PROPERTIES OF SEVERAL ANCORDENSE™ PROCESSED HIGH PERFORMANCE MATERIALS

T. M. Cimino, A. J. Rawlings, and H. G. Rutz
Hoeganaes Corporation
Riverton, NJ USA

Presented at PM² TEC '96 World Congress June 16-21 - Washington D.C.

ABSTRACT

The effect of powder and compaction temperature on the ANCORDENSE warm compaction system is evaluated. Detailed property analysis is presented on several warm compacted high performance materials systems. Properties evaluated include density, tensile, and impact performance. A detailed assessment of the microstructure resulting from various alloy compositions and processing techniques is performed. The materials involved in the tests were conventional and high temperature sintered and tested in the as sintered and heat treated condition.

INTRODUCTION

ANCORDENSE technology is a material and process combination that utilizes elevated temperature compaction techniques to increase green density, green strength and decrease ejection forces. This warm compaction technique utilizes a patented binder treated premix that provides the benefits of improved flow coupled with limited segregation and dusting of fine premix additions. The binder/lubricant system is engineered for optimal performance at the elevated temperatures encountered during warm compaction.[2]

In the first portion of this study a discussion of the concept of pore free density, as well as optimum compaction temperature, will be reviewed. The results for several warm compacted premix compositions will be presented including the mechanical properties for both the as-sintered and heat treated conditions. The effect of premix additions and sintering temperature will be evaluated and related to the resulting microstructure.

PORE-FREE DENSITY

Pore free density can be defined as the density of a premix if all the contained porosity was eliminated. To calculate the pore free density of a premix, it is necessary to determine the density and percent addition of the individual premix constituents. In ferrous powder metallurgy premixes, the base iron powder will be the dominant factor in calculating pore free density. The typical density of a pure iron powder is approximately 7.84 g/cm^3. Premix additions of elements with a high density such as nickel and copper will increase the pore free density by occupying volume with heavier materials. Additions of Low-density materials such as lubricant and graphite will have the opposite effect.[3] To demonstrate this, consider a diffusion alloyed base iron containing 4w/o Ni, 1.5w/o Cu and 0.5w/o Mo (Distaloy 4800A) with premix additions of 0.6w/o graphite and 0.75w/o lubricant (MPIF designation FD4805)[4]. The density and percentage of admixed materials are shown in Table I along with the volume occupied by the addition and the volume percent that each component occupies. It should be noted that the presence of a fairly large amount of nickel, copper and molybdenum in the diffusion alloyed material has raised the specific density of the base powder by about 0.05 g/cm^3 over a pure iron powder.

Table I: Pore Free Density Calculation - FD-4805 with 0.60w/o Graphite and 0.75w/0 Lubricant

Premix Component	Weight Percent Addition to Premix	Density (g/cm3)	Volume Occupied (cm^s) by 100 g of Premix	Volume Percent Occupied by Addition
Base Powder	98.65	7.90	12.49	92.7
Graphite	0.60	2.30	0.26	1.9
Lubricant	0.75	1.03	0.73	5.4

Total Addition 100 g Total volume cm^3 13.48

Pore Free Density = 100g / 13.48 cm^3 = 7.42 g/cm^3

For the above material, the pore free density is 7.42 g/cm^3. The addition of even a small weight percent of the lighter components, such as graphite and lubricant, can affect the pore free density of the premix significantly. Simply lowering the lubricant to 0.6w/o has the effect of raising the pore free density of the above composition to 7.49 g/cm^3.

In practice, it is impossible to achieve the pore free density during the compaction of a part. With conventional room temperature compaction methods, the density achievable is limited by the compressibility of the premix and a practical limit of about 50 to 60 tsi (690 to 825 MPa) in compaction pressure. Even with the warm compaction process it is not possible to reach pore free density levels due to springback of part and tool after ejection?

With the warm compaction process, it is possible to approach 98 to 98.5% of the calculated pore free density level. It is important therefore to understand the effects that premix additions will have on the pore free density and the resulting green density of the part. High additions of graphite, and particularly lubricant, can limit the potential green density of a given premix composition.

For the composition illustrated in Table I, the maximum green density that could be achieved is approximately 7.27 g/cm^3. Lowering the lubricant level by only 0.15w/o would raise the anticipated maximum density to about 7.34 g/cm^3. The compaction pressure required to attain this density level will vary with premix compositions. However, once 98% to 98.5% of the pore free density is attained, further increases in compaction pressure will not increase the green density and may result in the formation of laminations due to "over-compaction'. It is important to note that careful design and understanding of the effect of additives such as graphite and lubricant is necessary in order to obtain an appropriate premix composition.

DETERMINATION OF OPTIMAL COMPACTION TEMPERATURE RANGE

In order to evaluate the optimal temperature for compaction, the premix illustrated in Table I (FD-4805 / Distaloy 4800A+0.6w/o graphite+0.75w/o high temperature lubricant) was compacted at various temperatures. Both the powder and tooling were heated in the range of 70°F to 375°F (20°C to 190°C). Green strength specimens measuring 1.25 inch (31.75mm) x

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0.5 inch (12.7mm) x 0.5 inch (12.7mm) compacted at pressures of 30, 40 and 50 tsi (415, 550 and 690 MPa) were utilized for the investigation. The resulting green density and peak ejection force (the force needed to initiate the ejection of the part from the die) were determined to evaluate the lubricant performance. This data is plotted in Figures 1 and 2.

For all three compaction pressures, the density increased with increasing compaction temperatures. With the exception of 30 tsi (415 MPa), the density was not increased significantly by increasing the compaction temperature above approximately 300°F (150°C). At a compaction pressure of 50 tsi (590 MPa) and temperature of 300°F (150°C), the green density achieves 98% of the pore free density discussed above. Further increases in either compaction pressure or temperature do not result in increases in density. It would appear therefore that the optimal temperature needed to achieve maximum green density is approximately 300°F (150°C).

Ejection characteristics shown in Figure 2 illustrate clearly that the lowest pressure is found at a temperature of 300°F (150°C). Altering the compaction temperature above or below 300°F (150°C), regardless of pressure, results in an increase in ejection force.

Another key variable for warm compaction processing is powder flow. Without consistent powder flow, the variability of the process may be a concern. Table II details the flow rate over a range of temperatures for the FD-4805 premix.

