HIGH DENSITY PROCESSING OF Cr-Mn P/M STEELS

R. J. Causton and T. M. Cimino
Hoeganaes Corporation
Riverton, NJ 08077

Presented at 1994 International Conference &
Exhibition on Powder Metallurgy & Particulate Materials
May 8-11,1994 - Toronto, Canada

ABSTRACT

The use of chromium and manganese as alloying elements in P/M steels offers several potential advantages over copper and nickel that are used in conventional P/M alloy steels. The paper will illustrate how the principles used to improve the hardenability and performance of wrought steels can be applied to P/M chromium and manganese alloy steels using a systems approach. The use of chromium-manganese for P/M applications was made possible by binder-treated premix technology of a highly compressible prealloyed low alloy base material. The flexibility of alloy design will be illustrated by examples of through hardening, high strength low alloy steels.

BACKGROUND

The research described was prompted by recent discussion over the ability of P/M to produce highly stressed components such as transmission gears. Such parts require the development of P/M steels offering improved combinations of strength, hardenability, wear and fatigue resistance over those available today.

Ideally, the properties of such P/M steels and the components produced from them should approach those of the current wrought systems. This may be attained through the increased part density offered by powder forging or double pressing. However, the extra process steps required by these production routes reduce the competitiveness of P/M significantly. A key theme of the research was to examine the properties of alloy systems of high density achieved by single compaction using the patented ANCORDENSE™* process (1,2).

In wrought ferrous metallurgy, the combination of high strength, hardness, wear and fatigue resistance is best achieved with a microstructure of tempered alloy martensite. Indeed, the benefits of high tempered martensite upon the properties of P/M nickel-molybdenum alloy steels have been confirmed (3). However, copper and nickel that are widely used in P/M have lower hardenability, the ability to form martensite, than chromium or manganese that are used widely in wrought steels. P/M producers have compensated for this by employing high carbon contents to achieve high hardness and tensile strength. However, such alloys require high quench rates to produce fully martensitic microstructures. These high quench rates introduce residual stresses that exaggerate the natural brittleness of high carbon martensites. The need for high quench rates also limits the section size that can be hardened efficiently.

End users of highly stressed parts have expressed a preference for low alloy steels such as AISI 41XX and 86XX in which the use of more efficient alloying elements enables a fully martensitic microstructure to be attained at lower quench rates and in larger section size. The alloy martensites also develop high strength at lower carbon contents. These factors combine to reduce the risk of cracking during part production and service. However, the high affinity for oxygen of chromium and manganese makes it very difficult to suppress oxide formation during primary powder production or reduce their oxides during sintering. More widespread use of efficient high temperature sintering furnaces with improved atmosphere control enables part producers to sinter chromium and manganese alloy steels effectively. Recently, means to introduce chromium and manganese into P/M steels from high carbon ferroalloys have been described (4,5) This technique is more compatible with current powder production, and sintering processes than previous prealloying techniques. The second theme of the research program was to examine the properties of P/M alloy steels of improved hardenability produced with this technology.

HARDENABILITY

The hardenability of a steel is a measure of its ability to form martensite during cooling. Higher hardenability implies that a steel will form more martensite under given cooling conditions, or quench rate. A steel's hardenability is controlled by its carbon content, grain size and alloy composition. The interaction of these factors is complex and subject to debate (6,7). The hardenability of a steel is generally described in terms of a critical diameter, D_{IC}, that will form a microstructure possessing 50% martensite under “ideal quench” conditions. The separate contributions of the various factors is described by hardenability multipliers, such that:

$$D_{IC} = f_1\%C \bullet f_2 GS \bullet f_3\%Cr \bullet f_4\%Mn \bullet f_5\%Ni$$

where f_1 ....multiplying factors

%C........carbon content
GS........ASTM grain size
%Cr, %Mn..concentration of alloy elements

The effects of carbon and grain size are so important that hardenability is usually measured and reported at a known carbon content and grain size. The hardenability multipliers for common alloying elements, abstracted from ASTM A 255, are shown in Table I for a nominal 0.4% carbon content and ASTM 7 grain size.

Table I: Hardenability Multipliers of Alloys at 0.5% Concentration

Element	Multiplier
Chromium	0.318
Manganese	0.426
Molybdenum	0.398
Nickel	0.073
Silicon	0.13

It is apparent that the multiplier for nickel is less than those of chromium and manganese. The effects of this upon the estimated hardenability and critical diameter of widely-used P/M and wrought steels of 0.4% carbon content and ASTM 7 grain size are indicated in Table II.

Table II: Comparison of Estimated Hardenability of Steels

Factor	AISI 4140		AISI 8640		MPIF FL-4605	
	Wt. %	Multiplier	Wt. %	Multiplier	Wt. %	Multiplier
Carbon	0.4	0.33	0.4	0.33	0.4	0.33
Grain Size	7		7		7	
Chromium	0.98	0.49	0.5	0.32	0.05	0.05
Manganese	0.88	0.59	0.88	0.59	0.18	0.204
Molybdenum	0.2	0.2	0.2	0.2	0.60	0.447
Nickel	--	--	0.55	0.08	1.85	0.236
Sum of Multipliers	--	1.623	--	1.526	--	1.267
D_{IC} (inches)	--	4.200	--	3.360	--	1.85

Note: Effects of silicon and other residual elements are omitted.

The estimates show clearly the superior hardenability of the wrought steels through use of chromium and manganese as alloying elements. They also show that the hardenability of steels can be controlled through adjustments to alloy composition.

TEST PROGRAM

The test program was intended to assess whether the theoretical benefits of chromium and manganese, control of hardenability and thus, microstructure and properties, could be translated into P/M systems. The program was divided into three phases:

1. To confirm the effects of chromium and manganese upon hardenability.

2. To determine the effects of chromium, manganese and graphite upon the sintered properties of molybdenum prealloy steels.

3. To examine the effects of sintered density, achieved by single compaction ANCORDENSE processing upon the mechanical properties of specific compositions.

TEST MATERIALS

The test materials were designed to investigate the effects of alloy composition upon the compressibility, dimensional change and physical properties of P/M alloy steels. The major variables considered are listed below:

Molybdenum

Molybdenum has little solution-hardening effect, but improves hardenability significantly. Thus, two prealloyed molybdenum steels containing 0.85 and 1.50% molybdenum were used as the matrix of the test materials.

Chromium and Manganese

Chromium and manganese were introduced as finely ground high carbon ferroalloys with particle size below 20 µm as described in Reference 4. This technique reduces the problems of oxide formation and poor compressibility of prealloyed chromium-manganese steel powders.

Nickel

Nickel improves hardenability much less than chromium and manganese when used as a single alloying element in steels. However, it has proved very effective when combined with the prealloyed molybdenum steels (8). It also promotes shrinkage on sintering which is very useful for control of dimensional change. Nickel was added as Inco Type 123 powder.

Carbon

Carbon was introduced to the alloy systems as Asbury 3203 graphite.

EXPERIMENTAL PROCEDURE

A series of test premixes was prepared to assess the influence of the alloying elements, graphite, chromium, manganese and nickel content, upon the properties of the prealloy matrix. These test premixes were compacted to tests pieces for determination of physical properties, microstructure and hardenability. Throughout the test programs, the test pieces were sintered at 2350°F, in an atmosphere of 75% hydrogen/25% nitrogen for 30 minutes at temperature. The larger test pieces were equilibrated at 1600°F for 15 minutes before entering the hot zone. The sintered test pieces were stress-relieved at 400°F for one hour prior to testing.

Hardenability Testing

The effect of the alloying elements upon hardenability was determined using 1” diameter Jominy test pieces (Figure 1) in accordance with ASTM A 255. The test pieces were machined from 4” diameter, 1.25” high powder forged compacts, then austenitized at 1600°F for 30 minutes prior to quenching.

Mechanical Properties

Tensile testing was on a Tinius Olsen testing system in accordance with ASTM E 8 using a crosshead speed of 0.025-inch/minute. Testing was conducted using both as-sintered “dog-bone” and machined round test pieces for conventional and ANCORDENSE-processed alloys, respectively. Where quoted, the transverse rupture stress and dimensional change from die size were measured in accordance with ASTM B 528 and B 610, respectively.

Metallographic Examination

Cross-sections were cut from selected test pieces and prepared for metallographic examination following previously published procedures (9).

Chemical Analysis

The chemical composition of the test materials was determined by analysis of sections cut from sintered test pieces. Chromium, manganese, molybdenum and nickel contents were determined by optical emission spectrometry. Carbon and oxygen contents by LECO analyzers.

Effects of Chromium and Manganese Upon Hardenability

The effects of chromium and manganese upon hardenability were determined using the Jominy test (Figure 1).

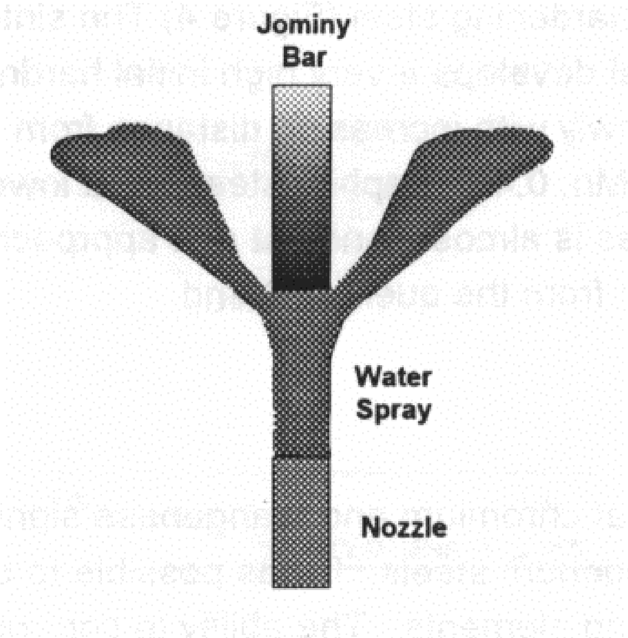


Figure 1: Schematic of Jominy Test.

Jominy Test Results

The effect of increasing chromium and manganese upon the Jominy test results for a 0.85% molybdenum, 1% nickel, 0.4% graphite steel is illustrated in Figure 2.

The hardness of the base, 0.85% molybdenum, 0.4% graphite steel, is approximately 47 HRC at the quenched end. Its hardness falls to less than 25 HRC within one inch. By introducing 0.75% chromium or manganese, a hardness above 40 HRC is maintained to approximately 1.5 inches. It appears that manganese has a slightly greater effect than chromium. The 0.75% manganese steel possesses a slightly higher hardness as distance from the quenched end increases. The multiplying effect of combinations of elements is shown by the curve of the steel with both 0.75% chromium and manganese. A hardness in excess of 50 HRC is maintained along the full length of the steel piece.

The hardenability of a 1.5% molybdenum, 1% nickel, 0.2% graphite steel is shown in Figure 3. This steel has a relatively low maximum hardness of 40 HRC because of its low carbon content. Its hardness falls below 20 HRC at one inch from the quenched end. Introducing 0.75% chromium increases hardenability significantly. The maximum hardness remains at 40 HRC but hardnesses above 30

HRC are achieved one inch from the quenched end. Manganese has a larger effect than chromium as the Jominy curve shows little decrease in hardness until two inches from the quenched end. Introducing both chromium and manganese has little effect on maximum hardness but the Jominy curve becomes almost flat at a value of 43 to 45 HRC at three inches from the quenched end.

Discussion of Jominy Test Results

The Jominy test results showed that chromium and manganese significantly increase the hardenability of powder forged steels. The results appeared to follow theoretical predictions in that manganese had a greater effect than chromium. The multiplying effects of combinations of elements was shown. A steel with a composition of 0.85% molybdenum, 1% nickel, 0.75% chromium and 0.75% manganese is “air hardening”. Its Jominy curve makes an interesting comparison with that of a P/F sinter-hardening steel (Figure 4).The sinter-hardening 1.8% Ni, 0.5% Mo, 2% Cu, 0.9% graphite steel develops a very high initial hardness due to its high carbon content. The hardness deceases slowly with increasing distance from the quenched end. The 0.85% Mo, 1% Ni, 0.75% Cr, 0.75% Mn, 0.4% graphite steel has a lower initial hardness due to its lower carbon content. Its hardness is almost constant and approaches that of the higher carbon steel with increasing distance from the quenched end.

