Mechanical Properties of MP35N as a Reinforcement Material for Pulsed Magnets

Ke Han, A. Ishmaku, Yan Xin, Hamid Garmestani, Vince J. Toplosky, Robert Walsh, Chuck Swenson, Benny Lesch, Hassel Ledbetter, Sudook Kim, Michael Hundley, and James R. Sims, Jr.

***Abstract*—A cobalt multiphase alloy, MP35N, is studied as one of the reinforcement materials for pulsed magnets. The mechanical properties of this alloy at room temperature and 77 K are examined. The cold-rolled and aged MP35N produces a hardness of 5650 MPa and yield strength of 2125 MPa at room temperature. At 77 K, the yield strength reached 2500 MPa and the work hardening rate was higher than that at room temperature. The Young's modulus increases about 6% upon cooling from 300 to 5 K. Therefore, the increase of the strength at low temperatures is attributed mainly to the increase of the work hardening rate rather than modulus. The potential for further increasing of the strength of this alloy is discussed.**

***Index Terms*—Defects, dislocations, elastic constant, high strength materials, mechanical properties, reinforcement materials.**

I. INTRODUCTION

THE CONSTRUCTION of various high field pulsed magnets needs to consider the properties of the reinforcement materials. The availability of the reinforcement materials in addition to the conductors determines the final construction of the magnet. The properties of various conductors have been addressed in various papers (e.g., [1]). The reinforcement materials require an optimum combination of mechanical strength, Young's modulus, fracture toughness, ductility, and fatigue resistance.

The pulsed magnets usually consist of separate coils that need different reinforcement materials. The requirements for the reinforcement materials of dissimilar coils are different because of their particular functions, sizes, mechanical forces applied on them, and the cost. In addition, the strength and the modulus of the conductors may have impact on the required properties of the reinforcement. For instance, the conductors with high Young's modulus should be reinforced by the reinforcement materials that have high Young's modulus so that load will be transferred to the reinforcement without significant plastic deformation strain.

TABLE I
ELASTIC PROPERTIES OF VARIOUS ELEMENTS IN MP35N (TEXTURE FREE VALUES)

Elastic Properties	Elements			
	Co	Ni	Cr	Mo
Young's modulus [GPa]	215.7	220.6	279.5	323.2
Shear modulus [GPa]	82.36	84.71	115.3	125
Bulk modulus [GPa]	188.9	186	161.9	259.5
Poisson's ratio	0.3096	0.3023	0.2122	0.2926

MP35N (35 wt%Co-35 wt%Ni-20 wt%Cr-10 wt%Mo) is one of the reinforcement materials with high Young's modulus. All the elements in MP35N have relatively high modulus, as shown in Table I. MP35N is a solid solution with a face-centered-cubic (fcc) structure in annealed condition. Therefore, the modulus can be estimated by a rule of mixture and it should be relatively high if it is compared with other fcc matrix materials, such as stainless steels.

Traditionally, MP35N (containing both cobalt and nickel) is described as a multiphase cobalt nickel alloy because some cobalt–nickel alloys are work-hardened by formation of the stress-induced hexagonal-close-packed (hcp) phase in platelet form within fcc matrix [2]–[4]. However, other studies on the role of fcc→hcp transformation suggest that work hardening of the MP35N alloys is not due to the formation of the hcp phase [5], and for the alloys with Co : Ni ratios (wt%) less than 45 : 25, it was not possible to detect the stress-induced hcp phase by X-ray diffraction techniques. Instead, the materials were considered to be strengthened by formation of deformation twins in the fcc matrix [6], [7]. Recently, it has been recognized that deformation introduces mainly the planar defects or stacking faults in the fcc matrix [8].

The cold deformed MP35N multiphase alloys can be further hardened by aging. After the materials reach the maximum strength at a defined temperature range, additional aging time contributed no further increase of the strength. Some work claimed that no over-aging was found. Most applications use the materials aged at between 813 to 873 K for 4 hours. However, earlier work reported that when swaged multiphase alloys were aged for more than 4 hours at 699 K, further increase of yield strength was able to be achieved. Therefore the optimum aging temperature and time remain to be confirmed.