Table II: Flow Rate and Apparent Density of ANCORDENSE – FD4805

Test Temperature	*260`F / 125`C*	*270`F / 130`F*	*280`F / 135`C*	*290`F / 140`C*	*300`F / 150`F*
Flow rate (s/50g)	**23**	**23**	**24**	**24**	**27**
Apparent Density (g/cm^3	**3.14**	**3.10**	**3.05**	**3.04**	**3.03**

When the compressibility data, ejection characteristics and powder flow are considered, it appears that compacting at approximately 290°F (145°C) provides optimum performance. In the temperature range of 290°F to 300°F (145°C to 150°C) the powder flow decreases, while in the temperature range of 280°F to 300°F (135°C to 150°C) the apparent density is consistent. Additional field studies have indicated that, depending upon the requirements of individual components, the best performance may be realized with a compaction temperature in the range of 265-310°F (125°C to 155°C). It is important also that the temperature of both the powder and tools be maintained at not less than +5°F (+2.5°C) of the specified temperature throughout the process. Maintaining consistency in temperature will insure proper weight control?

MATERIAL PROPERTIES

This section summarizes the mechanical property data for several warm compacted premix compositions and relates the resulting data to microstructure and density. The mixes were prepared using the high temperature lubricant and binder system required for the warm compaction process. Compaction was carried out with the die and powder heated to 290°F (145°C). The compositions of the materials evaluated are listed in Table II1. In all cases the lubricant addition was maintained at 0.6 w/o.

Table III - Experimental ANCORDENSE Premixes

Material	Nominal Alloy Content			Premix Additions			Pore Free Density (g/cm³)
	Mo (w/o)	Ni (w/o)	Cu (w/o)	Ni (w/o)	Graphite (w/o)	Past Fe3P (w/o)	
A	--	--	--	--	--	2.9	7.52
B	0.85	--	--	--	0.5	--	7.45
C	0.85	--	--	2.0	0.4	--	7.49
D*	0.55	4.0	1.5	--	0.5	--	7.46

*Alloy additions were diffusion alloyed

SPECIMEN PREPARATION AND TESTING PROCEDURE

Transverse rupture bars (for density measurement), tensile and impact specimens were compacted at 30, 40 and 50 tsi (415, 550, 690 MPa) using a 100 ton hydraulic press. Test specimens were sintered at 2050°F (1120°C) and 2300°F (1260°C) for 30 minutes at temperature in a 25 v/o N2/75 v/o H2 atmosphere. Sintered density was determined for the test specimens using the oil immersion method according to MPIF standard 45[5].

Mechanical testing was done to evaluate tensile and impact properties. Impact properties were obtained according to MPIF Standard 40 using specimens compacted to the following dimensions: length of 2.165 inches (55mm), width of 0.394 inches (10 mm) and height of 0.394 inches (10 mm). As-sintered tensile properties were determined using dogbone specimens according to MPIF Standard 40.[5]

Heat treatment was performed on samples from all premixes, except A, which is the material containing phosphorus. The process involved austenitizing the samples at 1600°F (850°C) for 30 minutes in an endothermic atmosphere with a slightly positive carbon potential, quenching into 165°F (75°F) oil and tempering at 375°F (190°C) for two hours in air. Heat-treated tensile properties were generated using machined round specimens with threaded ends. The finished samples had a gauge diameter of 0.2 inches (5mm) and a gauge length of 1.0 inch (25.4mm).

RESULTS AND DISCUSSION

Material A - ASTM Standard A 839

Material A is an iron-0.45w/o phosphorous alloy made with Ancorsteel® 1000B as the base material. The desired as-sintered carbon content typically is less than 0.01w/o. The density values obtained by warm compaction and sintering at traditional and elevated temperatures are shown in Table IV. As-sintered tensile and impact properties are presented in Tables V and VI, respectively. Due to the fact that the iron-0.45w/o phosphorus chemistry is designed to provide ductility and strength without the presence of carbon, no heat-treated values have been included. Examination of the data indicates that this material exhibits moderate tensile properties but shows good elongation and toughness.

The microstructure developed in the as-sintered state, which is shown in Figure 3, is composed entirely of ferrite. This is an excellent material for soft DC magnetic components and structural components, which require moderate strength with high ductility. The presence of phosphorus

promotes sintering in the alpha phase (ferrite), which induces the material to develop large round pores. These large pores act to enhance ductility, with the effect being more pronounced as the sintering temperature is increased.

Material B - MPIF Standard FL-4405 4

Material B is a premix composed of a highly compressible prealloyed iron powder containing 0.85w/o molybdenum (Ancorstee185 HP) with a premix addition of 0.6w/o graphite. The density values and as-sintered tensile and impact properties are listed in Tables VII through IX. A key characteristic of this material is that it exhibits good strength with a uniform apparent hardness and microstructure in both the sintered and heat-treated conditions compared with a typical F-0008 material. The uniformity of the microstructure as well as good core toughness is a feature that makes it a good candidate for induction hardening of gears and hydraulic components. The as-sintered microstructures, shown in Figure 4, are composed of divorced pearlite with the sample sintered at 2300°F (1260°C) showing a larger grain size than the sample sintered at 2050°F (1120°C).

The heat treated material shows a large improvement in strength (Table X) and apparent hardness over the as-sintered material but also maintains good impact energy (Table XI). The ultimate tensile strengths decrease slightly at the highest compaction pressure. This suggests that the material may have been over-compacted with the drop-off in strength indicating the onset of lamination formation within the test specimen. The quenched and tempered microstructures can be seen in Figure 5. At both sintering temperatures the material is 100% tempered martensite with the saml31e sintered at 2300°F (1260°C) showing slightly more pore rounding and a coarser grain size.[v]

Material C - MPIF Standard FLN2-4405 4

Material C consists of the molybdenum prealloyed base iron utilized above in material B (Ancorsteel 85 HP), but, in this case the premix is a hybrid which contains 2w/o admixed nickel with a graphite addition of 0.4w/o. The density values and as-sintered tensile and impact properties are listed in Tables XII through XIV. The values in Table XII indicate that although the green density is still approximately 98% to 98.5% of pore free, the green density achievable increased by 0.04 g/cm^3. The alloying effects of the 2w/o nickel addition can be seen when viewing the tensile data. At a sintering temperature of 2050°F (1120°C), material C shows an approximate increase in yield strength of 11% and an increase in ultimate strength of 27% in the as-sintered state over that of material B, which does not contain nickel.

The as-sintered microstructures at 2050°F (1120°C) and 2300°F (1260°C) are shown in Figure 5. The microstructure consists of divorced pearlite, unresolved pearlite, Ni rich martensite and other Ni rich areas. The material that was high temperature sintered resulted in essentially the same microstructure but with fewer Ni rich areas and a coarser grain size.