Summary of Jominy Testing

The Jominy test results confirmed that chromium and manganese significantly increased the hardenability of the prealloyed molybdenum steels. It was possible to develop air-hardening steels through combinations of alloying elements. The ability to control hardenability and

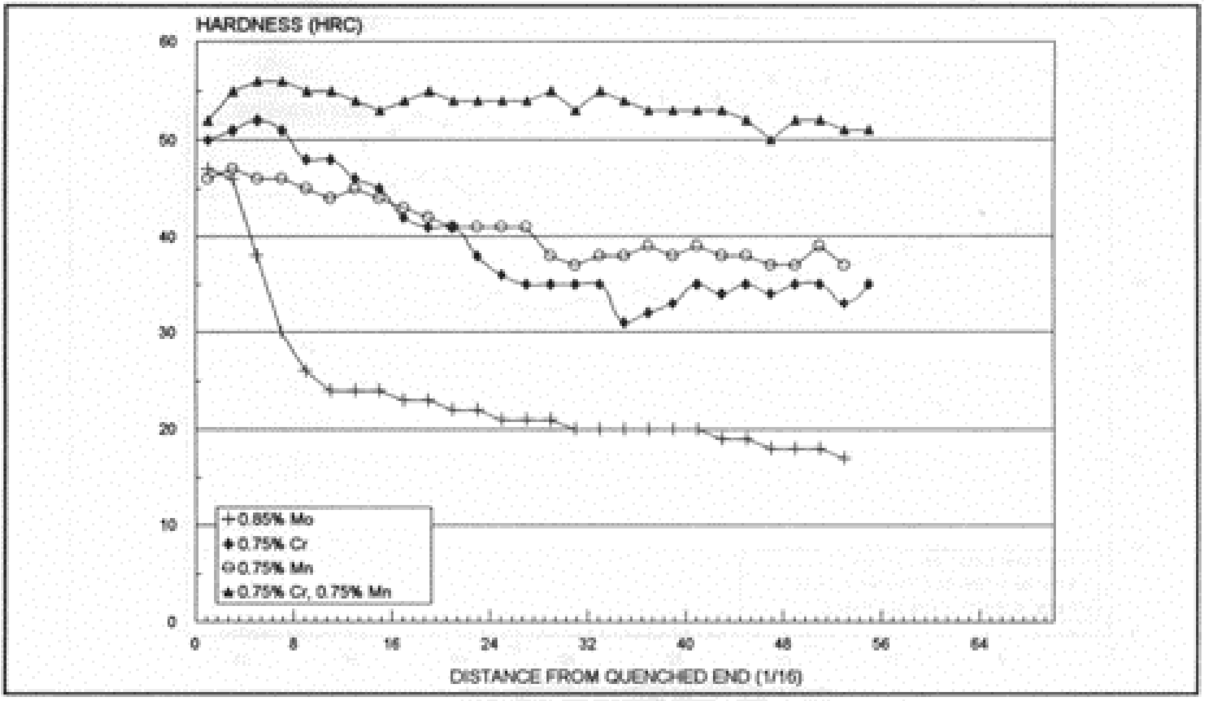


Figure 2: Effect of Chromium and Manganese Upon Jominy Hardenability of Powder Forged 0.85% Mo, 1% Ni, 0.4% Graphite.

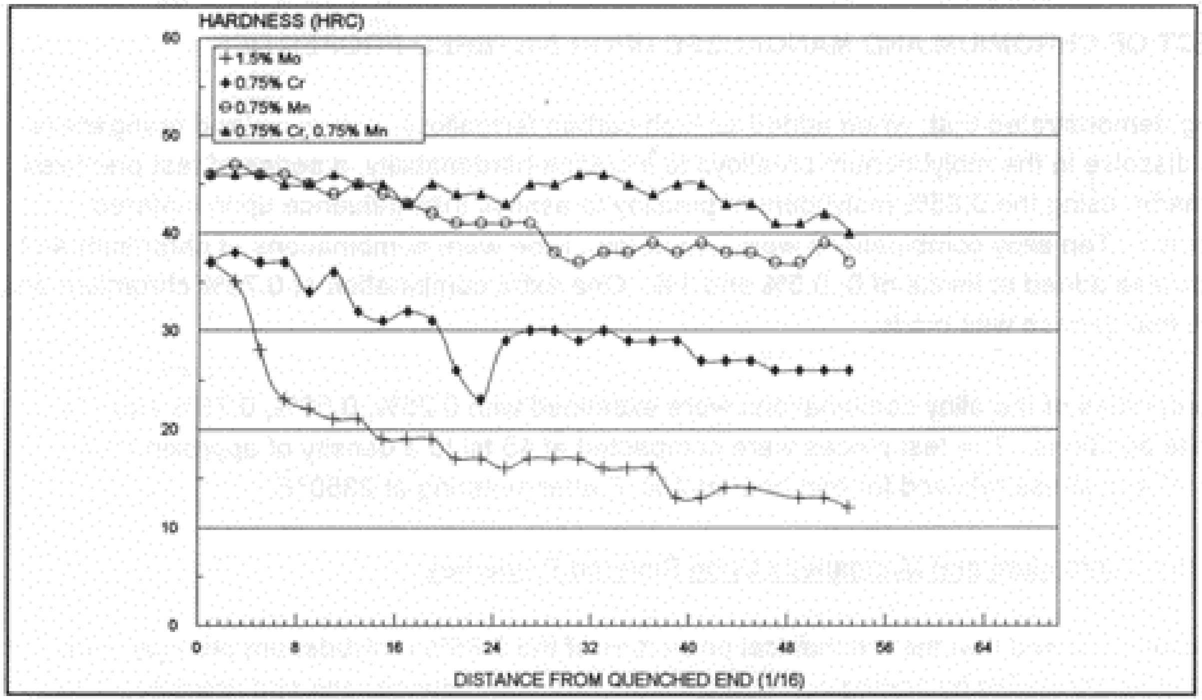


Figure 3: Effect of Chromium and Manganese Upon Jominy Hardenability of Powder Forged 1.5% Mo, 1% Ni, 0.2% Graphite.

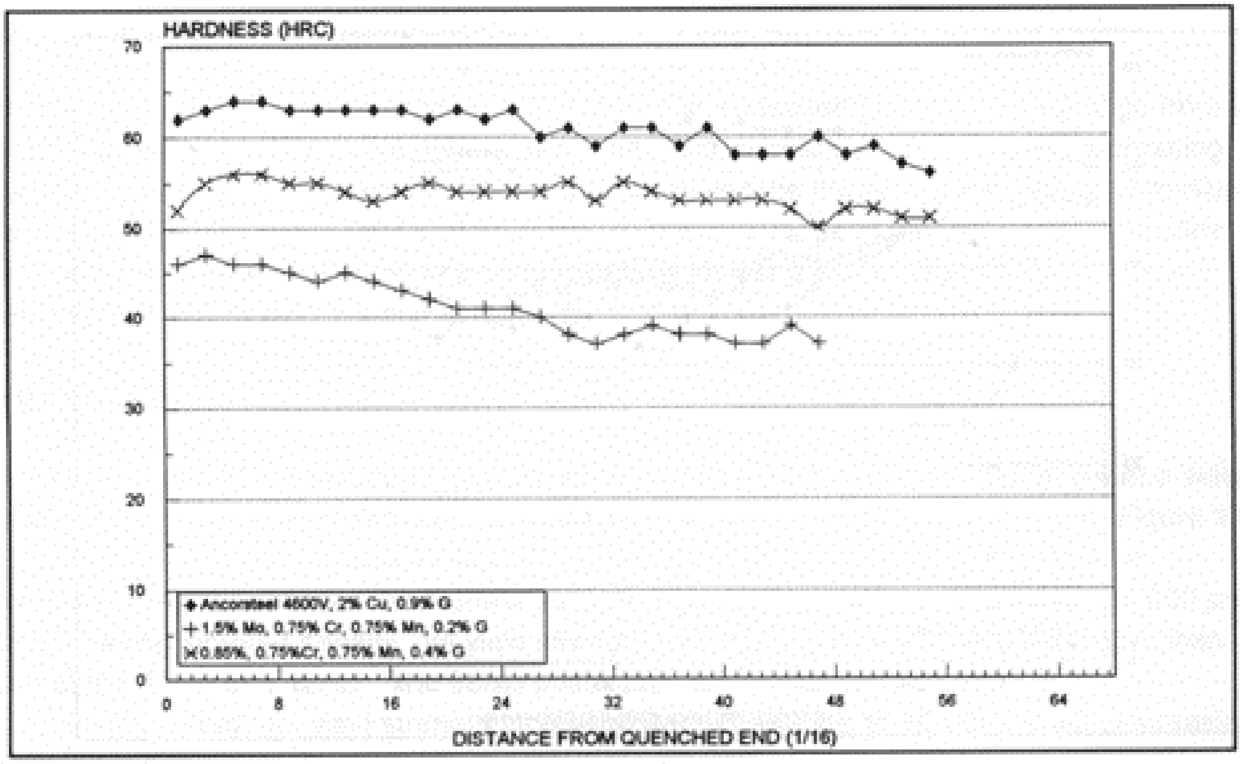


Figure 4: Comparison of Jominy Hardenability of Powder Forged Steels.

transformation characteristics was shown by the addition of chromium and manganese to the 1.5% molybdenum prealloy with 0.2% graphite. This alloy possessed a uniform relatively high hardness level despite its low carbon content.

EFFECT OF CHROMIUM AND MANGANESE UPON SINTERED PROPERTIES

Having demonstrated that, when added as high carbon ferroalloys, chromium and manganese could dissolve in the molybdenum prealloys to increase hardenability, a series of test premixes was made using the 0.85% molybdenum prealloy to assess their influence upon sintered properties. Ten alloy combinations were evaluated. Nine were combinations of chromium and manganese added at levels of 0, 0.5% and 1%. One extra combination of 0.75% chromium and 0.75% manganese was made.

The properties of the alloy combinations were examined with 0.25%, 0.50%, 0.75% and 1% graphite additions. The test pieces were compacted at 45 tsi to a density of approximately 7 g/cm^3 and stress relieved for one hour at 400°F after sintering at 2350°F.

Results of Chromium and Manganese Upon Sintered Properties

The results showed that the mechanical properties of the 0.85% molybdenum prealloy were increased significantly by adding combinations of chromium, manganese and graphite. The optimum combination of properties appeared to be obtained with a total alloy, chromium plus manganese, addition of 1.5% at 0.75% graphite content. Dimensional change increased with increasing alloy and graphite contents. In analyzing the results, it appeared that there was an overall relationship between sintered properties and the total alloy, chromium plus manganese, addition. The alloy combinations produce five levels of total alloy addition: 0, 0.5,1.0,1.5 and 2% (Table VIIIa). Figures 7-10 show the mean effect of these total additions upon the properties of the chromium-manganese alloy steels. The separate effects of chromium and manganese upon the properties of the chromium-manganese steels with 0.5% graphite content are illustrated in Tables III-VI.

Metallography

The microstructures of the 0.85% chromium-manganese alloys are illustrated in Figures 5 and 6. Overall, the microstructures change from alloy ferrite plus carbides to alloy martensite plus carbides with increasing alloy and graphite content.

The effects of increasing chromium and manganese contents upon microstructure are illustrated in Figure 5 for an 0.85% molybdenum, 0.5% graphite alloy. The 0.85% molybdenum alloy possesses a microstructure of ferrite plus carbides (Figure 5c). The carbides do not occur in lamellae typical of pearlitic microstructures. Increasing manganese content (Figures 5a and 5b) increases the proportion of carbides and refines the microstructure. Increasing chromium content (Figures 5d and 5e) has a similar effect, although the 1% chromium alloy possesses some lighter etching possibly martensitic areas. Increasing chromium content to 1% may have also accelerated sintering and pore-rounding when compared to the other alloys.