Because of its fcc structure and good performance at low temperatures, MP35N finds applications in pulsed magnets which operate between 77 K and 300 K. The reinforcement materials in pulsed magnets operate between room temperature and 77 K.

Manuscript received September 25, 2001. This work was supported in part by the U.S. National Science Foundation through the National High Magnetic Field Laboratory.

K. Han, A. Ishmaku, Y. Xin, H. Garmestani, V. J. Toplosky, R. Walsh, C. Swenson, B. Lesch are with the National High Magnetic Field Laboratory, Tallahassee, FL 32306 USA (e-mail: han@magnet.fsu.edu).

H. Ledbetter and S. Kim are with the Materials Science and Engineering Laboratory, National Institute of Standards and Technology, Boulder, CO 80305 USA.

M. Hundley and J. R. Sims, Jr. are with the Los Alamos National Laboratory, Los Alamos, NM 87544 USA.

Publisher Item Identifier S 1051-8223(02)04170-2.

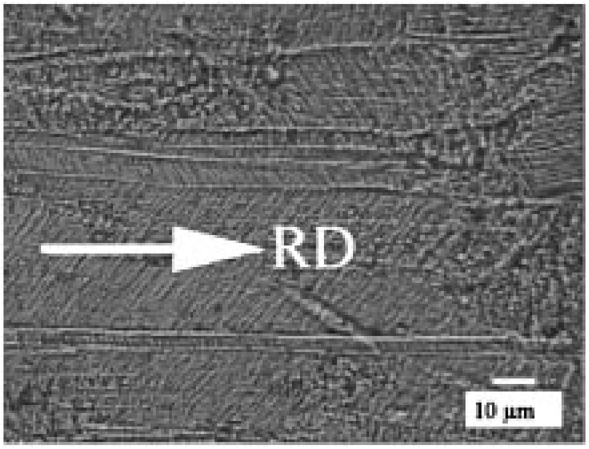
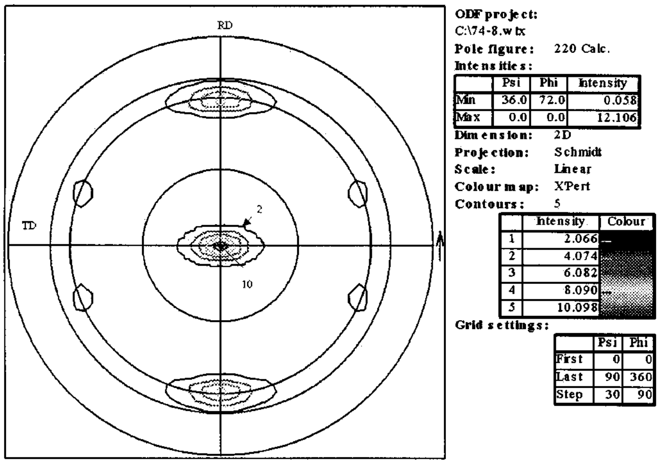


Fig. 1. Light optical microstructure image showing the structure of MP35N. RD = rolling direction. The microstructure consists of grain boundaries or twin boundaries more or less parallel to the RD and fine parallel striations on $\{111\}$ planes.



```
ODF project:
C:\74-8.wtx
Pole figure:      220 Calc.
Intensities:
      | Psi  | Phi  | Intensity
Min   | 36.0 | 72.0 |     0.058
Max   |  0.0 |  0.0 |    12.106
Dimension:        2D
Projection:       Schmidt
Scale:            Linear
Colour map:       XPert
Contours:         5
          | Intensity | Colour
        1 |     2.066 |
        2 |     4.074 |
        3 |     6.082 |
        4 |     8.090 |
        5 |    10.098 |
Grid settings:
                | Psi | Phi
          First |   0 |   0
          Last  |  90 | 360
          Step  |  30 |  90
```

Fig. 2. $\{110\}$ Pole figure of MP35N rolled to 74% showing maximum at $\{110\}$. The material have $\{110\}\ \langle\bar{1}11\rangle$ and $\{110\}\ \langle\bar{1}12\rangle$ textures.