As discussed with material B, this material combination will provide excellent heat treated properties in the quenched and tempered condition which is evident when viewing the data in Tables XV and XVI. The high apparent hardness and good heat treatment response provide good core properties for carburizing. Materials requiring high contact fatigue resistance are also good candidates for utilizing this material due to the inherent, hard nickel rich areas.

The heat-treated microstructures at 2050°F (1120°C) and 2300°F (1260°C) are shown in Figure 6. The microstructure at 2050°F (1120°C) consists of 100% martensite/bainite with nickel rich areas. Increasing the sintering temperature to 2300°F (1260°C) decreases the number of nickel rich areas significantly due to increased alloy diffusion at the higher temperature. The microstructures of this material exhibit slightly more pore rounding than those of material B due to the nickel content which would indicate that this material would be better for applications where more ductility and

strength are required. This can be seen when comparing the 2050°F (1120°C) heat treated tensile properties of this material with those of material B, which contains no nickel. Material C exhibits measurable yield strength and elongation in the heat treated state, whereas material B does not?

Material D - MPIF Standard FD-4805 4

Material D consists of an iron powder with the nickel, copper and molybdenum (Distaloy 4800A) diffusion alloyed to help maintain compressibility, even with 6% contained alloy content. The density values obtained by warm compaction and sintering at traditional and elevated temperatures are shown in Table XVII. As-sintered tensile and impact properties are presented in Tables XVIII and XIV. The balanced alloy content of material D contributes to an impact toughness of up to 30 ft-lbf (41J) at 2050°F (1120°C). However, is it also the main factor as to why no significant increase in impact toughness is realized as the sintering temperature is increased to 2300°F (1260°C). The microstructures in the as-sintered state can be seen in Figure 8. At 2050°F (1120°C), there is partial alloy diffusion with clearly defined high alloy areas. Increasing the sintering temperature to 2300°F (1260°C) results in a higher percentage of pearlite formation and a decrease in nickel rich areas?

Heat treated tensile and impact properties are presented in Tables XX and XXI, respectively. Heat treating the material results in an increase in the yield strength and more significantly, the ultimate tensile strength. Viewing the microstructure in the heat treated state explains the increase in strength. The microstructures (Figure 9) appear similar to that of material C, which is martensitc with nickel rich areas. However, the variation of alloy distribution is different than for material C.

Because of the uniformity of alloy distribution throughout the material, it is used in applications, such as geroters, requiring precise dimensional control within lot and from lot to lot. Additional applications range from induction hardened gears, to applications requiring high wear resistance in the as-sintered state

SUMMARY

Figure 10 details the as-sintered yield strength and ultimate tensile strength of materials A through D compacted at 40 tsi (550 MPa) and sintered at 2050°F (1120°C).

The plot demonstrates that while materials B, C and D all show comparable yield strengths, the ultimate tensile strength of Material D is far superior. This is an indication that while the alloying method has a minimal effect on yield properties for the premixes that were examined, it has a substantial effect upon the ultimate tensile properties.

The ultimate tensile strengths of Materials C and D in the as sintered and heat treated states are plotted in Figure 11. In the as-sintered condition, material D provides the highest ultimate tensile strength at a given density level. However, upon heat treatment the ultimate strengths of both materials become comparable. This response of material C is due to the pre-alloyed nature of Ancorstee185 HP base powder. This demonstrates why material C, is an excellent candidate for heat-treating applications.

The ultimate tensile strengths and impact energies of Materials B, C and D in the as-sintered state are compared in Figure 12. The plot indicates that nickel content is a factor for both properties. As the nickel content, which is zero for mix A, 2w/o for mix C, and 4w/o for mix D increases, the ultimate tensile strength increases proportionally. This trend is also present for impact energy to some degree. However this property appears also to be affected by the method of alloying. Mix D has the alloying agent diffusion alloyed to the base iron powder, while for mixes C and D the 2w/o nickel content is admixed. The data would suggest that the diffusion alloyed powder is more efficient at hampering crack propagation.

CONCLUSIONS

1) For optimization of powder properties and mechanical properties of ANCORDENSE processed material, compaction should be conducted in the temperature range of 265°F (127°C) to 300°F (150°C).

2) ANCORDENSE premixes can be compacted to 98% to 98.5% of their pore free density. The pore free density depends upon the premix composition. Increasing the compaction pressure to achieve a density above 98 to 98.5% of pore free may result in over-compaction and the formation of laminations.

3) ANCORDENSE processed iron-0.45w/o phosphorus material can reach a density of 7.5 g/cm^3 when compacted at 50 tsi (690 MPa) and sintered at 2300°F (1260°C). This results in a powder metallurgy material with exceptional ductility and impact resistance.

4) Nickel additions to ANCORDENSE processed Ancorstee185 HP plus graphite material enhance the toughness and ductility and make the material a prime candidate for heat treatment. Yield strengths in excess of 160,000 psi (1100 MPa) and ultimate tensile strengths in excess of 190,000 psi (1300 MPa) can be achieved when the material is heat treated following sintering at 2050°F (1120°C).

5) ANCORDENSE processed Distaloy 4800A, 0.5% graphite has excellent ultimate tensile strength and impact properties in the as-sintered and heat treated conditions. The diffusion alloyed base powder appears to be more efficient at blunting crack propagation.

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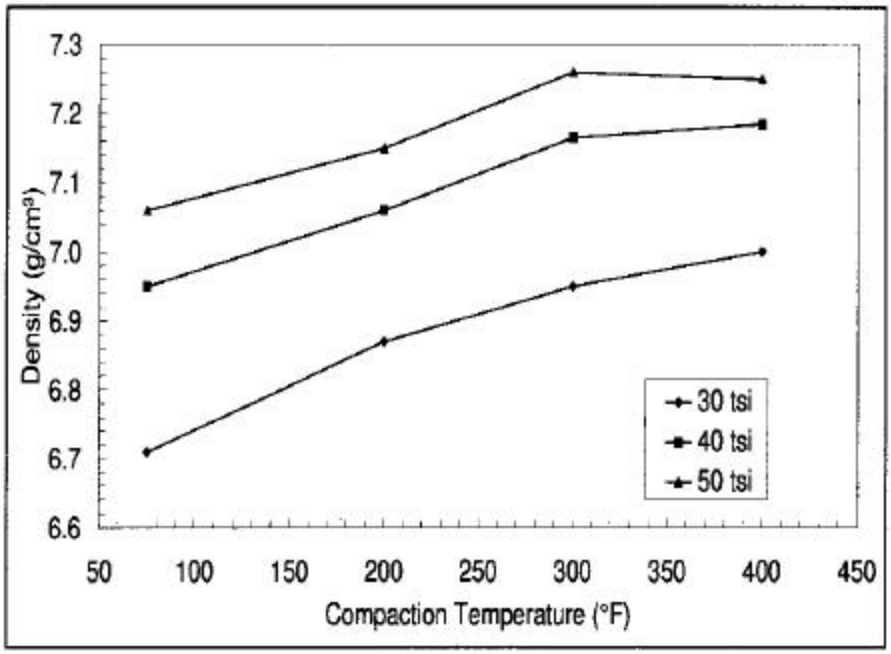