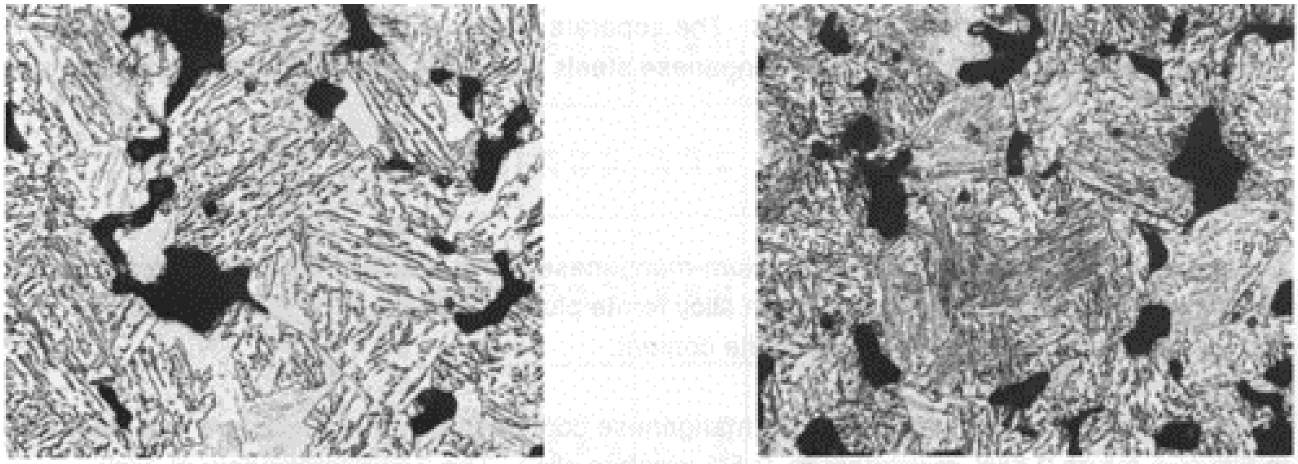
The effects of increasing graphite content upon microstructure are illustrated in Figure 6 for the 0.85% molybdenum, 0.75% chromium, 0.75% manganese alloy. At a 0.25% graphite content (Figure 6a), the microstructure consists of ferrite grains containing carbides. In some regions, the carbides tend to be lamellar forming pearlite, in others discrete, possibly indicating bainite. With an 0.5% graphite content (Figure 6b), the structure is finer and contains some acicular martensite in a matrix of very fine pearlite. Increasing the graphite addition to 0.75% (Figure 6c), increases the martensite content. There may be some retained austenite within the martensitic regions. At a 1%

graphite content (Figure 6d), the microstructure consists largely of martensite with some grain boundaries defined by light-etching carbides.

Overall, the qualitative metallography confirmed that the ferro-chromium and ferro-manganese are being reduced and dissolved in the molybdenum prealloy during sintering. They clearly modify the microstructures formed on cooling. Further study is necessary to clarify the interaction of composition, cooling rate and microstructure.

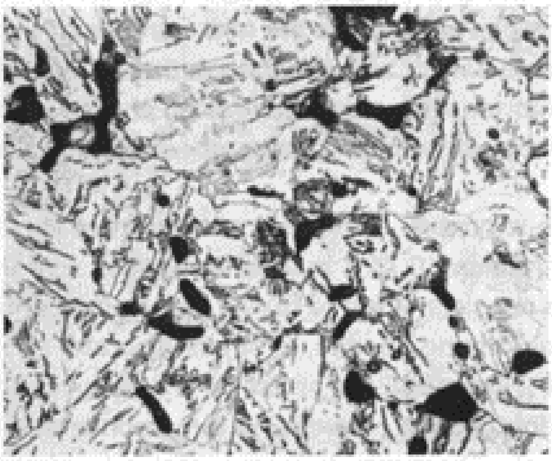
Dimensional Change

As shown in Figure 7, the dimensional change, from die size, of the 0.85% molybdenum prealloy increases with increasing alloy content and increasing graphite addition. There is a strong interaction between increasing alloy content and increasing graphite content, particularly 0.75% and 1% graphite contents. For example, at an 0.5% alloy addition, increasing graphite content from 0.25% to 1% increases growth from 0.1% to 0.26%. At a 2% alloy addition, increasing graphite content from 0.25% to 1% increases growth from 0.55 to 1.05%.

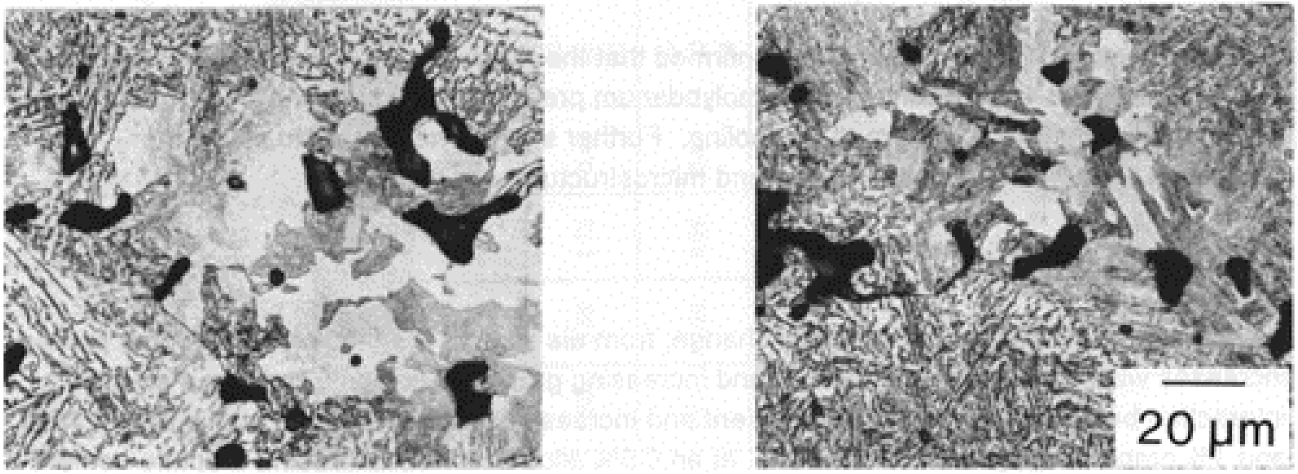


a) 0.5% Mn

b) 1.0% Mn



c) 0% Cr, 0% Mn

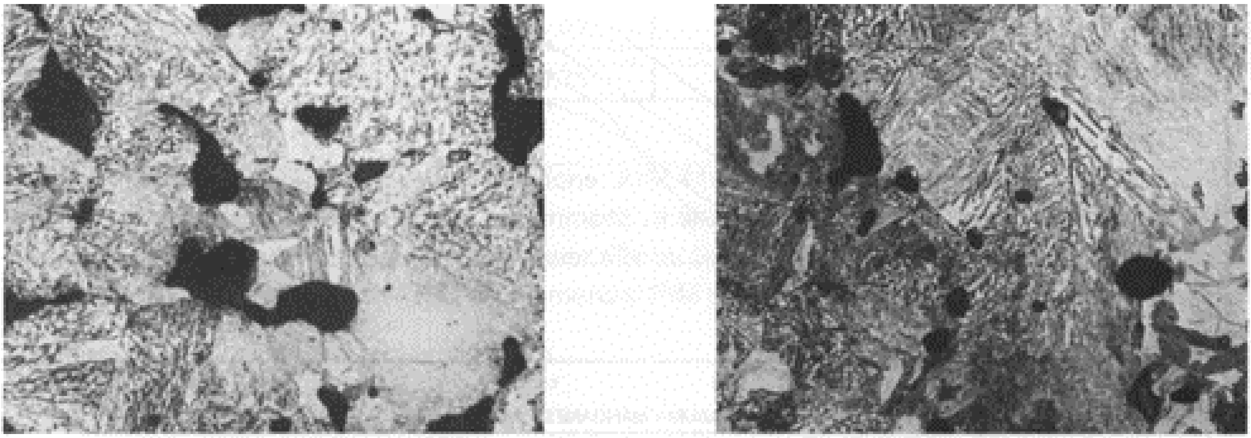


d) 0.5% Cr

e)1.0% Cr

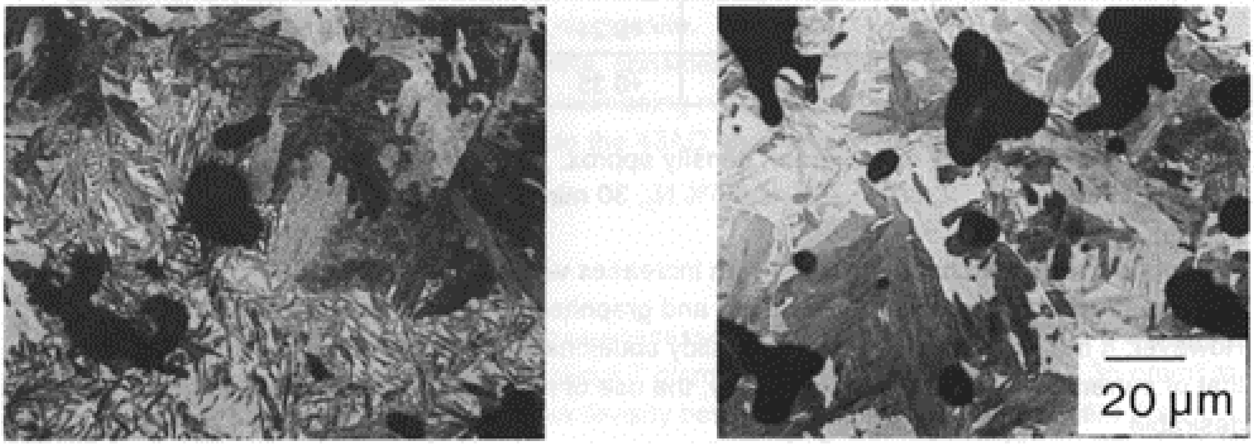
Figure 5: Microstructure of 0.85% Mo Prealloy Plus Chromium or

Manganese. Etched with a Combination of 2% Nital / 4% Picral. Original Magnification 500X.



a) 0.25% Graphite

b) 0.50% Graphite



c) 0.75% Graphite

d) 1.0% Graphite

Figure 6: Microstructure of 0.85% of Molybdenum, 0.75% Chromium, 0.75% Manganese Plus Graphite. Etched with a combination of 2% Nital / 4% Picral. Original Magnification 500X.

