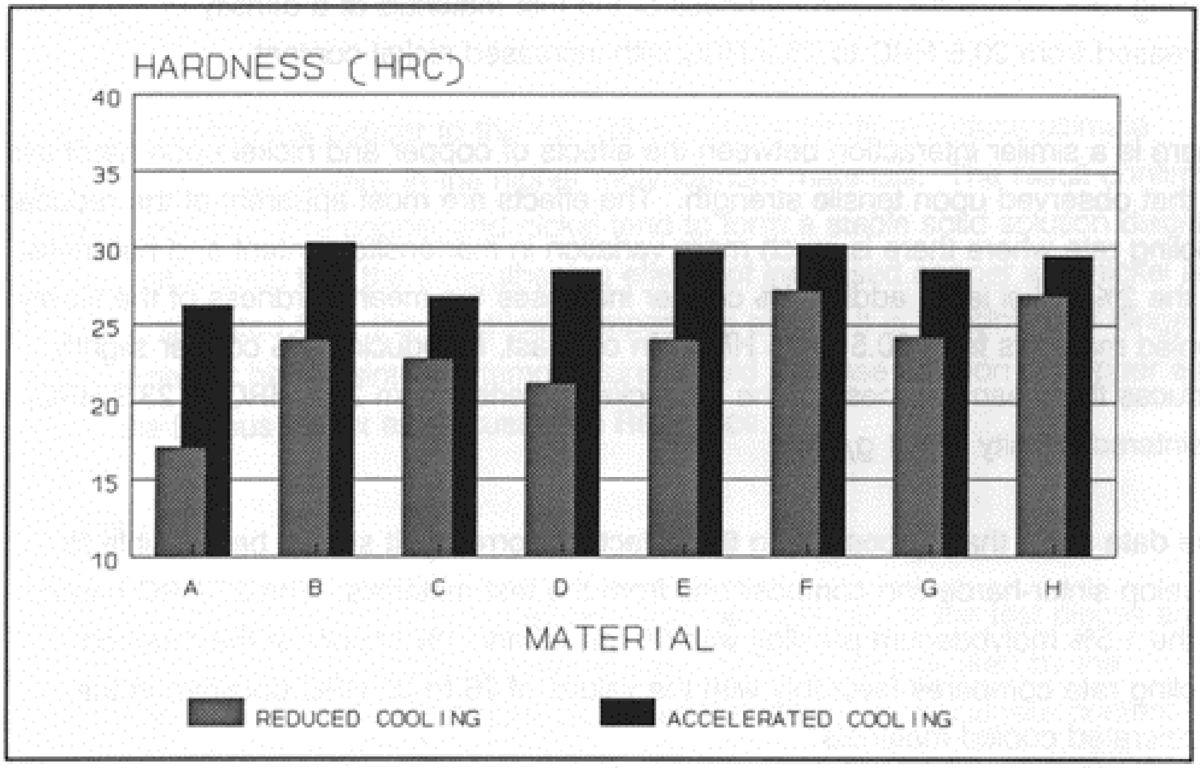

Figure 20: Effect of Cooling Rate Upon Hardness of Test Materials, 7.1 g/cm^3

Impact Energy

As discussed above, porosity has the greatest influence upon impact energy (Figure 21). The curves of impact energy versus sintered density for the materials based upon the 0.85% molybdenum prealloy show that other factors have almost no influence on impact energy.

With the exception of material F, that contains 2% nickel and 1% copper in the 1.5% molybdenum prealloy, cooling rate has no significant effect upon impact energy. It is possible that increasing alloy content may increase the impact energy of the test materials slightly. At a sintered density of 7.1 g/cm^3, the impact energy of materials containing 4% nickel and 1% copper is slightly higher than that of the materials that contain only 2% nickel. This may indicate that the presence of discrete nickel-rich areas in P/M materials tends to improve toughness (7,8)