Figure 1: Effect of Compaction Temperature on Green Density

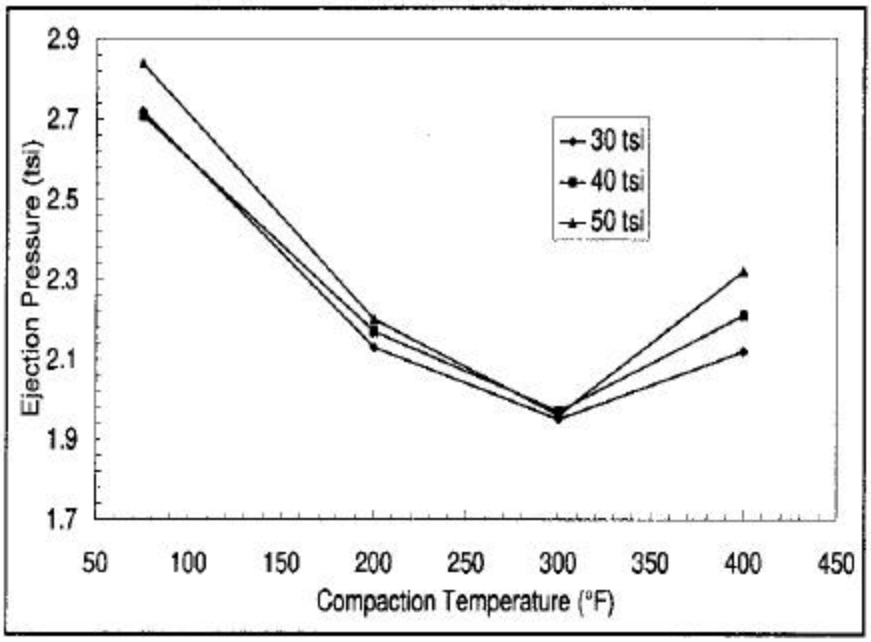
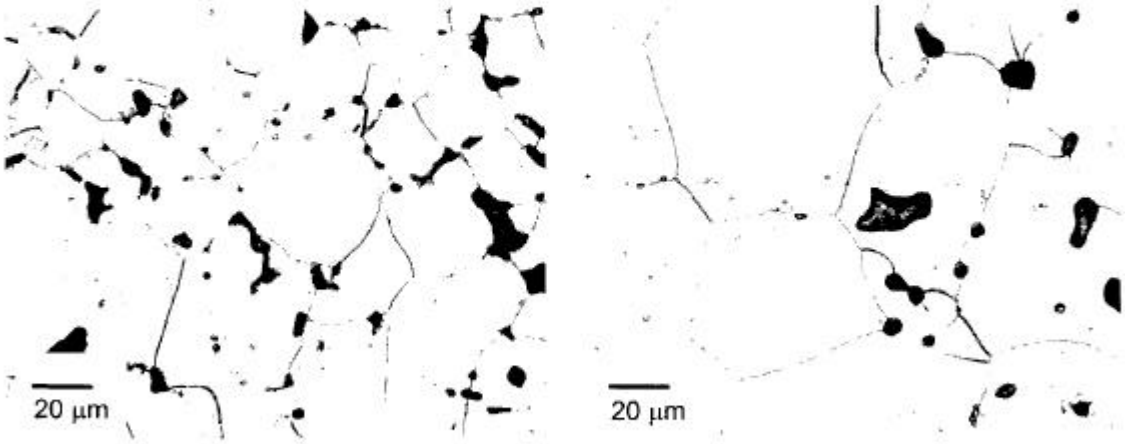


Figure 2: Effect of Compaction Temperature on Ejection Pressure

Table VI: As-Sintered Un-notched Charpy Impact Properties for Material A

2050°F/1120°C Sinter			2300°F/1260°C Sinter		
Sintered Density (g/cm^3)	Impact Energy (ft-lbf/J)	HRB	Sintered Density (g/cm^3)	Impact Energy (ft-lbf/J)	HRB
7.08	23 / 31	54	7.18	52 / 71	58
7.29	40 / 54	64	7.39	90 / 122	69
7.41	50 / 68	70	7.49	118 / 160	75



2050°F/1120°C Sinter 2300°F/1260°C Sinter

Figure 3: Microstructure of Material A, As-Sintered (Original Photographs at 500X, 2% Nital Etch)

Table VII: Density Results for Material B

Compaction Pressure (tsi/MPa)	Green Density (g/cm^3)	Green Density– % of Pore Free	Sintered Density 2050°F/1120°C (g/cm^3)	Sintered Density 2300°F/1260°F (g/cm^3)
30 / 415	7.11	95.4	7.03	7.08
40 / 550	7.30	97.9	7.24	7.28
50 / 690	7.34	98.5	7.32	7.37

Table VIII: As-Sintered Tensile Properties for Material B

2050°F/1120°C Sinter				2300°F/1260°C Sinter			
Sintered Density (g/cm^3)	0.2% Offset Yield Strength (10^3psi/MPa)	Ultimate Tensile Strength (10^3psi/MPa)	Elg. (%)	Sintered Density (g/cm^3)	0.2% Offset Yield Strength (10^3psi/MPa)	Ultimate Tensile Strength (10^3psi/MPa)	Elg. (%)
7.08	52 / 360	62 / 425	1.1	7.12	52 / 356	75 / 516	2.2
7.28	57 / 395	69 / 476	1.3	7.30	60 / 411	78 / 535	2.6
7.35	60 / 416	70 / 480	1.2	7.38	61 / 423	81 / 561	3.1