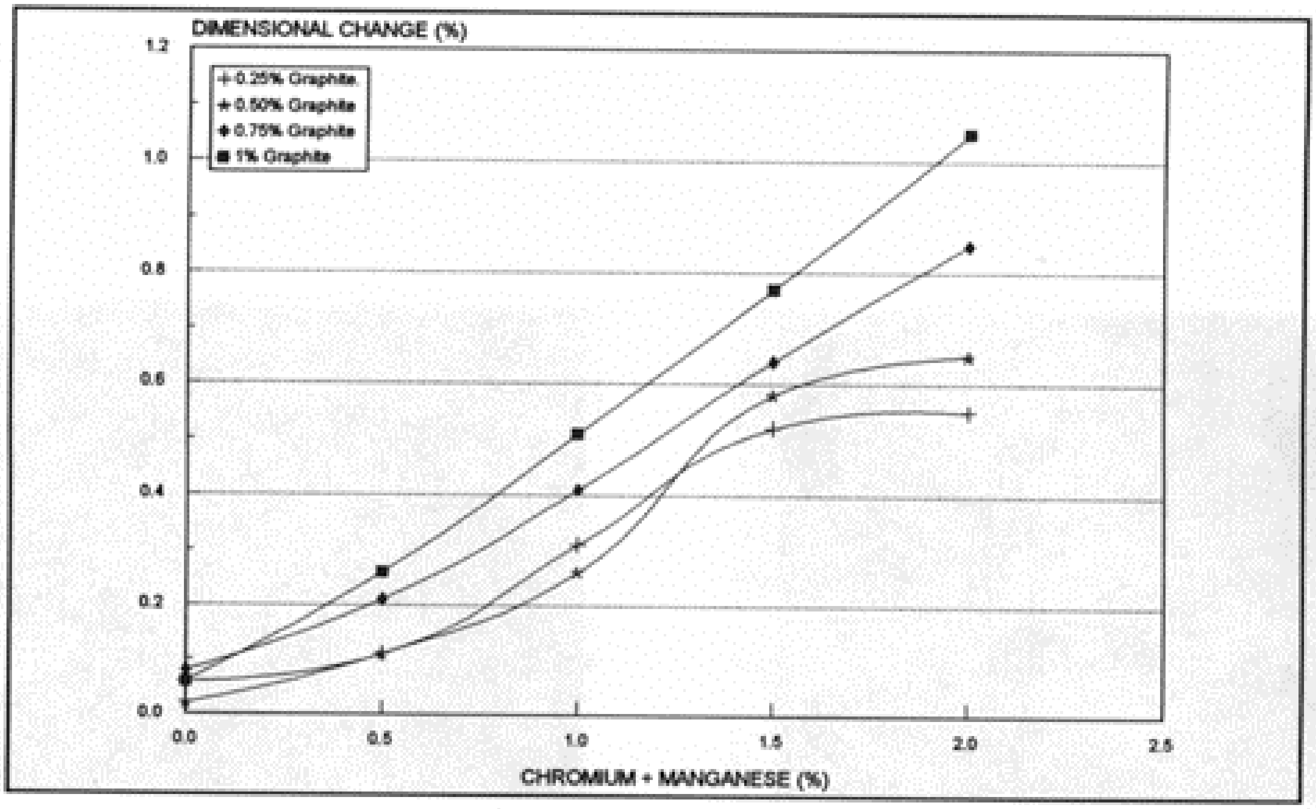


Figure 7: Dimensional Change vs Chromium and Manganese Content of 0.85% Mo Prealloy.

Table III: Dimensional Change (%) of P/M Alloy Steels

Graphite (%)	**No Addition**	**0.5% Alloy**		**1% Alloy**	
		Cr	**Mn**	**Cr**	**Mn**
0.25	+0.06	+0.16	+0.06	+0.30	+0.20
0.50	+0.02	+0.15	+0.07	+0.31	+0.23
0.75	+0.08	+0.24	+0.18	+0.51	+0.31
1.00	+0.06	+0.35	+0.16	+0.70	+0.33

Compaction: At 45 tsi, green density approx. 7 g/cm^3
Sintering: 2350°F, 75% H_2/25% N_2, 30 mins.

The relative effect of chromium on growth increases with graphite content. The data indicate that the effects of chromium, manganese and graphite are relatively predictable (Table III). However, it may be prudent to limit total alloy additions such that dimensional change is close to that of current P/M systems. Alternatively, the use of nickel to offset some of the growth may be desirable.

Yield Strength

In general, the yield strength of the 0.85% molybdenum prealloy increases with increasing alloy, chromium plus manganese, content and increasing graphite content in the range tested (Figure 8). Typically, increasing graphite by 0.5% increases yield strength about 20,000 psi. Increasing the alloy content by 1% increases yield strength by about 15,000 psi. Although, it appears that the maximum yield strength is attained with a 1.5% total alloy addition and 0.75% graphite content.

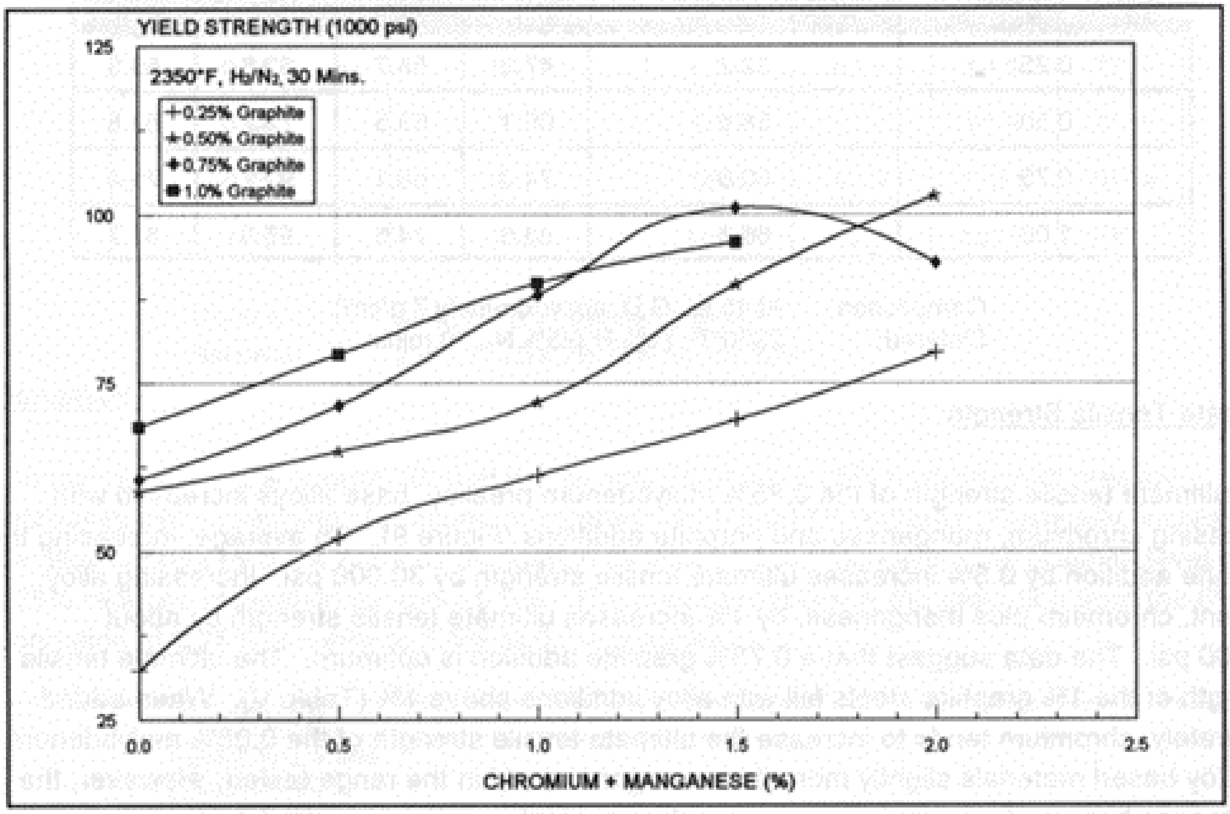


Figure 8: Yield Strength vs Chromium and Manganese Content of 0.85% Mo Prealloy.

The graph indicates that the effects of graphite and total alloy addition are additive for graphite contents up to 0.75% and alloy additions up to 1.5%. For the 0.85% molybdenum alloy, increasing the graphite addition from 0.25% to 1% increases yield strength from approximately 30,000 psi to approximately 70,000 psi. Increasing graphite from 0.25 to 0.75% for a 1.5% total alloy addition, increases yield strength from 70,000 psi to approximately 100,000 psi. The 1% chromium, 0.5% manganese, 1% graphite alloy did not show yield. Similar behavior was observed at 2% alloy content, where higher graphite contents of 0.75 and 1% did not increase yield strength.

When considered separately, the data suggest that chromium tends to increase yield strength of the 0.85% molybdenum-base steels more than manganese (Table IV). Manganese seems most effective as a 0.5% addition at lower graphite contents. Chromium appears to be more effective at graphite additions of 0.5% and above. Increasing the chromium addition from 0.5 to 1% increases yield strength significantly.

Table IV: Yield Strength (1000 psi) of 0.85% Molybdenum Alloy Steels

Graphite (%)	No Addition	0.5% Addition		1% Addition	
		Cr	Mn	Cr	Mn
0.25	32.2	47.2	56.7	62.8	59.8
0.50	58.8	66.1	63.5	74.2	68.8
0.75	60.6	74.3	69.1	92.7	79.4
1.00	66.3	83.6	74.6	95.5	82.7

Compaction: At 45 tsi, green density approx. 7 g/cm^3
Sintering: 2350°F, 75% H_2/25% N_2, 30 mins.

Ultimate Tensile Strength

The ultimate tensile strength of the 0.85% molybdenum prealloy base alloys increased with increasing chromium, manganese and graphite additions (Figure 9). On average, increasing the graphite addition by 0.5% increases ultimate tensile strength by 30,000 psi. Increasing alloy content, chromium plus manganese, by 1% increases ultimate tensile strength by about 25,000 psi. The data suggest that a 0.75% graphite addition is optimum. The ultimate tensile strength of the 1% graphite steels fell with alloy additions above 1% (Table V). When added separately, chromium tends to increase the ultimate tensile strength of the 0.85% molybdenum prealloy based materials slightly more than manganese within the range tested. However, the differences become less with increasing graphite content.

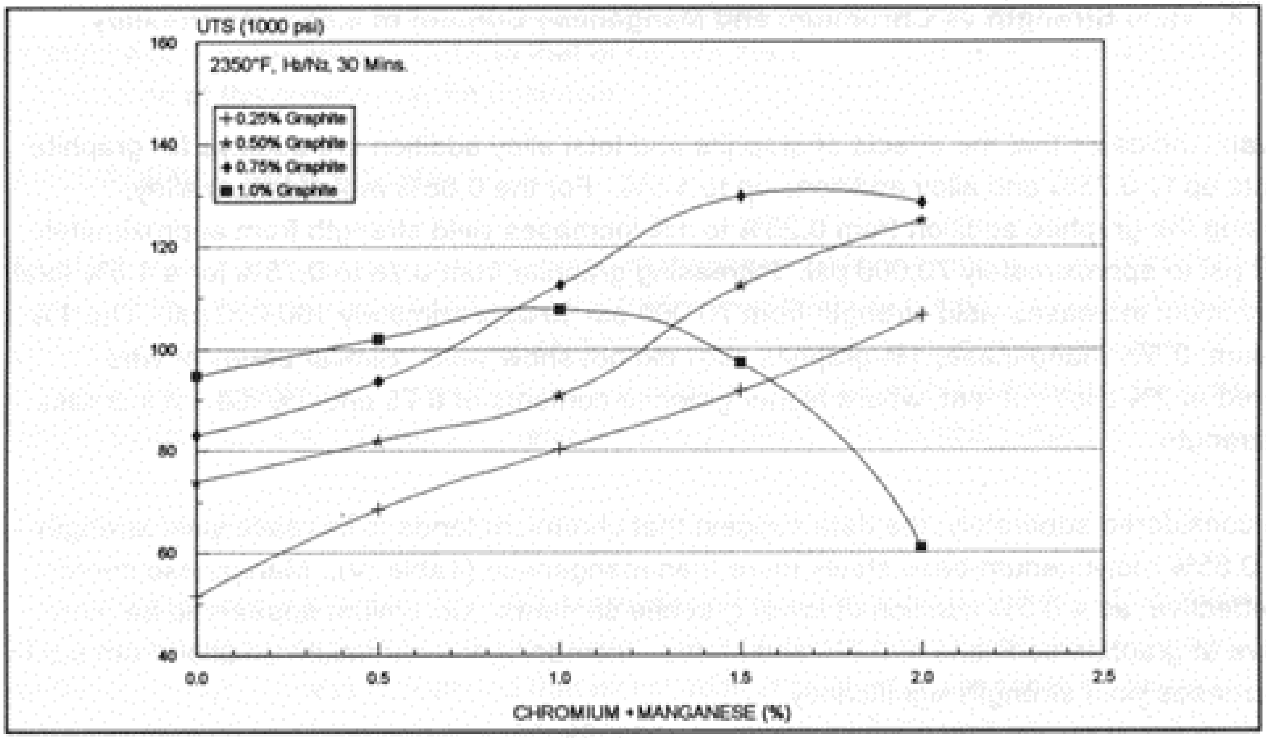


Figure 9: Ultimate Tensile Strength vs Chromium and Manganese Content of 0.85% Mo

Table V: Ultimate Tensile Strength (1000 psi) of 0.85% Molybdenum Alloy Steels

Graphite (%)	No Addition	0.5% Addition		1% Addition	
		Cr	Mn	Cr	Mn
0.25	51.5	67.1	69.8	83.6	77.5
0.50	73.9	86.1	77.7	97.5	85.8
0.75	83.1	96.4	91.0	119.1	101.4
1.00	91.2	105.4	99.6	107.5	105.5

Compaction: At 45 tsi, green density approx. 7 g/cm^3
Sintering: 2350°F, 75% H_2/25% N_2, 30 mins.