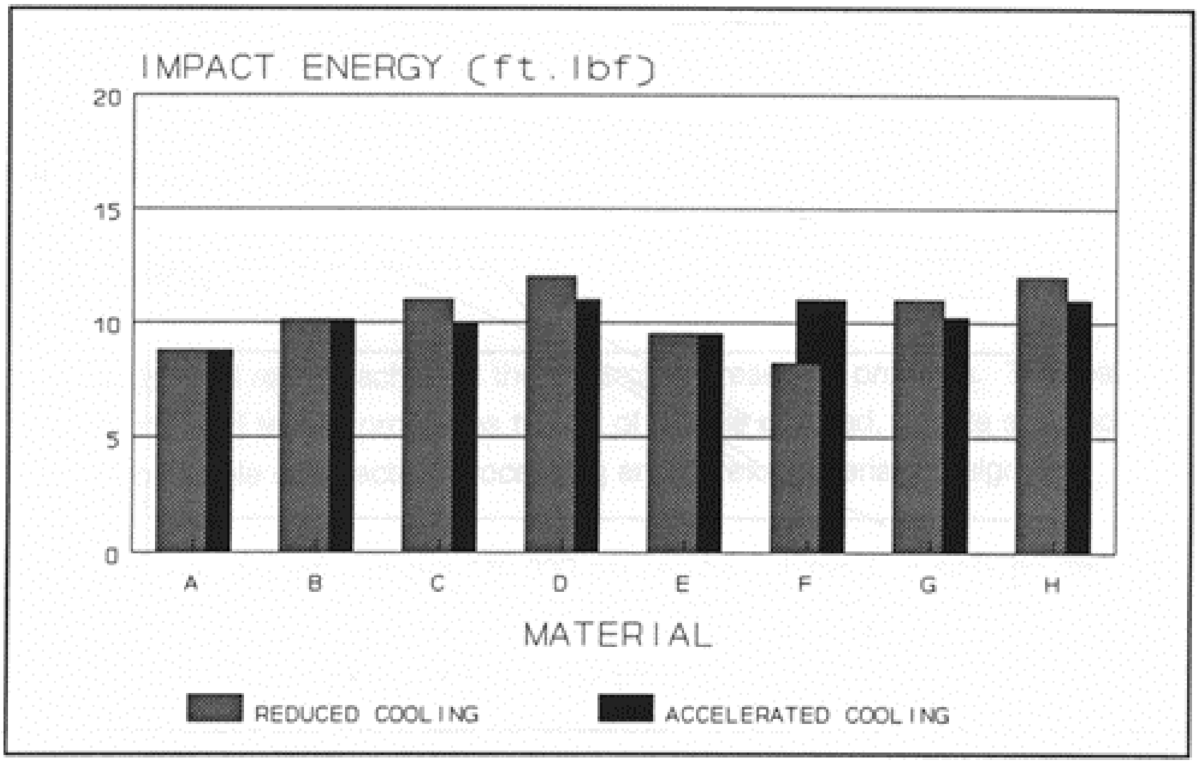

Figure 21: Effect of Cooling Rate Upon Impact of Test Materials, 7.1 g/cm^3

COMPARISON WITH DOUBLE PRESSED MATERIALS

The aim of this work was to achieve mechanical properties comparable to existing double pressed, double sintered (DPDS), materials by single compaction. The data indicate that the sintered density, 7.2 to 7.3 g/cm^3, and ultimate tensile strength of the test materials compare favorably with published data for DPDS materials (Figures 22 and 23), such as FN-0405HT published in MPIF Standard 35,1990-1991 Edition. The figures show that in the rapidly cooled condition (Figure 22), the ultimate tensile strengths of test materials based upon both the 0.85% and 1.5% molybdenum prealloys are equivalent or superior to those of the heat treated FN-0405HT at densities of 6.8 to 7.2 g/cm^3.

However, MPIF Standard 35 indicates that densities above 7.0 g/cm^3 were achieved by double pressing. Thus, the test materials offer a significantly more efficient route to high performance than conventional alternatives.

The comparison is more favorable if the properties obtained at the reduced cooling rate are compared to those of as-sintered FN-0405.

