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MECHANICAL PROPERTIES DATA OF CANDIDATE ALLOYS FOR EARTH PENETRATOR STRUCTURAL COMPONENTS

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MASTER

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ABSTRACT

Loading modes imposed on earth penetrators during impact and sub-surface travel include high rate axial compressive stresses and possibly large tensile bending stresses caused by off-axis impacts or collisions with hard sub-surface objects. These modes require that case structural alloys possess a high yield strength to prevent yielding under compressive loads and also possess high fracture toughness to resist fracture under tensile loading at stress concentrations. Tensile data were generated at intermediate strain rates ($\dot{\epsilon} < 300 \text{ sec}^{-1}$) between 219 K and 344 K for four candidate steels (9-4-20, maraging 250, HY-180, and D6AC). In general, yield strengths varied less than 10% over the ranges of strain rate and temperature tested. Charpy impact energy measurements on 9-4-20 showed a 10% decrease in toughness at low temperatures for samples subjected to a simulated heat-shrink fitting procedure. Additional fracture toughness tests (K_{IC}) were conducted on 9-4-20 with varied tempering treatments and on two forged billets of HY-180. Strength and toughness data for several candidate alloys gathered from the literature are presented, and recommendations are made for trade-offs in strength versus toughness.

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1. Introduction

Alloys used to fabricate earth penetrator cases and internal support structures must possess a good combination of strength and fracture toughness. Loadings imposed on these members during impact and sub-surface travel include a mean compressive stress superimposed with bending stresses. Compressive stresses result from the normal component of impact loading against a target, while bending stresses are caused by off-axis impacts or collisions with hard sub-surface objects. With high enough bending stress, the combination gives a net tensile stress along the outer surface on one side and a larger compressive stress on the opposite side; these maximum stresses are located approximately one-third to one-half the length of the penetrator up from the nose.⁽¹⁾ Stress magnitudes depend on velocity of impact, competency of the target, and size of the angle between the penetrator axis and the velocity vector. The high compressive stresses necessitate an alloy with high yield strength, but the presence of tensile stresses also requires an alloy with high toughness to resist cracking at stress concentrations or flaws.

Original materials selections for the Pershing II Earth Penetrator case and internal support structure were based on good engineering judgment without a detailed knowledge of expected stress environments or all the necessary mechanical property data. HP-9-4-20 steel was chosen as the case for its combination of moderate tensile strength (1.24 GPa), high fracture toughness ($142 \text{ MN-m}^{-3/2}$) and commercial availability. Maraging 250 steel was selected as the component support can because of its higher strength (1.72 GPa), good fracture toughness, and availability. In retrospect, these choices were good ones, as the penetrator cases have survived

required conditions, and the few failures which have occurred in the support structure have been local overload failures correctable by design modifications.

Structural response during impact has been measured in the Pershing II program by using strain gauge instrumented penetrators impacted in reverse ballistics tests and in Davis gun tests. These data have quantified stress distributions and strain rates as a function of target, velocity, and impact angle and have allowed development of more refined analytical codes to predict structural behavior.⁽¹⁾

At velocities of 610 m/sec, strain rates generated were 6 sec^{-1} in the case and 16 sec^{-1} in the support can. These are close to original estimates of the strain rate simply calculated by dividing the elastic strain to yield (ϵ_y) by the time necessary for the tapered nose section to enter the target. For 9-4-20 steel:

$$\dot{\epsilon} \approx \frac{\epsilon_y}{t} = \frac{\sigma_y/E}{l/v} = \frac{1.24 \text{ GPa}/206 \text{ GPa}}{.23 \text{ m}/610 \text{ m/sec}} = 16 \text{ sec}^{-1}.$$

Where σ_y is the yield stress, E is Young's modulus, l is the length of the nose, and v is the impact velocity. Original Pershing II requirements were for 900 m/sec velocities giving a calculated strain rate of 24 sec^{-1} .

Peak measured compressive stresses at 600 m/sec with a 3° off-axis impact angle were 0.93 GPa for the case and 1.97 GPa for the internal structural support.⁽¹⁾ These correspond to $3/4$ of yield for the case and in excess of yield for the internal structure. Thus it appears that the current structural design is yield strength limited, and for more severe impact conditions higher strength alloys would be useful. This must be done, however, without too great a sacrifice in fracture toughness.

Additional measurements of tensile behavior at intermediate strain rates ($< 200 \text{ sec}^{-1}$) over the operational temperature range were requested for 9-4-20 and maraging 250 steels. Test results for these steels plus two other candidate alloys, D6AC and HY-180 steels, are reported in Section 2.

Experiments to assess the possibility of temper embrittlement in 9-4-20 caused by a prolonged soak at 699 K were conducted and reported in Section 3. In addition, results of fracture toughness (K_{IC}) tests run on 9-4-20 for differing temper conditions are presented along with some K_{IC} values generated for HY-180 forged round billets.

Section 4 of this report explores strength/toughness combinations of other candidate alloys for advanced penetrator designs.