Elongation

The test results show (Figure 10) that the elongation of the 0.85% molybdenum prealloy decreases with increasing chromium, manganese and graphite contents. Generally, increasing the alloy content by 0.5% reduces elongation by about 0.5%. Increasing the graphite level by 0.25% reduces elongation by about 0.5%. The major exception is the reduction from the 6% elongation at 0.25% graphite to 3.5% at 0.5% graphite.

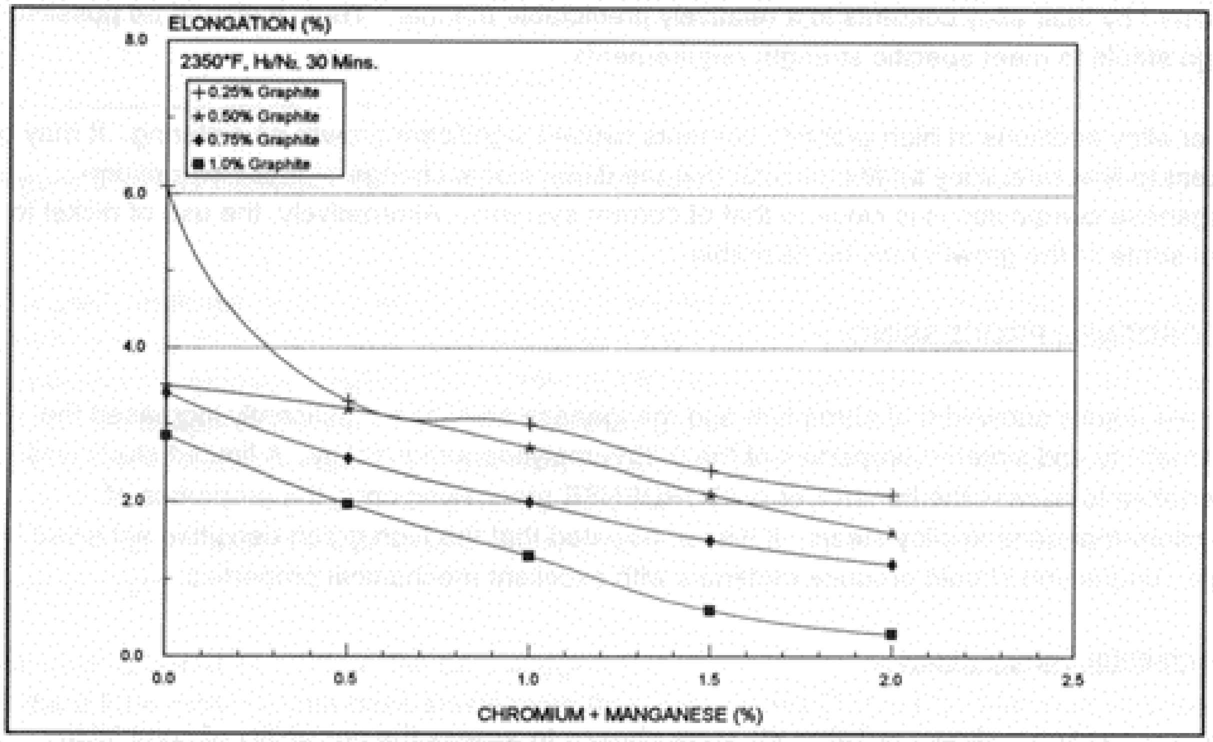


Figure 10: Elongation vs Chromium and Manganese Content of 0.85% Prealloy.

When considered separately, it appears that increasing graphite content in the presence of chromium reduces elongation more than in the presence of manganese (Table VI).

Table VI: Elongation of 0.85% Molybdenum Alloy Steels

Graphite (%)	No Addition	0.5% Addition		1% Addition	
		Cr	Mn	Cr	Mn
0.25	6.1	3.4	3.2	2.7	3.2
0.50	3.5	3.3	3.0	2.6	2.6
0.75	3.4	2.3	2.8	1.9	2.1
1.00	2.7	1.8	2.1	0.9	1.8

Compaction: At 45 tsi, green density approx. 7 g/cm^3
Sintering: 2350°F, 75% H_2/25% N_2, 30 mins.

For a 0.5% chromium steel, increasing graphite from 0.5 to 1% reduces elongation from 3.3 to 1.8%. For the 0.5% manganese steel, a similar increase reduces elongation from 3.0 to 2.1%.

Summary of Results

The results indicate that the P/M steels consisting of the 0.85% molybdenum prealloy plus chromium, manganese and graphite possess a wide range of properties. Their properties are explained by their alloy contents in a relatively predictable manner. Thus, it should be possible to design steels to meet specific strength requirements.

Higher alloy additions at high graphite contents caused significant growth on sintering. It may be prudent to limit total alloy additions such that the dimensional change of these chromium-manganese compositions is close to that of current systems. Alternatively, the use of nickel to offset some of the growth may be desirable.

ANCORDENSE PROCESSING

The test results showed that chromium and manganese additions significantly increased the hardenability and sintered properties of the 0.85% molybdenum prealloy. A limited study was undertaken to assess the benefits of ANCORDENSE processing upon the properties of chromium-manganese alloy steels. It was anticipated that the high green densities achieved by single compaction should produce materials with excellent mechanical properties.

Experimental Compositions

Four compositions, shown in Table VII, were chosen to assess the possibility of combining chromium-manganese with 0.85% prealloyed molybdenum to improve hardenability and, hence, sintered strength. It was anticipated that nickel additions would offset some of the growth on sintering caused by chromium and manganese. Graphite addition was limited to 0.4%. It was considered that this level would produce a good combination of strength and ductility.

Table VII: ANCORDENSE Test Compositions

Identity	Prealloyed Mo (%)	Chromium (%)	Manganese (%)	Nickel (%)	Graphite (%)
41AD	0.85	0.95	0.50	0.20	0.40
43AD	0.85	0.50	0.55	1.75	0.40
86AD	0.85	0.50	0.80	0.55	0.40
Ancorsteel 41AB	0.85	0.75	0.90	1.00	0.40

Three widely used wrought steel compositions: AISI 4140, 4340, 8640, designated as 41 AD, 43AD and 86AD were chosen for the experiment. It should be noted that the experimental steels have a higher molybdenum content and lower silicon content than the wrought AISI compositions. Ancorsteel** 41AB is a commercial P/M chromium-manganese alloy steel.

Results

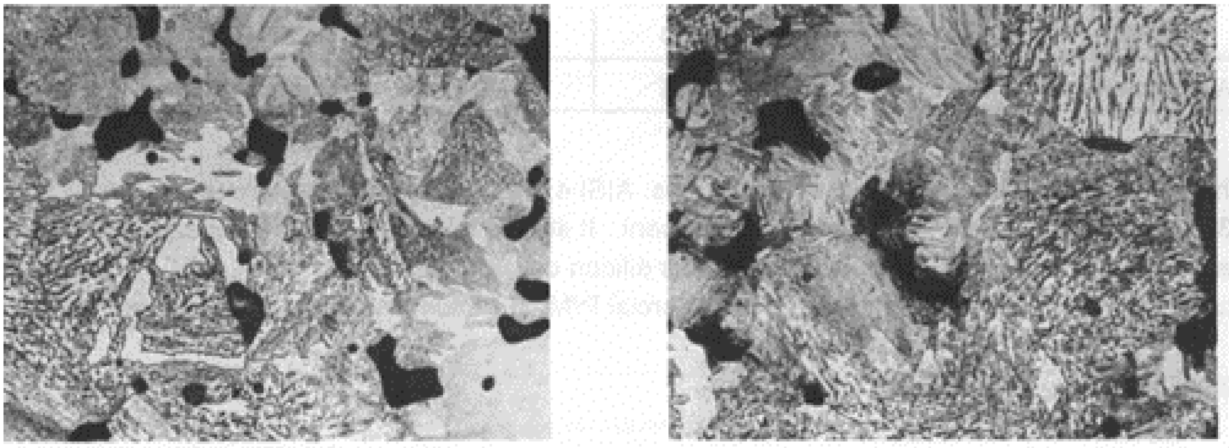
The properties of the experimental compositions are shown in Table VII lb. The results proved the principles of the experiment. The P/M steels attained high sintered densities of approximately 7.3 g/cm^3 following single compaction ANCORDENSE processing. They possessed growth, from die of +0.1% to +0.4% on sintering, equivalent to current P/M Steels. The experimental compositions attained high yield and tensile strength. These results are discussed further below.

Metallography

The microstructures of the ANCORDENSE processed alloys are shown in Figure 11. They are similar to those of the chromium-manganese alloys shown in Figures 5 and 6. The microstructures consist of alloy ferrite and martensite. The carbides may be both lamellar, generally considered to be pearlite or discrete, considered to be bainite. The proportion of martensite appears to increase either with increasing nickel content and increasing hardenability from the 41AD and 86AD (Figures 11a, b) to the 43AD and Ancorsteel 41AB compositions (Figures 11c, d).

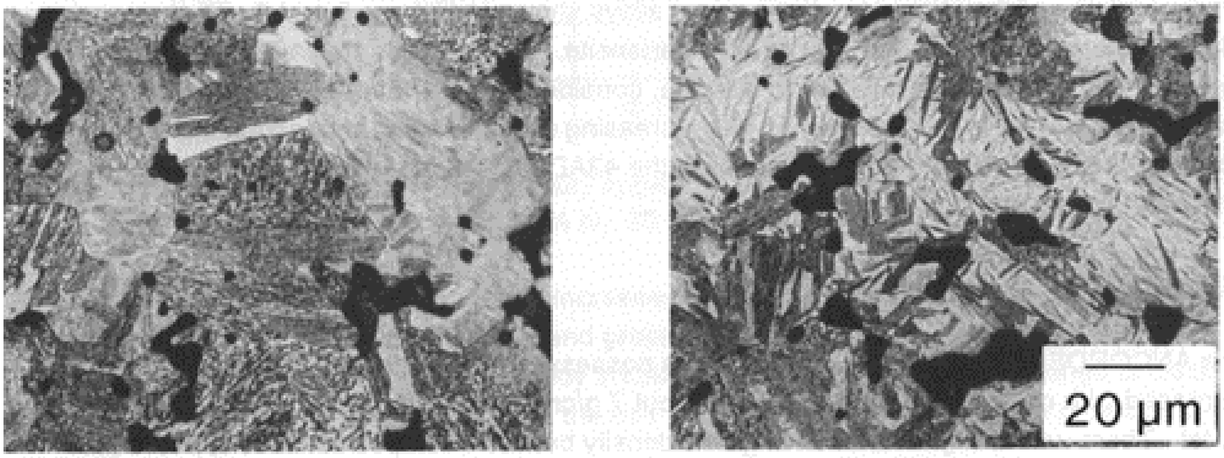
Compressibility

The ANCORDENSE processed test premixes possessed high densities (Figure 12). Densities increased with compaction pressure from about 7 g/cm^3 at 30 tsi to approximately 7.35 g/cm^3 at 50 tsi. There was a slight variation in green density between compositions. It appears that elemental nickel additions favor higher green density. The 43AD test composition, with a nickel content of 1.75%, possessed the highest green density; the 41AD, with a 0.2% nickel addition, the lowest.



a) 41AD

b) 86AD



c) 43AD

d) Ancorsteel 41AB

Figure 11: Microstructure of ANCORDENSE Processed Chromium-Manganese P/M Steels. Etched with a Combination of 2% Nital / 4% Picral. Original Magnification 500X.