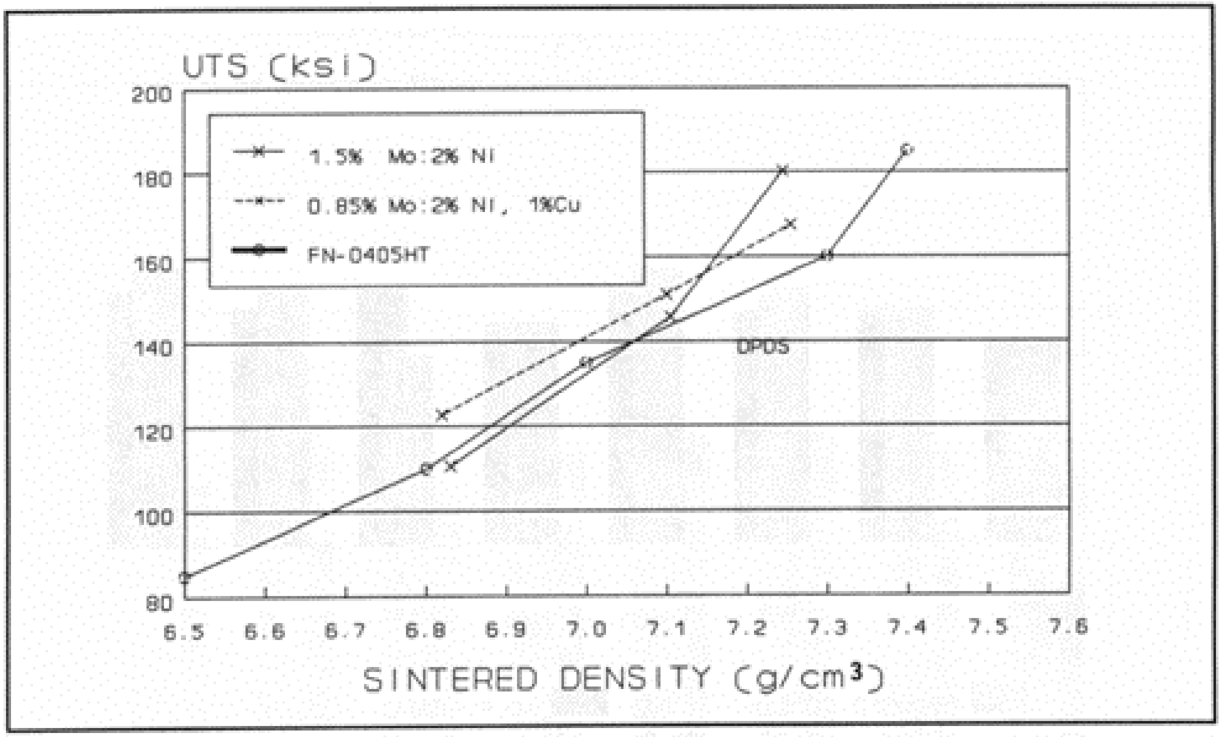

Figure 22: Comparison of Rapidly Cooled Test Materials with FN-0405HT

The ultimate tensile strength of test materials that were single compacted to a density of 6.85 g/cm^3, then slowly cooled from sintering temperature exceeds that quoted for FN-0405 at a sintered density of 7.2 g/cm^3 achieved by repressing.