2. Moderate Strain Rate Tensile Tests

2.1 Experimental

Uniaxial tensile tests were performed on four candidate earth penetrator (EP) structural alloys at strain rates ranging from 8×10^{-5} to 300 sec^{-1} . The lower value corresponds to rates employed in common "static" tensile tests; the upper strain rate was the maximum achievable by the test equipment for the chosen gauge length. Testing temperatures were 219 K, 297 K, and 344 K (-65, 70, and 160°F), values which bracket current weapons operational requirements.

The alloy steels tested were 9-4-20, Maraging 250, D6AC, and HY-180. The first two are, respectively, the selected alloys for the Pershing II EP case and internal support structure. D6AC has been used as the case material for previous EP designs, and HY-180 is a relatively new moderate strength, high toughness alloy which currently has limited commercial availability. It was developed by the Navy and the United States Steel Corporation as an advanced submarine hull material, and is used in the F-16 fighter.⁽²⁾ Standard alloy chemistry specifications for the four steels are listed in Table 1. All samples were obtained from excess material remaining from round forgings used to machine EP cases at Sandia. Table 1 also lists original forging diameter and heat number, if available.

Specimens were machined from the billets with their axes parallel to the longitudinal direction of the billets. The specimens were obtained from the outer circumference of each billet since it was probable the mechanical properties would vary across the diameter, and it was desirable to sample the portion of the billet which make up the final penetrator case. A drawing of the specimen used in these moderate strain rate tests is shown

in Figure 1. The gauge diameter (0.34 cm) was selected to keep test loads within the range of the test frame; the gauge length (4.0 cm) was long enough to mount a rather long (1.9 cm) high elongation strain gauge. The tapered ends of the specimen mounted in split, tapered collets in the grips; the top grip was rigidly attached to a quartz transducer load cell, while the bottom grip incorporated a sliding, tapered collet which permitted several centimeters of ram motion before load was applied to the specimen. This allowed the ram to reach a steady state velocity before impact with the collet.

The high rate testing frame, located at Sandia Laboratories, Livermore, CA, was manufactured by MTS Systems Corporation, Minneapolis, MN. The velocity (and kinetic energy) of its loading ram was controlled by a variable orifice dump valve which released a precharged pressure of hydraulic fluid through the ram actuator at a high rate. The tests were not conducted under feed-back servo control: the initial ram velocity decreased with specimen elongation as the ram lost kinetic energy by performing plastic work on the specimen. The system could produce initial ram velocities between 50 and 750 cm/sec.

At these displacement rates, resistance strain gauges provide the best technique to measure strain up to a reasonably high value. The gauge selected was a Micromeasurements, Inc. gauge No. EP-08-500GB-120 which is rated effective to 20% strain. The gauges were glued to the test specimens with Armstrong A-12 epoxy; this epoxy functions to high strain values, and in virtually all tests the gauge failed before the adhesive. The epoxy required curing under light pressure at 366 K for 1 hr. A photograph of a specimen with attached gauge is shown in Figure 2.

Strain and load signals were amplified and recorded as a function of time with a Biomation 8100 Transient Recorder digital data storage system. The instrument allowed storage of 1024 bits of data for each channel at a sampling rate of $2 \mu\text{s}$ per data point. This gave approximately 500 data values for the most rapid tests which lasted an average of 0.001 sec. The stored data was plotted on an X-Y recorder after each test.

The tensile specimens were heat treated after machining following standard commercial treatments. These procedures for each alloy are listed in Table 2. Following heat treating, the specimens were lightly abraded on the gauge length with 600 grit paper to provide a roughened surface for glueing the strain gauges. Strain measurements for the "static" tests ($\dot{\epsilon} = 8 \times 10^{-5} \text{ sec}^{-1}$) were made with an Instron extensometer (1.3 cm gauge length).

Tests were conducted in an Instron environmental chamber to provide temperature control. Evaporated liquid nitrogen cooled the chamber, and electrical resistance heated it. Specimens were instrumented with a digital readout thermocouple, and a constant temperature $\pm 1 \text{ K}$ was maintained for 5 minutes before the specimen was pulled.

2.2 Results

Representative examples of load vs. time and strain vs. time output are shown in Figure 3a for 9-4-20 at 297 K and $\dot{\epsilon}_2 = 2.5 \text{ sec}^{-1}$ and Figure 4a for D6AC at 297 K and $\dot{\epsilon}_2 = 137 \text{ sec}^{-1}$ (see Table 3 for definition of $\dot{\epsilon}_2$). Cross plots of load vs. strain are given in Figures 3b and 4b. These figures show several details which are representative of these tests on all four alloys:

1. Small steps are seen on all data traces; these are due to the incremental resolution of the analog to digital converters used in the

data storage device. These steps are a small fraction of the total signal, and it is reasonable to assume an average smooth line through them.