Therefore, it is useful to know the properties at these temperatures. However, limited 77 K test data are available for deformed and aged materials, although research was undertaken on un-aged 45% cold worked samples. It is therefore useful to characterize the cryogenic properties of the aged MP35N alloys. The service of the materials at those temperatures in the magnet will be considered in this paper. All the tests of MP35N also have been done at both room temperatures and at 77 K. In addition, the microstructure of the materials is examined and related to the properties of the materials.

II. FABRICATION AND CHARACTERIZATION

The alloys were fabricated by annealing, cold rolling, and aging. The detailed fabrication procedures were reported before. The materials were received from Latrobe, U.S.A. and 3.0 mm × 5.8 mm and 4 mm × 6 mm ones were fabricated by SSC RF Bochvar All Russia Science Research Institute Inorganic Ma, Russia.

Fig. 3. Transmission electron microscopy image showing fine planar defects formed on $\{111\}$ habit planes in MP35N.

Tukon 200 micro-hardness tester was used to perform the hardness test. The hardness measurements were taken from surfaces polished for optical microscopy without being etched. The load was applied mainly in the transverse direction with respect to the rolling direction. Twenty indentations were obtained from each specimen using a load of 300 grams. The minimum impression spacing (center to edge of adjacent impression) was about 3 times of the diagonal of the impression and at least 0.02 mm from the edge of the specimen.

Tensile tests were performed on the 100 kN MTS machine in displacement control at a rate of 0.5 mm/min. Both tensile strength (TS) and yield strength (YS) were recorded. The elastic modulus for sheet was determined by the stress-strain curves in an unload/reload cycle after the onset of plastic deformation (at 0.01 strain).

The elastic constants were also measured on bulk samples between 300 and 5 K with a cylindrical specimen (0.954 cm diameter × 0.636 cm long) and two dynamic methods (pulse-echo [9] and acoustic-resonance spectroscopy [10]).

The linear thermal expansion was measured on a bulk sample (a 4 mm cube) from 4 to 325 K using a capacitive dilatometer cell.

III. RESULTS

A. Microstructure of Sheet MP35N

The microstructures of cold rolled and aged materials were examined by various microscopic techniques. Fig. 1 is a light micrograph typical of the microstructures of the cold rolled and aged sample. The aging didn't change the microstructure significantly. Both X-Ray diffraction and transmission electron microscopy were used to study the crystallographic structures of the MP35N in both rolled and aged conditions. In the majority of the areas, the textures are close to $\{110\}\ \langle\bar{1}12\rangle$ or $\{110\}\ \langle\bar{1}11\rangle$, where $\{110\}$ is roughly parallel to the sheet surface whereas $\langle\bar{1}12\rangle$ and $\langle\bar{1}11\rangle$ are approximately parallel to the RD, as shown in Fig. 2. Fig. 3 is a typical TEM image of MP35N rolled to 65% and aged. Fine parallel platelets, which imaged as very fine striations and had habit plane of $\{111\}$, were observed. Some of

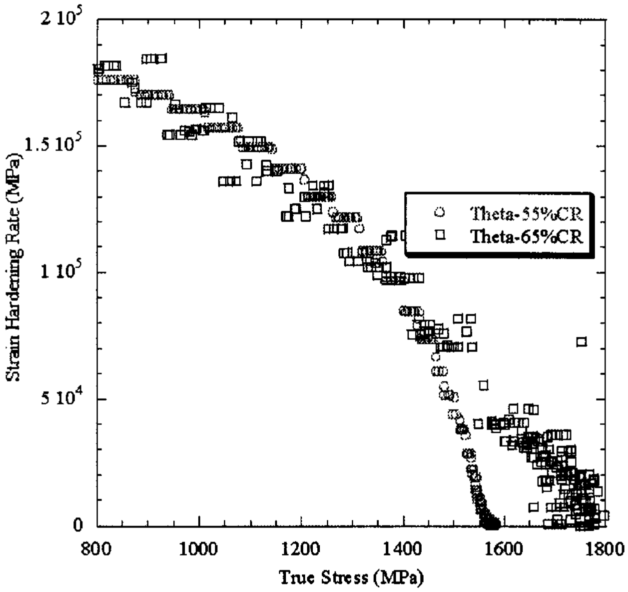


Fig. 4. Tensile test data showing the relationship between strain hardening rate and stress of cold rolled MP35N.