Table IX: As-Sintered Un-notched Charpy Impact Properties for Material B

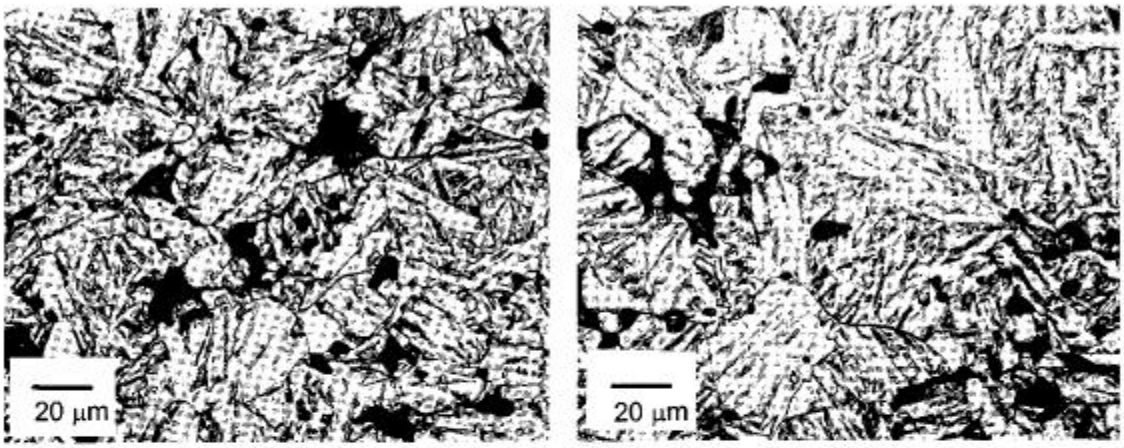
2050°F/1120°C Sinter			2300°F/1260°C Sinter		
Sintered Density (g/cm^3)	Impact Energy (ft-lbf/J)	HRB	Sintered Density (g/cm^3)	Impact Energy (ft-lbf/J)	HRB
7.06	9 / 12	73	7.07	12 / 16	76
7.25	11 / 15	80	7.27	21 / 28	84
7.30	12 / 16	82	7.35	25 / 34	84

Table X: Heat Treated Tensile Properties for Material B

2050°F/1120°C Sinter				2300°F/1260°C Sinter			
Sintered Density (g/cm^3)	0.2% Offset Yield Strength (10^3psi/MPa)	Ultimate Tensile Strength (10^3psi/MPa)	Elg. (%)	Sintered Density (g/cm^3)	0.2% Offset Yield Strength (10^3psi/MPa)	Ultimate Tensile Strength (10^3psi/MPa)	Elg. (%)
7.03	N/A	163 / 1122	<1	7.10	158 / 1088	180 / 1241	1.3
7.22	N/A	167 / 1154	<1	7.29	178 / 1226	207 / 1428	1.4
7.30	N/A	164 / 1129	<1	7.36	180 / 1240	202 / 1396	1.3

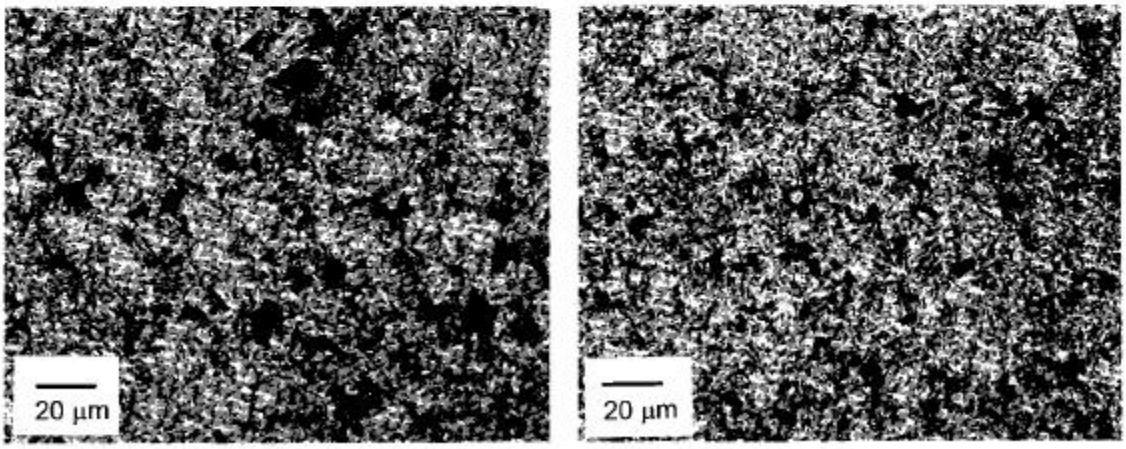
Table XI: Heat Treated Un-notched Charpy Impact Properties for Material B

2050°F/1120°C Sinter			2300°F/1260°C Sinter		
Sintered Density (g/cm^3)	Impact Energy (ft-lbf)	HRC	Sintered Density (g/cm^3)	Impact Energy (ft-lbf)	HRC
7.06	8 / 11	33	7.07	11 / 15	36
7.24	10 / 14	40	7.27	16 / 22	41
7.29	11 / 15	41	7.33	20 / 28	41



2050°F/1120°C Sinter 2300°F/1260°C Sinter

Figure 4: Microstructure of Material B As-Sintered (Original Photographs at 500X, 2% Nital Etch)



2050°F/1120°C Sinter 2300°F/1260°C Sinter

Figure 5: Microstructure of Material B Heat Treated (Original Photographs at 500X, 2% Nital Etch)

Table XII: Density Results for Material C

Compaction Pressure (tsi/MPa)	Green Density (g/cm^3)	Green Density-- % of Pore Free	Sintered Density 2050°F/1120°C (g/cm^3)	Sintered Density 2300°F/1260°C (g/cm^3)
30 / 415	7.12	95.5	7.10	7.14
40 / 550	7.31	98.1	7.30	7.34
50 / 690	7.37	98.9	7.42	7.45

Table XIII: As-Sintered Tensile Properties for Material C

2050°F/1120°C Sinter				2300°F/1260°C Sinter			
Sintered Density (g/cm^3)	0.2% Offset Yield Strength (10^3psi/MPa)	Ultimate Tensile Strength (10^3psi/MPa)	Elg. (%)	Sintered Density (g/cm^3)	0.2% Offset Yield Strength (10^3psi/MPa)	Ultimate Tensile Strength (10^3psi/MPa)	Elg. (%)
7.17	60 / 414	76 / 527	1.4	7.22	60 / 413	82 / 560	2.4
7.35	63 / 436	85 / 589	2.1	7.41	67 / 461	90 / 619	2.9
7.44	65 / 450	92 / 636	2.8	7.48	69 / 473	96 / 664	3.9