2. The load signals at the lower strain rates ($\approx 2 \text{ sec}^{-1}$) are well-behaved (Fig. 3a), but at the high rates (Fig. 4a) the signals show a superimposed wave form due to mechanical resonance of the load train. The period of the resonance is $90 \mu\text{s}$ corresponding to a frequency of 11100 Hz . These cycles are most evident in the plastic portion of the curve, but in many cases they also show up as a bump in the elastic loading segment.

The resonance is thought to result from stress waves formed on impact of the tapered collet into its mating fixture on application of load at high rate. Experiments showed the wave form could be mechanically filtered out by incorporating a lead or plastic segment into the load train. However, this also grossly altered the form of the elastic and initial plastic segments of the load versus time curve, making impossible measurement of a yield stress.

The method adopted for determining yield and ultimate stress loads was to fit an average smooth line through the cyclic curve. The ultimate load was, of course, the maximum load reached in the plastic portion of the curve; the yield load criterion is described below.

The strain signals at both low and moderate rates show an increase in strain rate as the sample becomes plastic. This occurs because, at relatively constant ram velocity as the specimen elastically stretches under increasing load, a significant fraction of the ram displacement is taken up as elastic strain in the load train. However, when the specimen yields, strain hardening causes only small increases in load so additional elastic strain in the load train is small. Thus the great majority of the ram displacement rate is taken up by the plastic gauge length. For this reason the strain rate measured by the gauge is low when the specimen is

elastic and high when it is plastic. Both these rates are reported in the data compilations.

The change in strain rate was used as an indication of specimen yielding: the intersection of straight lines drawn through each segment was the strain at which the yield load was measured. This was a useful technique in several cases where stress resonance peaks in the elastic portion made it difficult to determine a yield stress using the standard 0.2% plastic strain offset method. In the low rate samples where an 0.2% offset yield strength could be determined, values found by both methods were within one or two percent of each other.

Maximum strain values measured up to gauge failure were about 6% for alloys 9-4-20 and D6AC and 1 to 3% for Maraging 250 and HY-180. These values roughly correspond to uniform strain to necking measured on fractured specimens. Strain gauge readings after necking are meaningless in any case. In tests at room temperature and at 344 K the gauge grid fractured, while at 219 K the adhesive debonded from the specimens. Tabulated results of these tests are given for 9-4-20 in Table 3, Maraging 250 in Table 4, D6AC in Table 5, and HY-180 in Table 6.

2.2.1 9-4-20 Steel

Table 3 shows that ductility as expressed by RU and RA to be independent of the variations in temperature and strain rate. Increasing temperature causes a small drop in yield stress (Figure 5) for low and high strain rates; increasing temperature by 125 K produced an average 5% reduction in strength.

Strain rate effects on yield strength were small. Plotted in Figure 6, strain rate increases by six orders of magnitude produced increases in yield strength of 8% at 219 K, 11% at 297 K, and 6% at 344 K.

2.2.2 Maraging 250 Steel

Reduction in area values were slightly higher at the lowest strain rates. Yield strengths showed mild dependence on temperature: for high and low strain rates, levels decreased about 8% from 219 K to 344 K (Figure 7). The yield strength increased with increasing strain rate (Figure 8), with an average 8% change at each test temperature.

2.2.3 D6AC Steel

The ductility showed no systematic dependence on temperature vs. strain rate. Changes in yield stress were approximately a 7% increase going from 219 K to 344 K (Figure 9). There was no clear trend for strain rate effects on yield strength (Figure 10).

2.2.4 HY-180 Steel

Ductility values remained unchanged over the various test conditions. Shown in Figure 11, yield strength decreased with increasing test temperature an average of 11% at $\dot{\epsilon} = 8 \times 10^{-5} \text{ sec}^{-1}$ and 7% at $174 \leq \dot{\epsilon} \leq 330 \text{ sec}^{-1}$. The yield stress showed no dependence on strain rate at 219 K, but at 297 K and 344 K strength levels increased 10 and 9%, respectively, over the strain rate range (Figure 12).

2.3 Discussion

Strength and ductility values measured here in room temperature "static" strain rate tensile tests agree well with published data^(2,3) determined under the same conditions. In addition, scatter in data from the strain gauge-instrumented tests appears to be no worse than the "static" data generated using a standard axial extensometer (see Figures 6, 8, 10, and 12).

The relatively small effects of temperature and strain rate which generally averaged 10% or less are typical of moderate to high strength steels. For design purposes, the decrease in average strength measured at the upper temperature limit is compensated by the increase due to the higher strain rate expected in penetrator applications. Also, tensile data generated in this study are conservative for design in that compressive yield strengths for these alloys tend to be slightly higher ($< 10\%$).⁽⁴⁾

3. Experimental Toughness Data

3.1 Assessment of Temper Embrittlement in 9-4-20

One step in assembly of the Pershing II earth penetrator is to heat-shrink fit the ballast into the nose of the 9-4-20 penetrator case. The original procedure was to soak the case, which had previously been heat treated according to specifications of Table 2, at 699 K overnight to thermally expand it to accommodate the ballast. Typical soak times were 16 hours.