Table VIIIa: Properties of Chromium-Manganese Test Compositions

		Sintered Properties				
Total (Cr+Mn) (%)	Graphite (%)	G.D. (g/cm^3)	S.D. (g/cm^3)	D.C. (%)	TRS (1000 psi)	Hardness (HRB)

0	0.25	7.12	7.15	+0.06	103.0	49
	0.50	7.13	7.14	+0.02	150.8	76
	0.75	7.10	7.14	+0.08	162.6	82
	1.00	7.09	7.11	+0.06	176.5	86
0.5	0.25	7.12	7.13	+0.11	141.6	73
	0.50	7.13	7.11	+0.11	170.5	79
	0.75	7.10	7.08	+0.21	181.5	88
	1.00	7.08	7.05	+0.26	183.8	91
1.0	0.25	7.10	7.07	+0.31	165.5	78
	0.50	7.12	7.07	+0.26	191.7	86
	0.75	7.08	7.02	+0.41	201.3	92
	1.00	7.06	6.98	+0.51	187.8	95
1.5	0.25	7.10	7.04	+0.52	181.7	84
	0.50	7.11	7.03	+0.58	215.3	92
	0.75	7.08	6.97	+0.64	233.7	92
	1.00	7.05	6.92	+0.77	159.7	98
2.0	0.25	7.09	6.99	+0.55	200.6	88
	0.50	7.10	6.97	+0.65	244.9	23C
	0.75	7.07	6.92	+0.85	198.5	36C
	1.00	7.04	6.86	+1.05	103.1	26C

		Tensile Properties				
Total (Cr+Mn) (%)	**Graphite (%)**	**S.D. (g/cm^3)**	**Y.S. (1000 psi)**	**UTS (1000 psi)**	**Elong. (%)**	**Hardness (HRB)**
0	0.25	7.21	32.2	51.5	6.1	54
	0.50	7.20	58.8	58.8	3.5	76
	0.75	7.19	60.6	83.1	3.4	81
	1.00	7.18	68.4	94.7	2.9	86
0.5	0.25	7.19	52.0	68.5	3.3	72
	0.50	7.15	64.8	81.9	3.2	80
	0.75	7.17	71.7	93.7	2.6	87
	1.00	7.14	79.3	102.0	2.0	91
1.0	0.25	7.17	61.2	80.2	3.0	77
	0.50	7.07	72.2	90.8	2.7	86
	0.75	7.13	88.1	112.5	2.0	92
	1.00	7.09	89.9	107.7	1.3	95
1.5	0.25	7.13	69.5	91.7	2.4	83
	0.50	7.03	89.7	112.3	2.1	92
	0.75	7.09	101.0	129.8	1.5	93
	1.00	7.05	95.9	97.3	0.6	97
2.0	0.25	7.08	79.5	106.5	2.1	88
	0.50	6.97	102.7	125.2	1.6	21C
	0.75	7.06	92.9	128.6	1.2	34C
	1.00	7.01	N.Y.	61.0	0.3	28C

Test Mix: 0.85% Molybdenum low alloy, graphite, ferroalloys
Compaction: At 45 tsi
Sintering: 2350°F, 75% H_2 / 25% N_2, 30 mins.
Stress Relief: 400°F, one hour

Table VIIIb: Properties of ANCORDENSE Test Compositions

						Sintered Properties			
Mix I.D.	**Cr (%)**	**Mn (%)**	**Ni (%)**	**S.C(%)**	**Press (tsi)**	**G.D. (g/cm^3)**	**S.D. (g/cm^3)**	**D.C. (%)**	**TRS (1000 tsi)**
41AD	0.95	0.50	0.20	0.47	30	7.04	6.97	+0.30	177.0
					40	7.26	7.20	+0.42	220.7
					50	7.35	7.30	+0.46	243.4
43AD	0.50	0.55	1.75	0.45	30	7.05	7.04	+0.04	200.7
					40	7.28	7.25	+0.18	242.9
					50	7.36	7.33	+0.23	261.4
86AD	0.50	0.50	0.55	0.41	30	7.05	7.05	+0.23	184.8
					40	7.27	7.27	+0.31	216.4
					50	7.35	7.35	+0.35	240.0
Ancorsteel 41AB	0.75	0.75	1.00	0.48	30	7.04	6.98	+0.27	202.2
					40	7.27	7.19	+0.38	240.9
					50	7.36	7.29	+0.44	271.1

						Tensile Properties				
Mix I.D.	**Cr (%)**	**Mn (%)**	**Ni (%)**	**S.C. (%)**	**Press (tsi)**	**S.D. (g/cm^3)**	**Y.S. (1000 psi)**	**UTS (1000 psi)**	**Elong (%)**	**Hardness (HRB)**
41AD	0.95	0.50	0.20	0.47	30	7.00	75.3	101.8	2.5	84
					40	7.16	88.3	118.4	3.0	91
					50	7.29	88.3	112.9	3.6	93
43AD	0.50	0.55	1.75	0.45	30	7.07	79.2	110.7	2.4	89
					40	7.25	88.8	124.7	3.2	94
					50	7.36	97.1	134.8	3.9	97
86AD	0.50	0.50	0.55	0.41	30	7.03	70.0	94.6	2.9	82
					40	7.24	77.6	106.1	3.8	87
					50	7.33	79.9	122.0	4.1	90
Ancorsteel 41AB	0.75	0.75	1.00	0.48	30	7.04	95.8	127.7	1.9	15C
					40	7.24	105.7	146.5	2.7	21C
					50	7.28	104.6	148.0	2.5	23C

Test Composition: 0.85% Molybdenum Pre alloy, 0.4% Graphite
Plus Alloying Additions
Sintering: 2350°F, 75% H_2 / 25% N_2, 30 mins.
Stress Relief: 400°F, 60 minutes

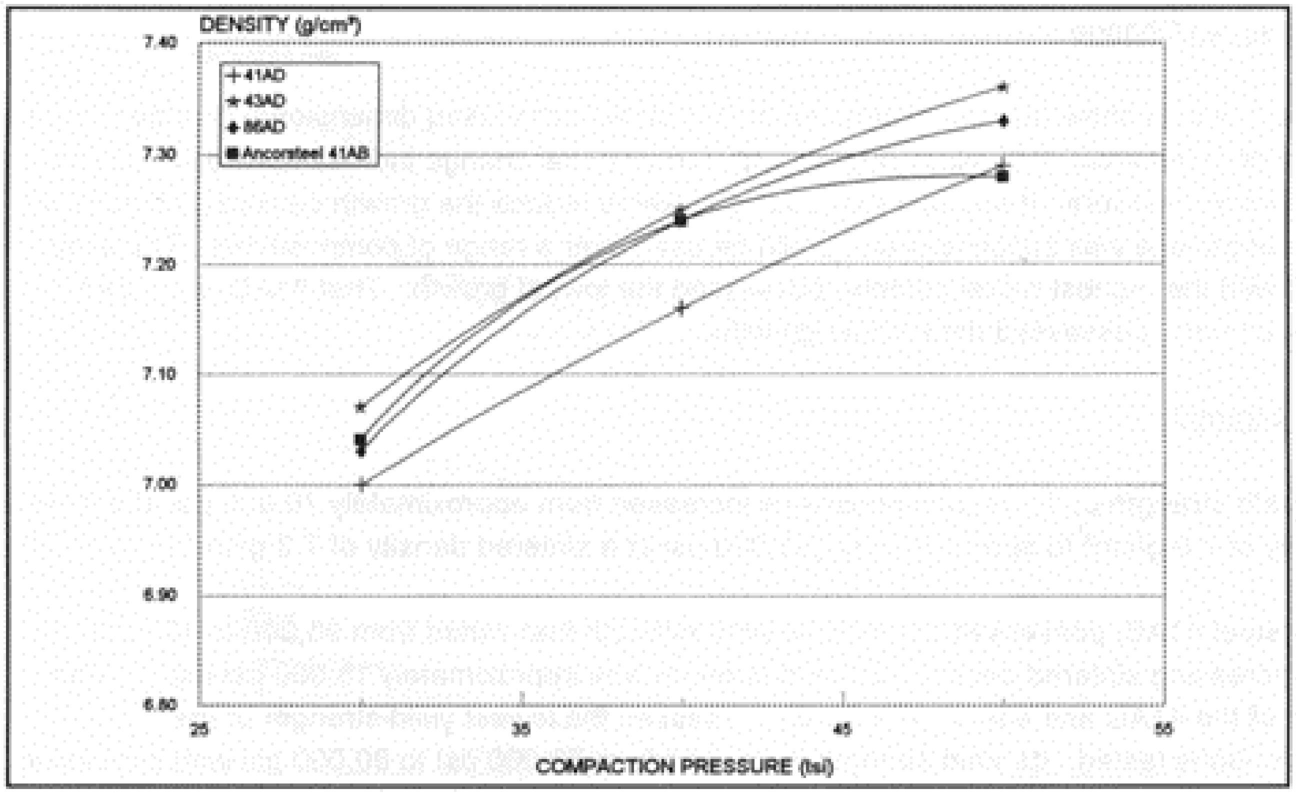


Figure 12: Sintered Density vs Compaction Pressure for ANCORDENSE Nickel-Chromium-Manganese P/M Steels.

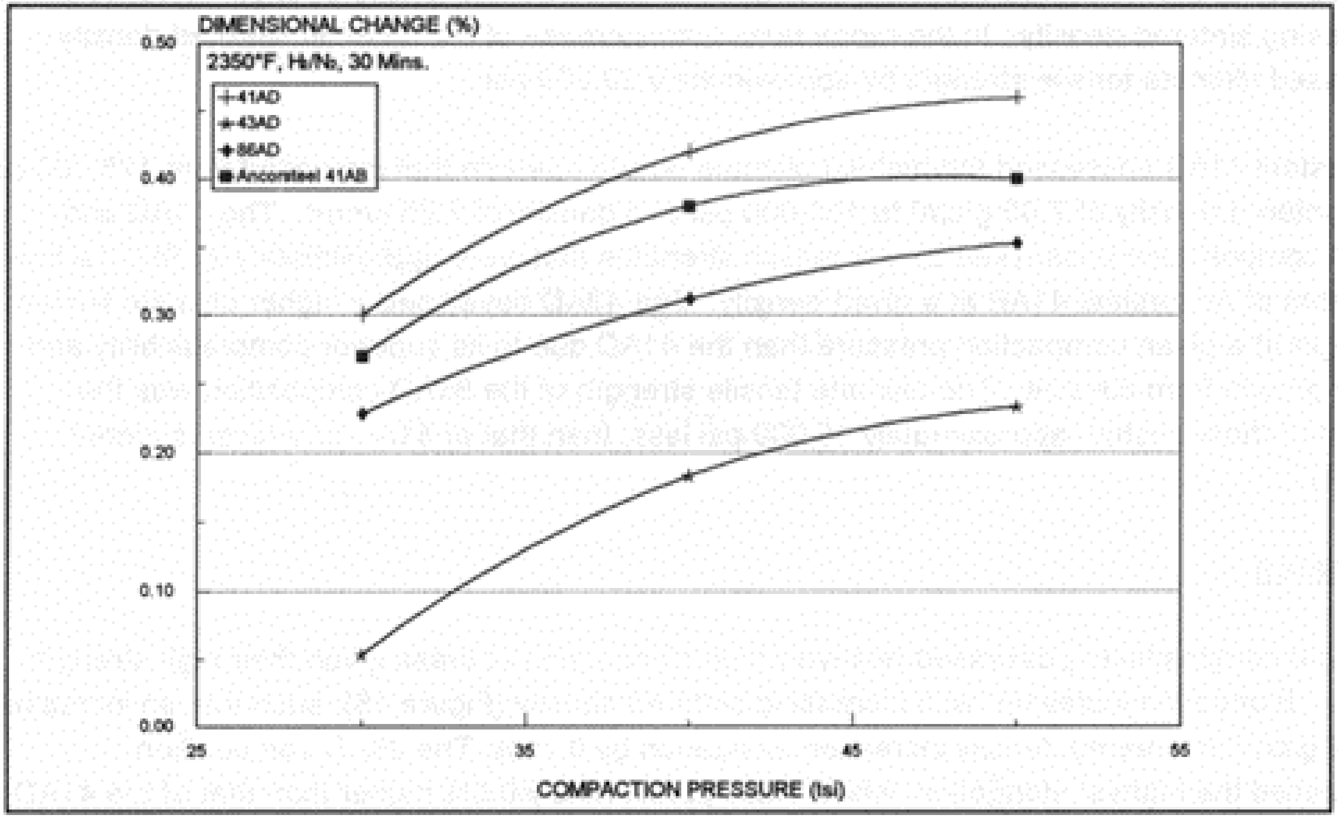


Figure 13: Dimensional Change VS Compaction Pressure of ANCORDENSE Nickel-Chromium-Manganese P/M Steels.