Table XIV: As-Sintered Un-notched Charpy Impact Properties for Material C

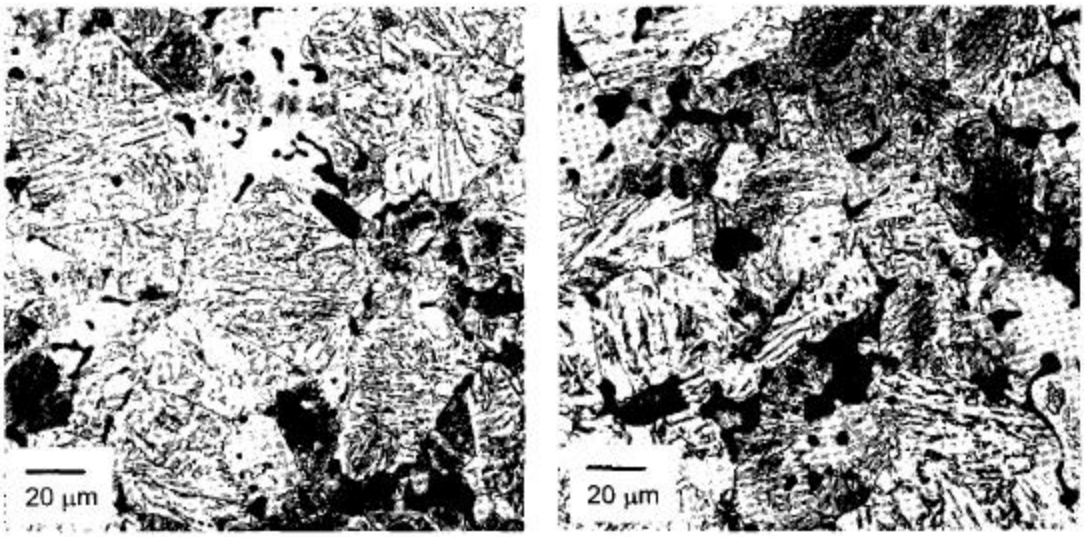
2050°F/1120°C Sinter			2300°F/1260°C Sinter		
Sintered Density (g/cm^3)	Impact Energy (ft-lbf/J)	HRB	Sintered Density (g/cm^3)	Impact Energy (ft-lbf/J)	HRB
7.10	12 / 16	80	7.12	15 / 20	81
7.30	14 / 19	85	7.34	27 / 37	88
7.40	21 / 28	89	7.43	29 / 39	89

Table XV: Heat Treated Tensile Properties for Material C

2050°F/1120°C Sinter				2300°F/1260°C Sinter			
Sintered Density (g/cm^3)	0.2% Offset Yield Strength (10^3psi/MPa)	Ultimate Tensile Strength (10^3psi/MPa)	Elg. (%)	Sintered Density (g/cm^3)	0.2% Offset Yield Strength (10^3psi/MPa)	Ultimate Tensile Strength (10^3psi/MPa)	Elg. (%)
7.12	141 / 972	166 / 1145	1.4	7.16	148 / 1023	178 / 1229	1.6
7.31	159 / 1098	182 / 1253	1.3	7.34	167 / 1153	200 / 1376	1.6
7.40	164 / 1129	192 / 1326	1.3	7.45	180 / 1241	213 / 1469	1.7

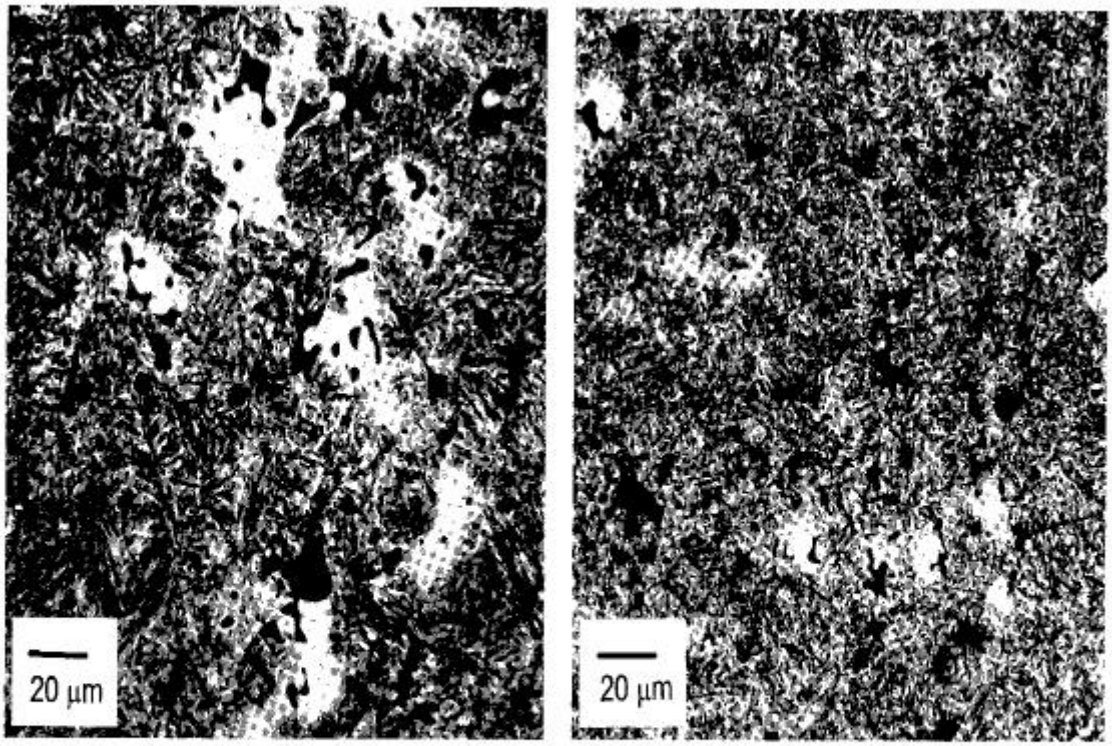
Table XVI: Heat Treated Un-notched Charpy Impact Properties for Material C

2050°F/1120°C Sinter			2300°F/1260°C Sinter		
Sintered Density (g/cm^3)	Impact Energy (ft-lbf/J)	HRC	Sintered Density (g/cm^3)	Impact Energy (ft-lbf/J)	HRC
7.09	8 / 11	33	7.16	15 / 20	36
7.29	10 / 14	39	7.34	22 / 30	41
7.39	14 / 19	40	7.42	24 / 33	44



2050°F/1120°C Sinter 2300°F/1260°C Sinter

Figure 6: **Microstructure of Material C As-Sintered (Original Photographs at 500X, 2% Nital Etch)**



2050°F/1120°C Sinter 2300°F/1260°C Sinter

Figure 7: **Microstructure of Material C Heat Treated (Original Photographs at 500X, 2% Nital Etch)**