Temper embrittlement occurs in many high strength steels after they are held between 673-838 K for prolonged periods. The embrittlement shows up in high strain rate impact tests or fracture toughness tests as a decrease in absorbed energy and a significant increase in ductile to brittle transition temperature. Published data⁽⁵⁾ showed tempering in this range for 4 hours had little effect on Charpy impact energy (C_v), but it was decided to experimentally measure the effects of a 16 hour soak.

Standard 1 cm x 1 cm cross section Charpy V-notch specimens were machined with the length of the specimen parallel to the length of the round forging. This gave a crack propagation perpendicular to the forging or penetrator axis. All specimens received the standard heat treatment (Table 2), and half received an additional 16 hr. at 699 K, corresponding to the typical thermal expansion time. Round bar tensile specimens were also included to check for strength differences. Impact tests were run at 211, 253, 273, 298, and 368 K.

Room temperature tensile properties were identical for the two treatments as shown below (average of two specimens).

Temper	σ_y (MPa/ksi)	σ_u (MPa/ksi)	RA (%)
Standard	$1.27 \times 10^3/184$	$1.34 \times 10^3/194$	61
Standard + 699 K/16 hr	$1.27 \times 10^3/185$	$1.34 \times 10^3/195$	60

The results of the impact tests (Figure 13) show that no drastic decrease in toughness occurs over this temperature range. Taking into consideration the uncertainty in data, it appears there is no difference in C_V above room temperature and at most a 10% lower value for the long-term soaked samples below room temperature. However, this decrease is significant, and a shorter heat-up period was recommended.

3.2 Effect of Tempering Heat Treatment on Strength and Toughness of 9-4-20

Strength and plane strain fracture toughness (K_{IC}) values were measured for different tempering treatments of 9-4-20. The standard temper condition (Table 2) calls for 4 hr. at 838 K in inert environment plus air cooling. By changing the tempering time and temperature it is possible to vary the morphology of the strengthening carbide precipitate; this affects strength and toughness. The three non-standard treatments selected were greatly different from the standard in time or temperature. This allowed a rough assessment of effects of errors in heat treating. In addition, baseline K_{IC} data was generated for the standard temper for cracks oriented in the important direction for an earth penetrator case: cracks with their plane perpendicular to the penetrator axis growing inward in a radial direction.

Compact tension fracture toughness specimens 3.2 cm thick were machined from the same 9-4-20 billet used in the high strain rate tests. Companion tensile specimens 0.64 cm in diameter were also machined and subjected to

the heat treatments concurrently with the toughness specimens. Fracture toughness tests were performed at room temperature in accordance with ASTM Standard E399-74⁽⁶⁾. Tensile tests were run at a strain rate of $1.4 \times 10^{-4} \text{ sec}^{-1}$; two tests were performed for each condition.

The data in Table 7 show that moderate changes in strength and toughness were achieved, although the standard temper of 838 K/4 hr. gives the best combination of σ_y and K_{IC} . Strength and ductility values reported are averages of two tensile tests. Underaging at 673 K/4 hr. results in both lowered strength and ductility, while overaging at 638 K/48 hr., as expected, decreases strength and increases toughness. The general trend of increased K_{IC} with increased tempering temperature agrees with published data on 9-4-30 steel⁽²⁾ (0.3 percent carbon).

K_Q values are reported for the last two tests since each failed an ASTM criterion for valid K_{IC} determination; however, the data are useful to show trends. Uncertainty in K due to inaccuracies in measured load and specimen dimensions was calculated to be $\pm 8 \text{ MN-m}^{-3/2}$.

The average K_{IC} found for the standard heat treatment was $111 \text{ MN-m}^{-3/2}$; this value is significantly lower than reported levels of $121\text{-}154 \text{ MN-m}^{-3/2}$ for rolled plate.^(7,8) Probably this is a result of decreased toughness in the transverse direction of the forged round billet.

3.3 Fracture Toughness Measurements of HY-180 Steel

Plane strain fracture toughness (K_{IC}) measurements were conducted on two forged billets of HY-180 steel previously used for penetrator stock (Heat No. C-52345). Tests were performed using the same size specimens and procedures described for 9-4-20 steel in Section 3.2. The standard heat treatment is described in Table 2. Companion tensile tests were also carried out.

The purposes of the tests were to compare K_{IC} for the two round billets to available plate stock data and also to assess whether a toughness difference existed between the two forgings, as was indicated by Charpy impact data supplied by a certified properties report.⁽⁹⁾ This report listed average room temperature Charpy impact energies (C_v) of 73 J for a forging with standard processing (denoted LB) versus 84 J for a forging with an interrupted process history which included a cool down (denoted SB).

Strength and toughness data are listed in Table 8. Tensile data are an average of three tests. Strength, ductility, and toughness levels were not significantly different for the two billets, and no correlation was found with the previously measured C_v values.