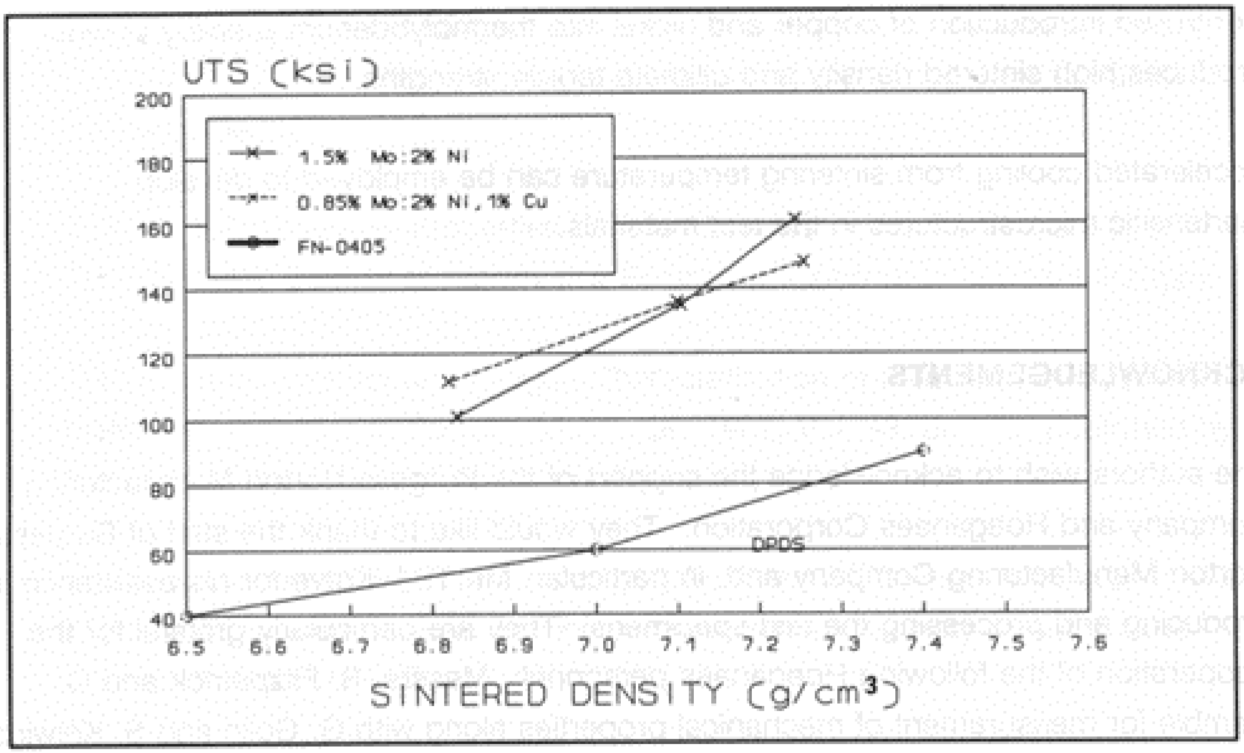

Figure 23: Comparison of Test Materials with FN-0405

CONCLUSION

The experimental results achieved the aims of the research program. The test -materials attained tensile properties typical of double pressed, double sintered materials by single compaction processing and careful materials design.

Ultimate tensile strengths above 170,000 psi can be achieved, at sintered densities of 7.25 g/cm^3, following accelerated cooling from sintering temperature. Strengths in excess of 160,000 psi can be developed at reduced cooling rates simulating increased section size.

The results confirmed the basic principles of the program.

The molybdenum prealloy steel powders offer an attractive basis for developing high performance materials.

Increasing the molybdenum content of the prealloy from 0.85 to 1.5% has a beneficial effect on hardenability.

Controlled introduction of copper and nickel into the molybdenum prealloy powder produces high sintered density and ultimate tensile strengths.

Accelerated cooling from sintering temperature can be employed to develop martensitic microstructures in the test materials.

ACKNOWLEDGMENTS

The authors wish to acknowledge the support of the Burgess-Norton Manufacturing Company and Hoeganaes Corporation. They would like to thank the staff of Burgess-Norton Manufacturing Company and, in particular, Mr. T. J. Krave for his 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 G. Golin and S. Kolwicz for metallography.

REFERENCES

1. Hamill, J.A., Jr., Causton, R. J., Shah, S., “High Performance Ferrous P/M Materials Utilizing High Temperature Sintering,” to be published, Advances in Powder Metallurgy, 1992, published by Metal Powder Industries Federation, Princeton, NJ.

2. Causton, R. J., James, W. B., Fulmer, J. J., “Performance Characteristics of a New Sinter-Hardening Low-Alloy Steel,” Advances in Powder Metallurgy, 1991, Vol. 5, p 91, published by Metal Powder Industries Federation, Princeton, NJ.

3. McDermott, M.J., “P/M Parts Fabrication with ANCORBOND (Binder-Treated) Premixes,” Advances in Powder Metallurgy, 1990, Vol. 1, p 209, published by Metal Powder Industries Federation, Princeton, NJ

4. U.S. Patent 4,483,906, “Homogeneous Iron-Based Powder Mixtures”.

5. U.S. Patent 4,834,800, “Iron-Based Powder Mixtures”.

6. Causton, R.J., Murphy, T.F. et al, “Non-Metallic Inclusion Measurement of Powder Forged Steels Using an Automatic Image Analysis System,” Hodzons of Powder Metallurgy, 1986, Part II, p 727, published by Verlag Schmid, GmbH, Freiburg, Germany.

7. O’Brien, R.C., “Fatigue Properties of P/M Materials,” SAE, Technical Paper 880165, 1988, Society of Automotive Engineers, Cobo Hall, Detroit, Michigan.

8. O’Brien, R.C., “Impact and Fatigue Characterization of Selected Ferrous P/M Materials,” Progress in Powder Metallurgy, 1987, Vol. 43, pp 749, published by Metal Powder Industries Federation, Princeton, NJ.

9. Potter, V.C., James, W.B. and Murphy, T.F., “Steering Column

Tilt Lever - P/M Material Development,” SAE Technical Paper 900381, Society of Automotive Engineers, Cobo Hall, Detroit, Ml, 1990.

Notes:

[1] Ancorsteel and ANCORBOND are registered trademarks of Hoeganaes Corporation.