Dimensional Change

The test results show that the experimental P/M steels possessed dimensional change from die, typical of commercial P/M alloys (Figure 13). Dimensional change increased with increasing compaction pressure. It appears that adding nickel to reduce the growth caused by chromium and manganese was successful and could be used over a range of compositions. The alloy, 43AD with the highest nickel content, possessed the lowest growth. That 41AD, with lowest nickel content, possessed the highest growth.

Yield Strength

The yield strength of the test compositions increased from approximately 70,000 psi at a sintered density of 7.0 g/cm^3 to approximately 105,000 psi at a sintered density of 7.3 g/cm^3 (Figure 14).

Ancorsteel 41AB, possessed the highest yield strength that varied from 95,000 to 105,000 psi with increasing sintered density. Its yield strength was approximately 15,000 psi higher than those of the 41AD and 43AD. The 86AD possessed the lowest yield strength of the compositions tested. Its yield strength increased from 70,000 psi to 80,000 psi with increasing sintered density.

Ultimate Tensile Strength

The P/M chromium-manganese alloy steels showed similar variation in ultimate tensile strength (Figure 15) to that observed with yield strength. Overall, ultimate tensile strength increased with increasing sintered density. In the range tested, an increase of 0.2 g/cm^3 in sintered density increased ultimate tensile strength by approximately 20,000 psi.

Ancorsteel 41AB possessed the highest ultimate tensile strength that increased from 125,000 psi at a sintered density of 7.05 g/cm^3 to 150,000 psi at a density of 7.25 g/cm^3. The 41AD and 43AD compositions possessed similar tensile strengths that were approximately 20,000 psi lower than that of Ancorsteel 41AB at a given density. The 43AD developed a higher ultimate tensile strength at a given compaction pressure than the 41AD due to its superior compressibility and lower growth from die size. The ultimate tensile strength of the 86AD composition was the lowest of those tested, approximately 15,000 psi less, than that of 41AD at a given sintered density.

Elongation

The test compositions possessed relatively high elongations at break given their high strength levels. Elongation increased with increasing sintered density (Figure 16), such that an increase of 0.2 g/cm^3 in sintered density increased elongation by 0.75%. The 86AD composition possessed the highest elongation, which was approximately 0.5% higher than that of the 41AD and 43AD at similar density. These P/M steels possessed an elongation approximately 0.75% higher than that of the Ancorsteel 41AB for a given density.

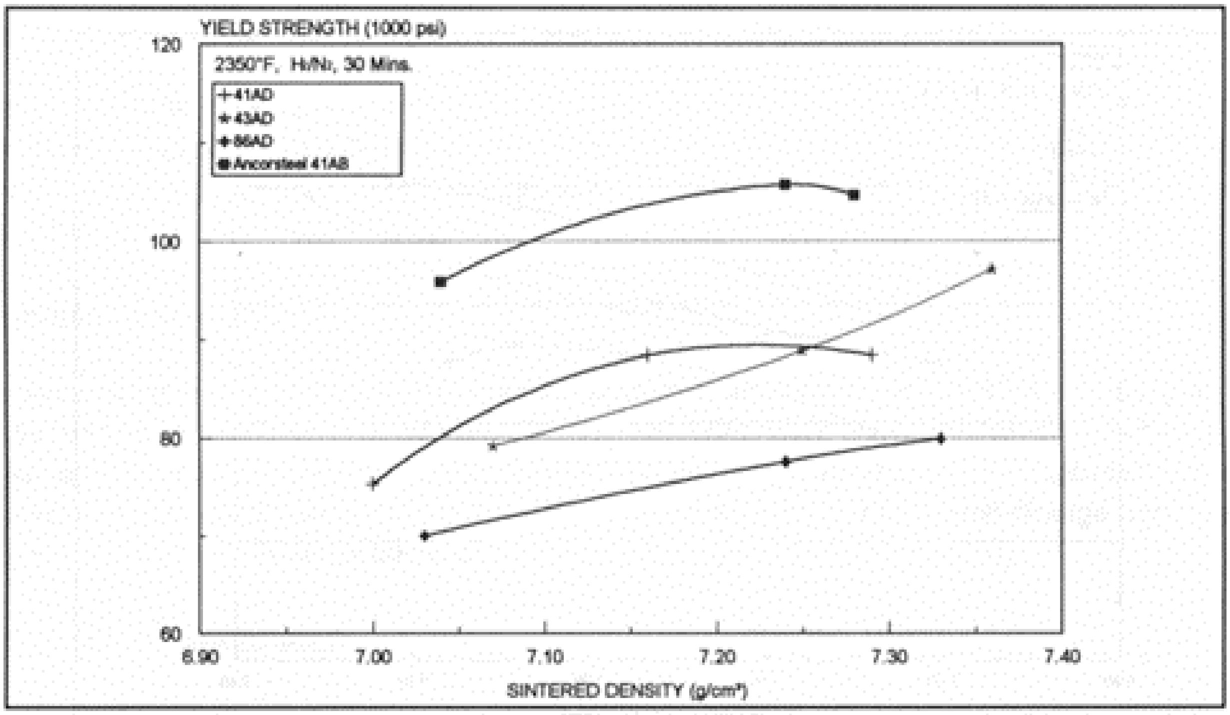


Figure 14: Yield Strength vs Sintered Density of ANCORDENSE Nickel-Chromium-Manganese P/M Steels.

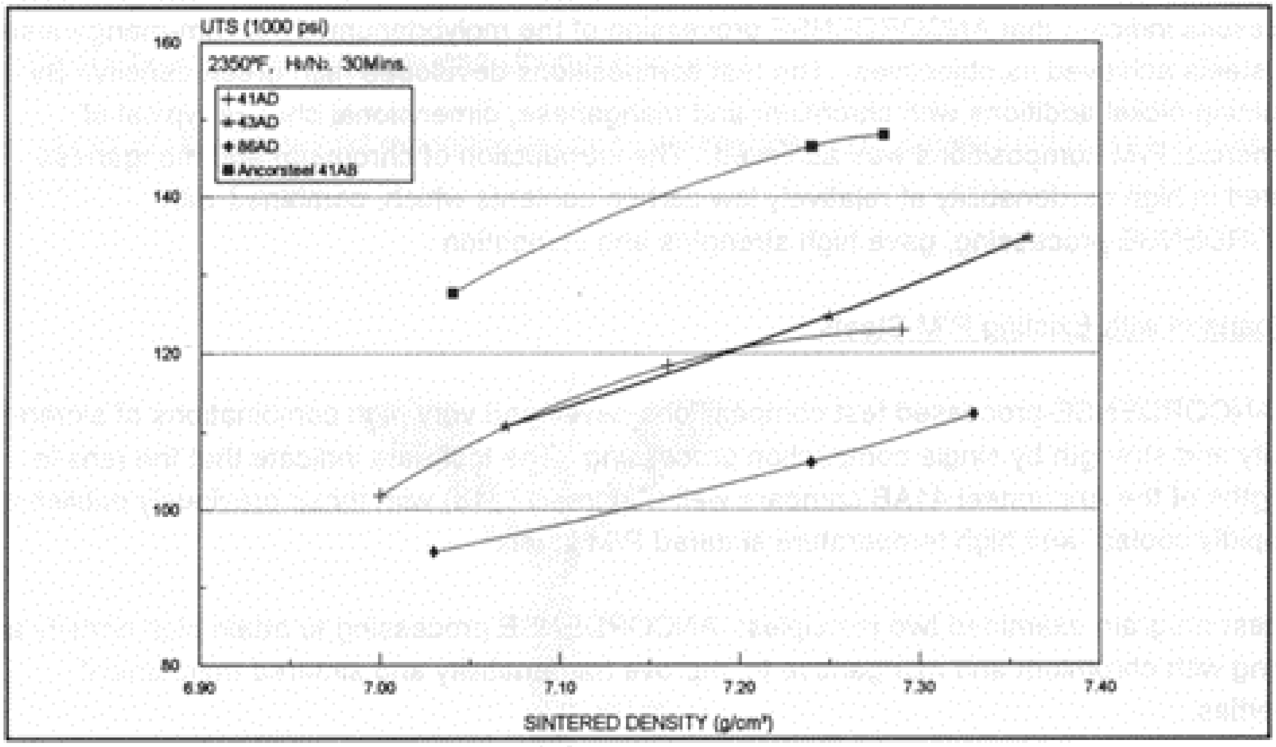


Figure 15: Ultimate Tensile Strength vs Sintered Density of

ANCORDENSE Nickel-Chromium-Manganese P/M Steels.

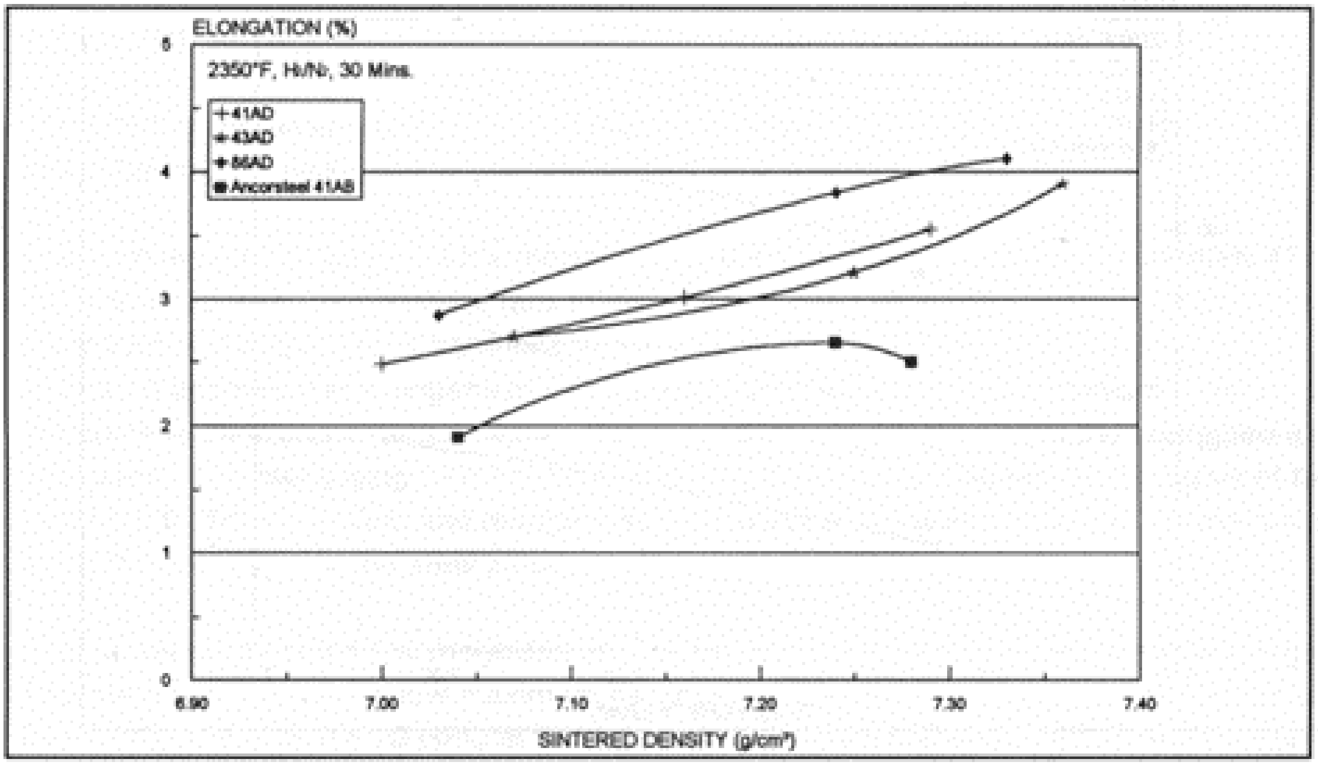


Figure 16: Elongation vs Sintered Density of ANCORDENSE Nickel-Chromium-Manganese P/M Steels.