As with 9-4-20, the fracture toughness measured here for HY-180 steel round forging billets (129 to 139 $MN\cdot m^{-3/2}$) was significantly lower than published data for plate material (159 to 205 $MN\cdot m^{-3/2}$),⁽¹⁰⁻¹³⁾ C_v values measured by Ref. 9 are also at the low end of data reported in Refs. 10-13. It appears that transverse toughness levels are lower for these forged billets compared to rolled plate; this conclusion is supported by reported^(2,14) low short transverse impact values in a 7.6 cm thick plate of HY-180 steel.

4. Strength Versus Toughness for Candidate Alloys

As mentioned in the introduction to this report, recent experiences with penetrators using 9-4-20 steel as penetrator cases and maraging 250 steel as internal cans have shown the structures to be yield strength limited. That is, strain gauge measurements for severe tests indicated near yielding in some situations, but no evidence of crack propagation leading to brittle structural failure was observed. Utilizing higher yield strength alloys for these components would be an attractive means to improve survivability; however, it is generally true that increased strength will result in decreased fracture toughness.

The real problem, then, is to decide what lower limit of toughness is reasonable, and these limits may be different for the case and internal can. Penetrator cases have typically been machined from monolithic forgings of material with thick walls (typically 2-4 cm) and no stress concentrations in regions of maximum bending stress. In the absence of internal flaws, which should be observable by non-destructive examination, cracking should not occur before general yielding if the material has moderate fracture toughness over temperatures and strain rates of interest. A linear elastic fracture toughness (K_{IC}) assessment of the relatively thick case, based on minimum observable flaw size, should be possible because criteria for plane strain cracking would hold.

The internal support can presents a different materials and analysis problem though, because it is thinner and cracking under elastic plane strain conditions might not occur. The cans are also machined from solid billets, but they are complex in geometry, including various grooves, threads, and holes as stress concentrators. The presence of stress concentrations increases the need for higher fracture toughness.

Commercially available steel possessing yield strengths significantly above 1.38 GPa (200 ksi) with good toughness are limited in number. Metals other than steel seem entirely unsuitable: no alloys of aluminum, titanium, or uranium possess the high strengths necessary, and they all exhibit much lower fracture toughness. Many high strength steels, including bearing and tool steels, are too brittle for penetrators.

A plot of tensile yield strength versus fracture toughness (K_{IC}) is shown in Figure 14 for several candidate steels with strengths over 1.38 GPa. HY-180 and 9-4-20 are included for comparison, with values of toughness measured on round forgings in this study compared to published data on cross-rolled plate. Individual values for a given steel may vary depending on changes in heat treatment or processing (i.e., plate versus forging properties of 9-4-20), but the commercial heat treatments listed tend to produce the best combination of properties.

Of commonly available alloys, the maraging 250 and 300 steels give improved yield strengths without too great a sacrifice in K_{IC} when compared to 9-4-20 steel. Maraging 300 grade in plate form has comparable toughness to maraging 250, but it is likely this would drop somewhat for larger size forgings. Maraging 300 steel is as machinable as maraging 250, which is currently used as the internal can, and it can easily be aged to full hardness in thick sections (aging treatment is 756 K for 3 to 5 hr.). To obtain maximum toughness, close control on alloy chemistry must be maintained, and strict acceptance criteria on notch toughness and fracture toughness (K_{IC}) should be specified.

There has been one past unfavorable experience in using maraging 300 steel as a penetrator case. A test was conducted in 1966^(18,19) in which a 25.9 cm diameter penetrator was impacted at a velocity of 251 m/sec

(825 ft/sec) into Tres Hermano sandstone; the penetrator fractured at a depth of 3 m. However, two factors were present which suggest that the failure was not strictly a materials problem. First, the case was designed with an abrupt thickness decrease about one-quarter up from the nose where the wall thickness was reduced to 1.27 cm. Failure occurred at this stress concentration. Second, it was reported⁽¹⁹⁾ that the penetrator encountered a harder boulder at a depth of approximately 2 m and that this rock had deflected the penetrator from its original path. This would have imposed a very large tensile bending stress on the penetrator as the nose encountered the stronger object at some angle and the rear of the case was constrained to the original hole. It appears that the combination of poor design and extreme test environment were the primary causes of failure of this test, and it is not reasonable to rule out maraging 300 steel based on this one experience.

A relatively new alloy which has clearly superior strength-toughness properties (Figure 14) is AF1410 steel (14 Co-10 Ni-2 Cr-1 Mo-0.16 C-bal Fe). This alloy, developed at United States Steel under contract to the Air Force Materials Laboratory, is a higher strength (1.66 GPa/240 ksi) modification of HY-180 steel. It utilizes the same strengthening mechanisms, and is processed and heat treated in a similar manner (double austenitize: 1172 K - water quench + 1088 K - water quench; age 783 K for 5 hr., air cool). The alloy is categorized as a "production material" by Cyclops Corp., Universal Cyclops Division, who has produced approximately 59,000 kg (130,000 lb.) of the steel, the largest heat being 27,000 kg (60,000 lb.).