Table XVII: Density Results for Material D

Compaction Pressure (tsi)	Green Density (g/cm^3)	Green Density--% of Pore Free	Sintered Density--2050°F (g/cm^3)	Sintered Density--2300°F (g/cm^3)
30	7.14	95.1	7.08	7.16
40	7.31	97.4	7.24	7.32
50	7.36	98.0	7.32	7.39

Table XVIII: As-Sintered Tensile Properties for Material D

2050°F/1120°C Sinter				2300°F/1260°C Sinter			
Sintered Density (g/cm^3)	0.2% Offset Yield Strength (10^3psi/MPa)	Ultimate Tensile Strength (10^3psi/MPa)	Elg. (%)	Sintered Density (g/cm^3)	0.2% Offset Yield Strength (10^3psi/MPa)	Ultimate Tensile Strength (10^3psi/MPa)	Elg. (%)
7.06	56 / 384	93 / 639	2.1	7.14	68 / 467	107 / 738	2.0
7.25	59 / 407	108 / 745	2.5	7.33	76 / 522	125 / 861	2.8
7.32	65 / 451	114 / 785	2.4	7.37	76 / 526	134 / 825	3.0

Table XIX: As-Sintered Un-notched Charpy Impact Properties for Material D

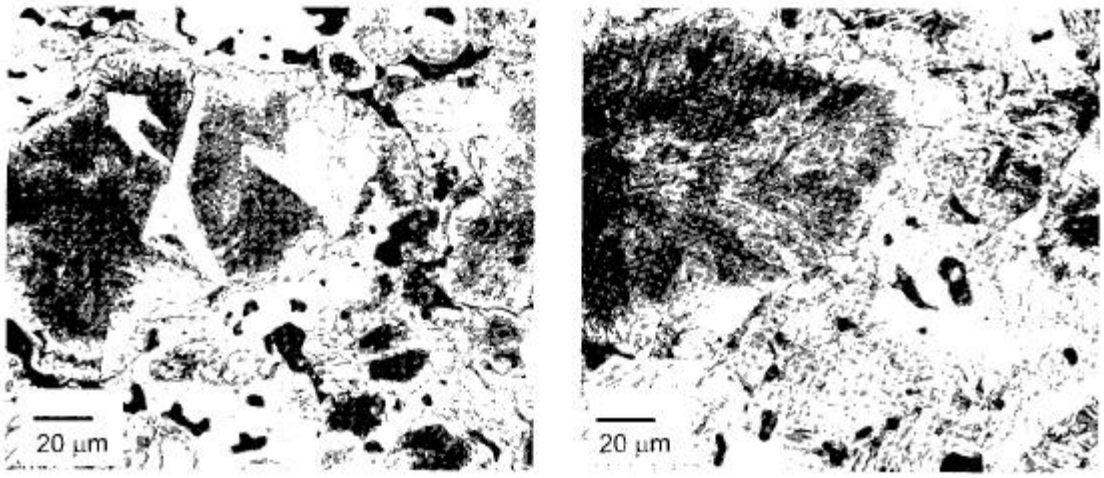
2050°F/1120°C Sinter			2300°F/1260°C Sinter		
Sintered Density (g/cm^3)	Impact Energy (ft-lbf/J)	HRB	Sintered Density (g/cm^3)	Impact Energy (ft-lbf/J)	HRB
7.13	19 / 26	88	7.15	17 / 23	91
7.23	25 / 34	90	7.31	28 / 38	94
7.30	31 / 42	94	7.35	31 / 42	95

Table XX: Heat Treated Tensile Properties for Material D

2050°F/1120°C Sinter				2300°F/1260°C Sinter			
Sintered Density (g/cm^3)	0.2% Offset Yield Strength (10^3psi/MPa)	Ultimate Tensile Strength (10^3psi/MPa)	Elg. (%)	Sintered Density (g/cm^3)	0.2% Offset Yield Strength (10^3psi/MPa)	Ultimate Tensile Strength (10^3psi/MPa)	Elg. (%)
7.10	137 / 947	166 / 1147	1.5	7.15	152 / 1047	192 / 1321	1.8
7.27	149 / 1029	188 / 1293	1.6	7.33	168 / 1158	217 / 1494	2.2
7.35	157 / 1080	196 / 1348	1.6	7.40	177 / 1217	226 / 1559	2.0

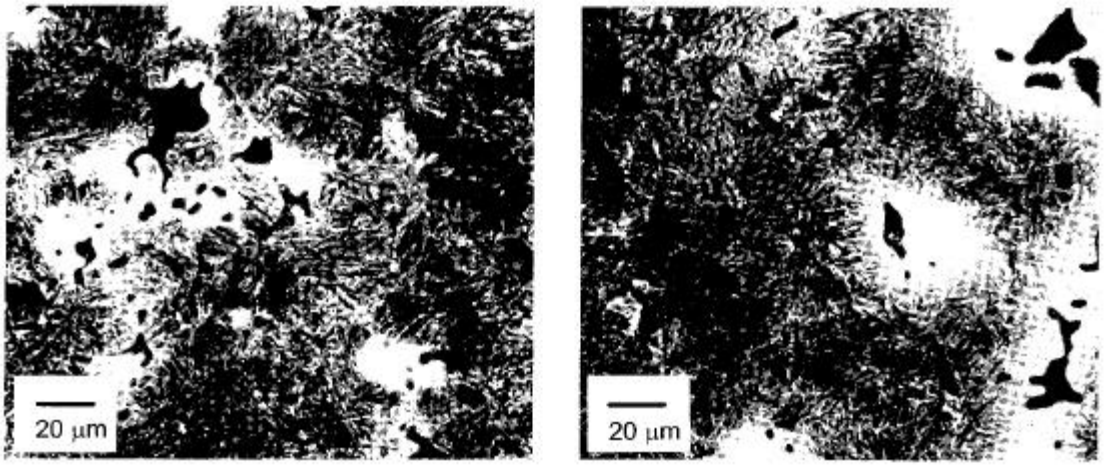
Table XXI: Heat Treated Un-notched Charpy Impact Properties for Material D

2050°F/1120°C Sinter			2300°F/1260°C Sinter		
Sintered Density (g/cm^3)	Impact Energy (ft-lbf)	HRC	Sintered Density (g/cm^3)	Impact Energy (ft-lbf)	HRC
7.11	12 / 16	31	7.15	15 / 20	33
7.28	15 / 20	37	7.32	19 / 26	39
7.34	16 / 22	39	7.38	22 / 30	41



2050°F/1120°C Sinter 2300°F/1260°C Sinter

Figure 8: Microstructure of Material D As-Sintered (Original Photographs at 500X, 2% Nital Etch)



2050°F/1120°C Sinter 2300°F/1260°C Sinter

Figure 9: Microstructure of Material D Heat Treated (Original Photographs at 500X, 2% Nital Etch)