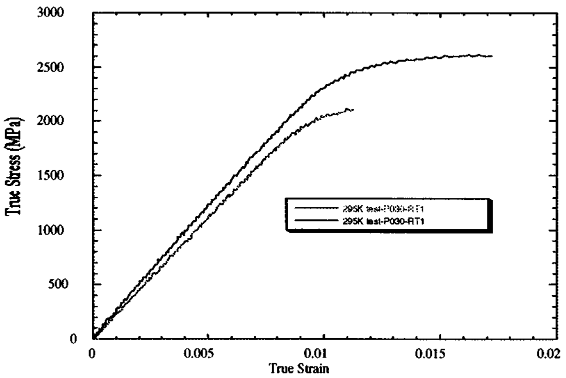


Fig. 5. Stress-strain curves of aged MP35N sheet. The apparent Young's modulus increases slightly upon decreasing test temperatures.

TABLE II
MECHANICAL TEST RESULTS OF MP35N SHEET*
*The materials were cold rolled to 65% and aged at 824 K for 8 hrs in argon atmosphere.

Test Temp. K	Microhardness MPa	Young's Modulus GPa	Yield Strength MPa	Tensile Strength MPa
295	5647±78	215±5	2024±108	2097±38
77	-	226±4	2510±26	2567±20

TABLE III
MECHANICAL TEST RESULTS OF MP35N ROD**

Specimen	Test Temp. (K)		Yield Strength (M Pa)	Tensile Strength (M Pa)	% Elong.
As Deformed	295	Average	1436	1707	12.8
		Stdev	91	8	0.1
	77	Average	1783	2161	12.7
		Stdev	22	6	0.1
Heat treated	295	Average	2023	2052	11.3
		Stdev	1	3	0.1
	77	Average	2387	2483	11.6
		Stdev	49	26	-

****Heat treated = Aged at 843 K for 4 hrs in argon atmosphere; elongation is from strain measurement over 12.7 mm gage length, stdev = standard deviation**

the striations are intercepted. The distance between the parallel platelets is from a few nanometers to 50 nanometers. The thickness of the platelets is below 1 nanometer. These fine platelets form after the deformation and aging, and strengthen the material by providing barriers for dislocation motion. Two types of {111} habit planes for platelets are observed and are perpendicular to the rolling planes. Because two types of {111} planes within one grain are visible under the imaging condition, the platelets are formed at least on both habit planes in a single grain. However, it appears the majority of the platelets within one grain are formed on one set of {111}.

B. Mechanical Properties of Sheets

Typical room temperature strain-hardening curves of MP35N deformed to 55% and 65% reduction-in-area are shown in Fig. 4. The increase of the deformation strain increases the strength of the materials by formation of various defects as shown in Section A. During plastic deformation, one kind of defect stored is dislocations [8]. In MP35N, additional obstacles to dislocation motion are produced as a consequence of plastic flow. These can be twins, stacking faults or hcp second phases produced as a consequence of flow in supersaturated solid solutions where dynamic phase transformation can occur during plastic flow. These cases are more complex than the case when an additional set of obstacles are present at the onset of plasticity because in MP35N the density of the additional obstacles increases during the flow process itself. Therefore, it is interesting to note that at high stress levels, the strain-hardening rate of the materials with a greater percentage of cold work has greater strain hardening rate than the other one, as shown in Fig. 4. In addition to the strain hardening rate, the large strain deformation introduces the internal stresses and influences elastic-plastic transition behavior of the materials. Because the onset of the plastic flow of the materials is dependent on the crystallographic orientations of the materials, the property changes must also be related to the texture evolutions shown in Section A. Hence, by modification of the textures, one can improve the mechanical properties of the MP35N according to the requirement of the design.