Unfortunately, AF1410 lacks the large base of industrial experience necessary for rapid incorporation into a weapons system. To date, it has

not been used to build hardware in a major program. However, considerable characterization of the alloy has been performed,⁽¹⁶⁾ including areas of strength, toughness, fatigue, weldability, and corrosion. Several heats of differing chemistries have been investigated, and properties have been optimized with respect to composition and aging treatment.

It would be difficult to introduce an alloy with as little industrial experience into Sandia weapons systems. If its good strength-toughness properties were clearly necessary, it would be possible to require extremely rigid quality control procedures on material acceptance, machining, heat treating, assembly, and component testing. Depending on specific design, proof tests might be instituted. With concurrent research into the alloy's properties, it would be possible to relax the rigid (and expensive) quality controls as confidence in the alloy increased.

5. Conclusions

1. In tensile tests of 9-4-20, maraging 250, D6AC, and HY-180 steels yield strength variations were 10 percent or less over the temperature range $219\text{ K} < T < 344\text{ K}$ ($-65^{\circ}\text{F} < T < 160^{\circ}\text{F}$) and strain rates $8 \times 10^{-5}\text{ sec}^{-1}$ and 300 sec^{-1} . No significant changes in ductility were noted.
2. A small (10 percent) decrease in Charpy impact energy at low temperature was measured for 9-4-20 steel samples subjected to a thermal aging sequence simulating a heat-shrink fitting procedure used to fit ballast into the Pershing II penetrator. A shorter time sequence was recommended.
3. Plane strain fracture toughness values (K_{IC}) of 9-4-20 and HY-180 steels measured from penetrator forged billet stock were significantly lower than published data from cross-rolled plate.
4. A survey of commercially available steels with strengths in excess of 1.38 GPa (200 ksi) was conducted. Three candidates for penetrator cases provided improved strength with good toughness: maraging 250, maraging 300, and AF1410 steels. Little industrial experience has been accumulated on AF1410.

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TABLE 1

Chemistry, Forging Diameter, and Heat Number of Tested Alloy Steels

Element (Weight Percent)	9-4-20 Dia. = 20.3 cm --	Maraging 250 Dia. = 17.1 cm Latrobe No. 51817 ^(a)	D6AC Dia. = 16.8 cm --	HY-180 Dia. = 16.8 cm U.S.S. ^(b) No. C- 52345
	Min - Max ⁽²⁾	Min - Max ⁽²⁾	Min - Max ⁽²⁾	Min - Max ⁽³⁾
C	0.16 - 0.23	-- - 0.03	-- - 0.35	0.09 - 0.13
Co	4.25 - 4.75	7.0 - 8.5	*	7.5 - 8.5
Mn	0.20 - 0.40	-- - 0.10	0.60 - 0.90	0.07 - 0.17
Mo	0.90 - 1.10	4.6 - 5.2	0.90 - 1.10	0.9 - 1.1
Ni	8.5 - 9.5	17.0 - 19.0	0.40 - 0.70	9.5 - 10.5
P	-- - 0.010	-- - 0.01	-- - 0.025	-- - 0.010
Si	-- - 0.10	-- - 0.10	0.15 - 0.30	-- - 0.15
S	-- - 0.10	-- - 0.01	-- - 0.025	-- - 0.008
Ti	*	0.3 - 0.5	*	*
B	*	-- - 0.003	*	*
Ca	*	-- - 0.05	*	*
Zr	*	-- - 0.02	*	*
Al	*	0.05 - 0.15	0.45 - 0.50	-- - 0.25
Cr	0.65 - 0.85	*	0.90 - 1.20	1.8 - 2.2
V	0.06 - 0.12	*	0.08 - 0.15	*

*Element not listed

(a) - Latrobe Steel Co.

(b) - United States Steel Co.

TABLE 2

Standard Heat Treatment Schedules

9-4-20 Steel

1. Heat to 1185 ± 14 K for 1.5 hr. in neutral salt or inert atmosphere; cool to room temperature at a rate approximating air cooling, but in an inert atmosphere.
2. Heat to 1102 ± 14 K for 1 hr. in neutral salt; cool as Step 1.
3. Hold at $200 + 5-11$ K for 1 hr.
4. Temper at 838 ± 14 K for 4 hr. in neutral salt or inert atmosphere; air cool to room temperature.

D6AC Steel

1. Heat to $1173 + 14$ K for 1 hr. in neutral salt or inert atmosphere; oil quench.
2. Temper 888 K for 4 hr. in neutral salt or inert atmosphere; air cool.
3. Hold at $200 + 5-14$ K for 1 hr.
4. Temper 888 K for 4 hr.; air cool.

Maraging 250 Steel

1. Age at 755 ± 5 K for 4 hr. in neutral salt or inert atmosphere; air cool.

HY-180 Steel

1. Heat to 923 ± 14 K for 1 hr. in neutral salt or inert atmosphere; quench in ice brine.
2. Stabilize at 775 ± 5 K for 15 min. in neutral salt or inert atmosphere.
3. Raise temperature to 783 ± 5 K; hold for 10 hr.; air cool to room temperature.