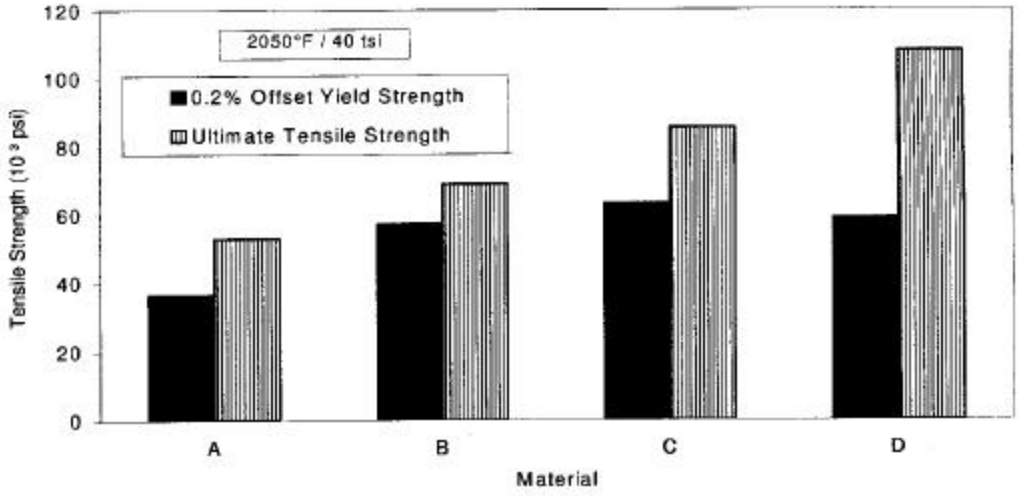


Figure 10: Tensile Properties of Materials A through D

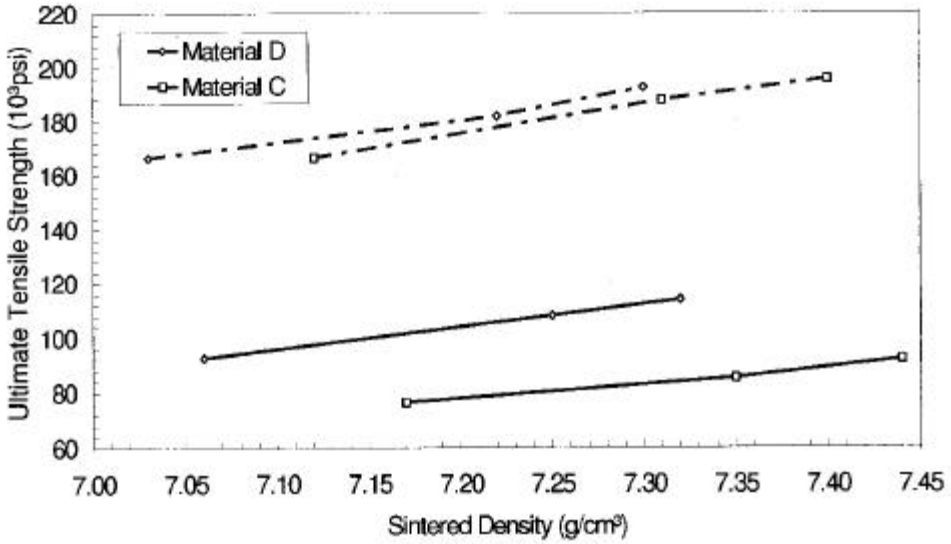


Figure 11: Tensile Properties / Heat Treated And As-Sintered Condition

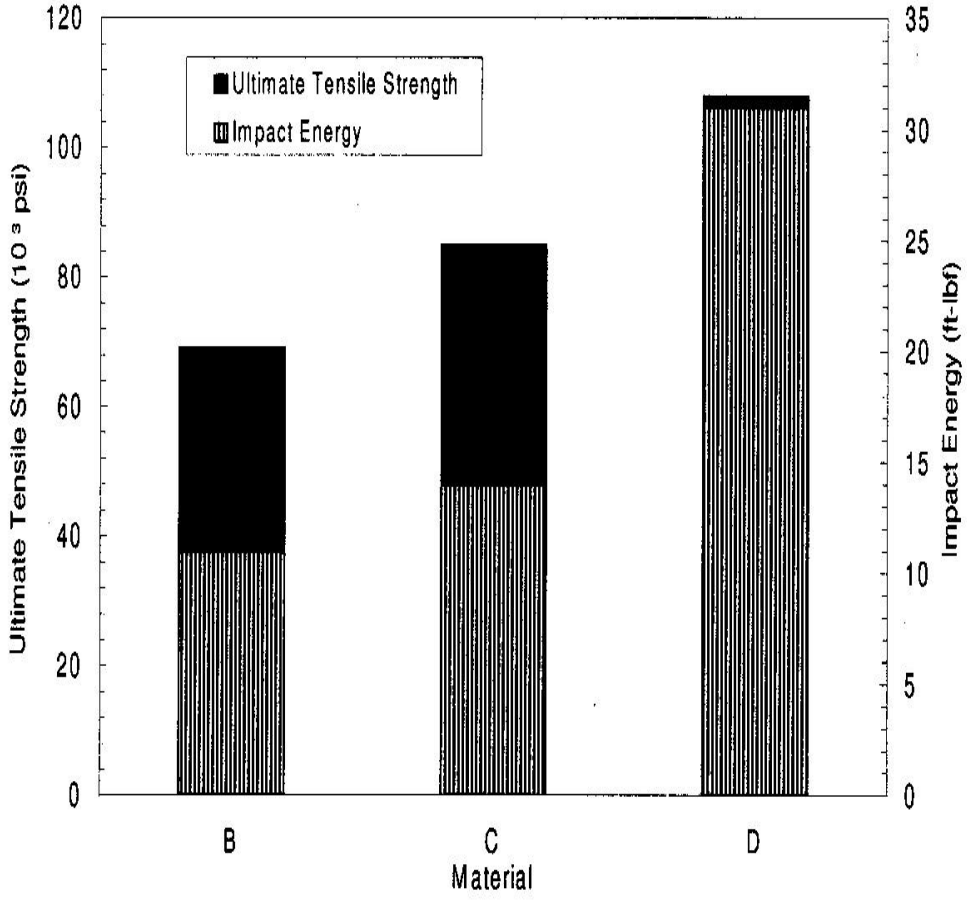


Figure 12: Ultimate Tensile Strength and Impact Energy - As-Sintered 2050°F/1120°C, 40 tsi/550 MPa