Aging improves the mechanical strength of the MP35N, as shown in Fig. 5. The cold-rolled and aged MP35N produced hardness more than 5600 MPa and yield strength of more than 2000 MPa at room temperature. At 77 K, the yield strength increases about 24% (Table II) and the strain-hardening rate was higher than that at room temperature. The higher strain-hardening rate at 77 K may be related to the formation of more planar defects and dislocations which act as obstacles for the dislocation motions. The Young's modulus increases about 5% upon cooling from 295 to 77 K.

C. Properties of Rods

The tensile tests were conducted on both as-deformed and aged samples at 295 K and 77 K. The results are shown in Table III. The data show that aging increases the room temperature tensile strength by about 20%.

TABLE IV
DYNAMIC ELASTIC PROPERTIES OF MP35N ROD
ρ (g/cm^3)=mass density=8.5772; C_l ==longitudinal modulus; G=shear modulus; B=bulk modulus; E=Young modulus; *v*=Posson ration.

T (K)	C_l(GPa)	G(GPa)	B(GPa)	E (GPa)	ν
298.4	304.93	86.953	188.99	226.17	0.30054
295	305.11	87.04	189.05	226.38	0.30043
290	305.36	87.162	189.15	226.67	0.30027
270	306.37	87.65	189.5	227.82	0.29963
250	307.42	88.195	189.83	229.1	0.29885
230	308.29	88.661	190.08	230.19	0.29816
210	309.27	89.15	190.4	231.34	0.29749
190	310.09	89.663	190.54	232.52	0.29662
170	311.01	90.138	190.82	233.63	0.29595
150	311.89	90.622	191.06	234.75	0.29522
130	312.66	91.074	191.22	235.79	0.29449
110	313.44	91.479	191.47	236.74	0.29393
90	314.22	91.855	191.75	237.62	0.29346
76	314.78	92.085	192	238.18	0.29325
5	315.58	92.463	192.4	239.06	0.29277

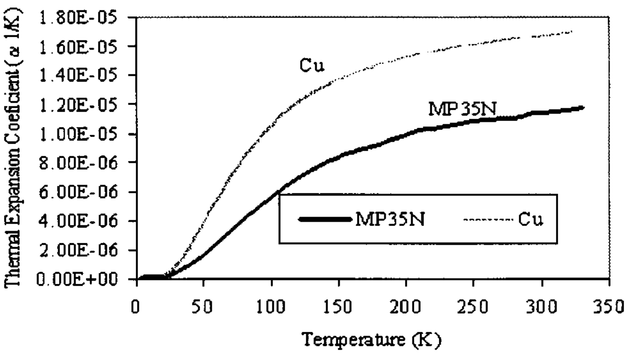


Fig. 6. Comparison of thermal expansion of MP35N and pure Cu [12] at various temperatures.

The material elastic properties are isotropic within 3%. All the elastic constants (G = shear modulus, E = Young's modulus, C_l = longitudinal modulus, ν = Poisson ratio) show regular temperature behavior, as indicated in Table IV. This presents a surprise because alloys containing magnetic atoms such as chromium, cobalt, and nickel usually show irregular temperature behavior.

An improved Einstein-oscillator-based Varshni function [11]: $C(T) = C(OK) - s/[e^{(\theta/T)} - 1]$ was fit to the measurements. Here, C denotes elastic constant, T temperature, θ an approximate Einstein temperature, and s a parameter that depends on the atomic volume V_a, Einstein temperature θ, and Grüneisen parameter γ: $s = 3\kappa\theta\gamma(\gamma + 1)/V_a$. Parameter s arises from quantum-mechanical zero point vibrations. In the high-temperature (linear) limit, $dC/dT = -s/\theta$.