Summary of ANCORDENSE Processing

The results indicate that ANCORDENSE processing of the molybdenum-chromium-manganese alloy steels achieved its objectives. The test compositions developed high green density. By combining nickel additions with chromium and manganese, dimensional change typical of commercial P/M compositions was achieved. The introduction of chromium and manganese resulted in high hardenability at relatively low carbon contents which, combined with ANCORDENSE processing, gave high strengths and elongation

Comparison with Existing P/M Steels

The ANCORDENSE-processed test compositions developed very high combinations of sintered density and strength by single compaction processing. The test data indicate that the tensile strengths of the Ancorsteel 41AB compare well (Figures 17,18) with those previously published for rapidly cooled (3) and high temperature sintered P/M steels (9).

The test program examined two principles: ANCORDENSE processing to attain high density and alloying with chromium and manganese to improve hardenability and sintered mechanical properties.

The data in Figure 17 show that ANCORDENSE processing produced sintered densities in the Ancorsteel 41AB composition superior to those attained in a sinter-hardening Ancorsteel 4600V, 2% copper, 0.9% graphite system processed by double pressing and sintering (3). The density of the Ancorsteel 41AB is only slightly less than that achieved when the more compressible 0.85% molybdenum prealloy is used as the matrix of the sinter-hardening composition. The tensile strength of the ANCORDENSE processed Ancorsteel 41AB exceeds that of the sinter-hardening grades at similar density level, even when these compositions are double pressed and sintered.

The benefits of improved hardenability are shown by comparing the properties of the Ancorsteel 41AB with those of high temperature sintered 0.85% molybdenum-base prealloy, 4% nickel steels (8) (Figure 18). The 4% nickel steels have excellent compressibility and develop high sintered density through shrinkage at high sintering temperatures. They attain sintered densities slightly higher than the ANCORDENSE processed Ancorsteel 41AB. However, their ultimate tensile strength is significantly lower than that of the Ancorsteel 41AB.

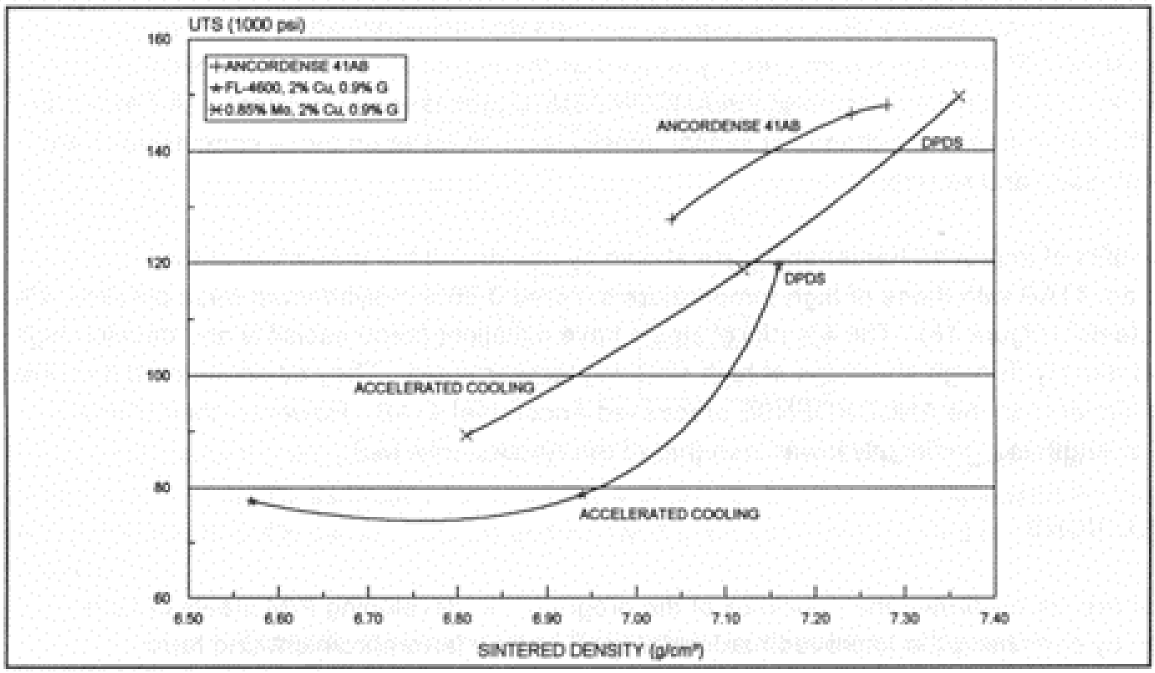


Figure 17: Comparison of Ultimate Tensile Strength of P/M Steels.

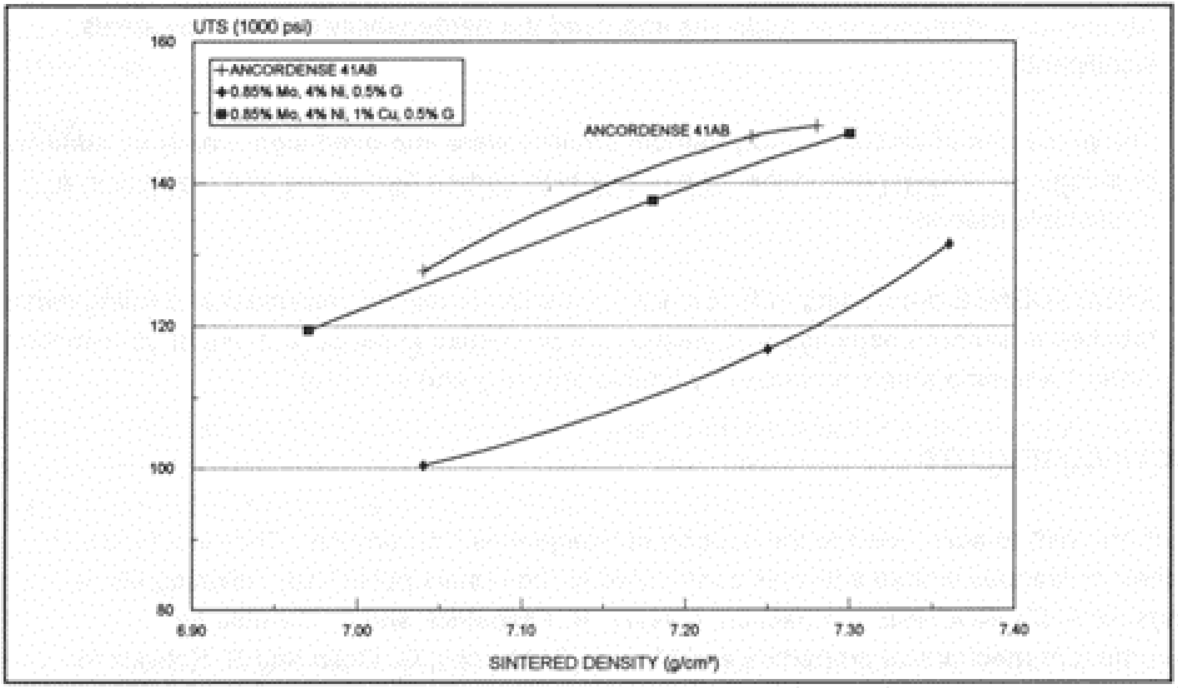


Figure 18: Ultimate Tensile Strength of High Temperature Sintered P/M Steels.

CONCLUSIONS

The test results confirmed the principles of the program, i.e. developing P/M steels of high strength by combining the improved hardenability offered by ferro-chromium and ferro-manganese additions with the high green density offered by ANCORDENSE processing.

ANCORDENSE processing enabled P/M low alloy steels to develop densities typical of double pressed and sintered materials by single compaction.

The results showed:

> Chromium and manganese additions improved the hardenability of P/M alloy steels significantly.
>
> The properties of an 0.85% molybdenum prealloy were improved significantly by additions of chromium, manganese in the form of fine high carbon ferroalloys and graphite in a predictable manner.
>
> ANCORDENSE processing of P/M low alloy steels containing chromium and manganese resulted in sintered densities and mechanical properties superior to those

of conventional sinter-hardening steels produced by double pressing and sintering.

ACKNOWLEDGMENTS

The authors wish to acknowledge the support of Hoeganaes Corporation. They would like to thank their colleagues whose activities contributed to the results published, including Mr. A. Rawlings for ANCORDENSE compaction, Messrs. R. Fitzpatrick and C. Gamble for measurement of mechanical properties and Messrs. T. Murphy, G. Golin and S. Kolwicz for metallography and Mrs. S. Tworzydlo, without whom this work would not have been published.

REFERENCES

1. Rutz, H.G., and Hanejko, F.G., “High Density Processing of High Performance Ferrous Materials”, presented at the 1994 International Conference & Exhibition on Powder Metallurgy & Particulate Materials, May 1994, Toronto, Canada, to be published in Advances in Powder Metallurgy & Particulate Materials by Metal Powder Industries Federation, Princeton, NJ.

2. Luk, S.H., Lutz, M.A. and Rutz, H.G., “Properties of High Density Ferrous P/M Materials -A Study of Various Processes”, presented at the 1994 International Conference & Exhibition of Powder Metallurgy & Particulate Materials, May 1994, Toronto, Canada, to be published in Advances in Powder Metallurgy & Particulate Materials by Metal Powder Industries Federation, Princeton, NJ.

3. Causton, R.J. and Fulmer, J.J., “Sinter-Hardening Low-Alloy Steels”, Advances in Powder Metallurgy & Particulate Materials, 1992, Vol. 5, pp 17-52, Metal Powder Industries Federation, Princeton, NJ.

4. James, W.B., and Causton, R.J., “Surface-Hardenable Heat Treated P/M Steels”, Advances In Powder Metallurgy & Particulate Materials, 1992, Vol.5, pp 62-92, Metal Powder Industries Federation, Princeton, NJ.

5. Schaeffler, D.J., Lawley, A., and Causton, R.J., “Low Carbon P/M Alloy Steels”, Advances In Powder Metallurgy & Particulate Materials, 1992, Vol.5, pp 93-102, Metal Powder Industries Federation, Princeton, NJ.

6. Doane, D.V., “Hardenability Concepts with Applications to Steel”, The Metallurgical Society of AIME, Warrendale, PA.

7. Krauss, G., “Steels: Heat Treatment and Processing

Principles”, ASM, 1990.

8. Hamill, J.A., Causton, R.J., Shah, 8.0., “High Performance Ferrous P/M Materials Utilizing High Temperature Sintering”, Advances in Powder Metallurgy & Particulate Materials, 1992, Vol.5, pp 193-214, Metal Powder Industries Federation, Princeton, NJ.

9. Causton, R.J., Murphy, T. et al, “Non-Metallic Inclusion Measurement of Powder Forged Steels Using an Automatic Image Analysis System”, Horizons of Powder Metallurgy, Part II, pp 727-730, Verlag Schmid Gmbh, 1986.

Notes:

*ANCORDENSE™ is a trademark of Hoeganaes corporation
**Ancorsteel is a registered trademark of Hoeganaes Corporation