TABLE 3
Tensile Testing Results of 9-4-20 Steel

Specimen No.	Temperature (K)	$\dot{\epsilon}_1$ (sec ⁻¹)	$\dot{\epsilon}_2$ (sec ⁻¹)	RU (%)	RA (%)	σ_y (GPa/ksi)	σ_u (GPa/ksi)	σ_f (GPa/ksi)
A-1	297	52	195	4.5	63	1.27/184	1.34/194	---
A-2	297	49	181	4.5	64	1.28/186	1.36/197	---
A-3	297	0.47	2.5	5.9	62	1.22/178	1.31/190	---
A-4	297	0.55	2.2	7.4	62	1.25/181	1.30/189	---
A-5	344	51	185	5.9	64	1.25/181	1.28/187	---
A-6	344	50	207	4.5	61	1.28/186	1.31/190	---
A-7	219	56	161	4.5	61	1.34/194	1.38/201	---
A-9	219	47	150	5.9	60	1.36/197	1.42/206	---
A-10	294	--	8 x 10 ⁻⁵	5.9	65	1.24/180	1.31/190	2.07/300
A-11	294	--	8 x 10 ⁻⁵	5.9	64	1.20/174	1.28/186	---
A-12	344	--	8 x 10 ⁻⁵	5.9	64	1.19/173	1.28/186	2.08/302
A-13	344	--	8 x 10 ⁻⁵	5.9	64	1.19/173	1.26/183	2.02/294
A-14	219	--	8 x 10 ⁻⁵	4.5	63	1.22/178	1.33/193	2.12/308
A-15	219	--	8 x 10 ⁻⁵	5.9	62	1.29/188	1.40/203	2.14/310
A-16	219	--	8 x 10 ⁻⁵	3.0	62	1.24/180	1.38/201	2.09/303

Legend

$\dot{\epsilon}_1$ = strain rate before yielding

$\dot{\epsilon}_2$ = plastic strain rate

$RU = \frac{A_o - A_u}{A_o} \times 100$ = uniform reduction in area

$RA = \frac{A_o - A_f}{A_o} \times 100$ = reduction of area at neck

$\sigma_y = P_y/A_o$ = yield stress

$\sigma_u = P_u/A_o$ = ultimate stress

$\sigma_f = P_f/A_f$ = fracture stress

A_o = original gauge area

A_u = post test uniform area

A_f = area of neck

P_y = yield load (see text)

P_u = ultimate (peak) load

P_f = fracture load

TABLE 4
Tensile Testing Results of Maraging 250 Steel

Specimen No.	Temperature (K)	$\dot{\epsilon}_1$ (sec ⁻¹)	$\dot{\epsilon}_2$ (sec ⁻¹)	RU (%)	RA (%)	σ_y (GPa/ksi)	σ_u (GPa/ksi)	σ_f (GPa/ksi)
C-1	297	--	---	1.5	56	---	---	---
C-2	297	--	---	3.0	57	---	---	---
C-3	297	28	45	1.5	58	1.77/257	1.80/262	---
C-4	297	55	111	0	57	1.82/264	1.85/264	---
C-5	297	54	165	0	59	1.79/260	1.85/269	---
C-6	297	0.48	2.00	1.5	59	1.76/255	1.82/265	---
C-7	297	0.55	1.43	1.5	60	1.71/248	1.76/256	---
C-8	344	46	186	1.5	58	1.72/250	1.90/276	---
C-9	344	89	179	1.5	58	1.78/259	1.94/281	---
C-10	219	--	---	1.5	57	---	1.98/288	---
C-11	219	76	140	1.5	55	1.90/276	1.97/286	---
C-15	294	--	8×10^{-5}	0	--	1.69/245	1.74/253	---
C-16	294	--	8×10^{-5}	1.5	66	1.67/242	1.72/250	---
C-17	344	--	8×10^{-5}	0	66	1.62/235	1.67/243	2.66/386
C-18	344	--	8×10^{-5}	0	65	1.63/237	1.69/246	2.63/381
C-19	219	--	8×10^{-5}	0	66	1.73/251	1.85/269	2.64/383
C-21	219	--	8×10^{-5}	0	64	1.80/261	1.88/273	2.84/412

See Legend in Table 3.