The alloy's Young's modulus increases about 6% upon cooling from 300 to 5 K or 5% from 295 to 76 K, respectively. This compares with 7.5% for cobalt, 7% for nickel, 6.5% for chromium, and 3.0% for molybdenum.

At 77 K, the materials show 27% and 20% increase of strength for as-deformed and aged samples, respectively, if one compares to the 295 K test data. The alloy's Young's modulus increases about 5%. These changes are similar to those of MP35N in sheet form. Therefore, the increase of the strength at the low temperatures is mainly due to the increase of the strain-hardening rate. The higher strain-hardening rate also increases the elongation at failure.

The thermal expansion data of MP35N are shown in Fig. 6. The data from 4 K to 325 K show the temperature behavior of a single phase material. No sign of a phase transition can be detected when MP35N was heated from 4 K to 325 K.

IV. CONCLUSION

Because of its high modulus and strength, MP35N becomes an excellent candidate as a reinforcement material in pulsed magnets. Increasing the percentage of cold work improves the strength of the materials but reduces the ductility slightly. Upon cooling to 77 K from 295 K, the defect accumulation rate and strain hardening rate increase. Consequently, the strength increases by more than 20% accompanied by an increase of the elongation. Thus, the strengthening of the materials can be related to the crystallographic orientation and the nano-size defects formed in the materials. Decreasing testing temperature from 295 K to 77 K increases Young's modulus by 5%. All the elastic constants show regular temperature behavior within the temperature range measured.

REFERENCES

[1] J. D. Embury and K. Han, "Conductor materials for high field magnets," *Current Opinions in Solid State and Materials Science (1998)*, vol. 3, no. 3, pp. 304–308, 1998.
[2] J. M. Drapier, P. Viatour, D. Coutsouradis, and L. Habraken, "Hardening mechanisms in multiphase alloy MP35N," *Cobalt*, no. 49, pp. 171–186, 1970.
[3] A. H. Graham and J. L. Youngblood, "Work strengthening by a deformation-induced phase transformation in MP alloys," *Metall. Trans.*, vol. 1, pp. 423–430, 1970.
[4] R. P. Singh and R. D. Doherty, "Strengthening in multiphase (MP35N) alloy: Part I.I Ambient temperature deformation and recrystallization," *Metall. Trans.*, vol. 23A, pp. 321–334, 1992.
[5] M. Raghavan, B. J. Berkovitz, and R. D. Kane, "A transmission electron microscope investigation of phase transformation in MP35N," *Metall. Trans.*, vol. 11A, pp. 203–207, 1980.
[6] S. Asgari, E. El-Danaf, S. R. Kalidindi, and R. D. Doherty, "Strain hardening regimes and microstructural evolution during large strain compression of low stacking fault energy fcc alloys that forms deformation twins," *Metall. Mater. Trans.*, vol. 28A, pp. 781–1795, 1997.
[7] E. El-Danaf, S. R. Kalidini, and R. D. Doherty, "Influence of grain size and stacking-fault energy on deformation twinning in fcc metals," *Metal Mater. Trans.*, vol. 30A, pp. 1223–1233, 1999.
[8] A. Ishmaku and K. Han, "Characterization of cold-rolled and aged MP35N alloys," Materials Characterization, 2001, to be published.
[9] H. Ledbetter, N. Frederick, and M. Austin, "Elastic-constant variability in stainless-steel 304," *J. Appl. Phys.*, vol. 51, pp. 305–309, 1980.
[10] H. Ledbetter, C. Fortunko, and P. Heyliger, "Orthotropic elastic constants of a boron–aluminum fiber-reinforced composite: An acoustic-resonance-spectroscopy study," *J. Appl. Phys.*, vol. 78, pp. 1542–1546, 1995.
[11] Y. Varshni, "Temperature dependence of the elastic constants," *Phys. Rev. B2*, pp. 3952–3958, 1970.
[12] F. R. Kroeger and C. A. Swenson, *J. Appl. Phys.*, vol. 48, p. 853, 1977.