TABLE 5
Tensile Testing Results of D6AC Steel

Specimen No.	Temperature (K)	$\dot{\epsilon}_1$ (sec ⁻¹)	$\dot{\epsilon}_2$ (sec ⁻¹)	RU (%)	RA (%)	σ_y (GPa/ksi)	σ_u (GPa/ksi)	σ_f (GPa/ksi)
B-1	297	--	---	7.4	60	---	---	---
B-2	297	34	131	6.6	56	1.18/171	1.35/196	---
B-3	297	50	137	5.9	58	1.21/176	1.35/196	---
B-4	297	0.34	1.51	5.9	55	1.21/176	1.27/184	---
B-5	297	0.38	1.68	5.9	55	1.21/176	1.27/184	---
B-6	344	38	117	7.4	56	1.22/178	1.30/189	---
B-7	344	39	159	7.4	58	1.17/170	1.31/190	---
B-8	219	69	130	4.5	55	1.30/189	1.36/197	---
B-9	219	39	158	7.4	56	1.24/180	1.38/200	---
B-10	294	--	8 x 10 ⁻⁵	3.0	55	1.21/176	1.26/183	---
B-11	294	--	8 x 10 ⁻⁵	4.4	55	1.22/177	1.29/187	1.99/289
B-12	344	--	8 x 10 ⁻⁵	4.5	56	1.17/170	1.26/183	2.02/294
B-13	344	--	8 x 10 ⁻⁵	4.5	52	1.16/169	1.25/182	1.89/275
B-14	219	--	8 x 10 ⁻⁵	4.5	51	1.29/187	1.35/196	1.98/287
B-15	219	--	8 x 10 ⁻⁵	5.9	54	1.24/180	1.35/196	2.19/318

See Legend in Table 3.

TABLE 6
Tensile Testing Results of HY-180 Steel

Specimen No.	Temperature (K)	$\dot{\epsilon}_1$ (sec ⁻¹)	$\dot{\epsilon}_2$ (sec ⁻¹)	RU (%)	RA (%)	σ_y (GPa/ksi)	σ_u (GPa/ksi)	σ_f (GPa/ksi)
D-1	297	45	185	1.5	66	1.47/213	1.50/218	---
D-2	297	57	182	1.5	65	1.43/207	1.47/213	---
D-3	297	0.40	3.0	3.0	66	1.37/199	1.43/207	---
D-4	297	0.40	2.7	3.0	66	1.37/199	1.45/210	---
D-5	344	91	330	3.0	67	1.37/199	1.41/205	---
D-6	344	42	334	3.0	67	1.39/202	1.41/205	---
D-7	219	59	200	3.0	67	1.51/219	1.53/222	---
D-8	219	44	174	3.0	66	1.47/214	1.51/219	---
D-10	293	--	8×10^{-5}	3.0	70	1.30/189	1.37/199	---
D-11	293	--	8×10^{-5}	0	69	1.31/191	1.40/203	---
D-12	344	--	8×10^{-5}	0	71	1.27/184	1.35/196	2.82/409
D-13	344	--	8×10^{-5}	0	71	1.27/184	1.35/196	2.51/364
D-14	219	--	8×10^{-5}	3.0	69	1.40/203	1.47/214	2.63/381
D-15	219	--	8×10^{-5}	0	69	1.45/211	1.49/216	2.58/374
D-16	219	--	8×10^{-5}	1.5	70	1.40/203	1.49/216	2.67/387

See Legend in Table 3.

TABLE 7
Effects of Tempering Treatment on Strength and Fracture Toughness of 9-4-20

Temper K/hr	σ_y (GPa/ksi)	σ_u (GPa/ksi)	RA	RU	K_Q (MN/m ^{-3/2} /ksi-in ^{1/2})	K_{IC} (MN/m ^{-3/2} /ksi-in ^{1/2})
400/4	1.20/173	1.41/204	56.1	3.0	87/80	87/80
538/4	1.28/185	1.43/207	64.6	3.5	102/94	102/94
565/4	1.27/184	1.39/201	64.6	3.6	108/99	108/99
565/4	1.27/184	1.39/201	64.6	3.6	119/109	119/109
565/4	1.27/184	1.39/201	64.6	3.6	107/98	(a)
565/48	1.11/161	1.16/168	67.0	4.4	128/117	(b)

(a) Invalid because of precrack front shape.

(b) Did not meet thickness criterion: $2.5 \left(\frac{K_Q}{\sigma_y} \right)^2 = 3.35 > t = 3.18 \text{ cm.}$

TABLE 8
Strength and Toughness of Two HY-180 Steel Forgings

Specimen No.	σ_y (GPa/ksi)	σ_u (GPa/ksi)	RA (%)	RU (%)	$C_v^{(9)}$ (J/ft-lb)	K_Q (MN/m ^{-3/2} /ksi-in ^{1/2})	K_{IC} (MN/m ^{-3/2} /ksi-in ^{1/2})
HY-180-LB-1	1.35/195	1.42/204	70	2.0	73/54	139/127	139/127
HY-180-LB-2	1.35/195	1.42/204	70	2.0	73/54	136/125	136/125
HY-180-SB-1	1.32/191	1.40/202	70	2.0	84/62	129/118	129/118
HY-180-SB-2	1.32/191	1.40/202	70	2.0	84/62	136/125	(c)

(c) Invalid because of crack front shape.

DIMENSIONS IN MILLIMETERS

Figure 1. Moderate strain rate tensile specimen.

Figure 2. Tensile specimen with attached strain gauge.

Figure 3a. Output of load and strain versus time for specimen No. A-3 (9-4-20 steel, $\dot{\epsilon}_2 = 2.5 \text{ sec}^{-1}$, 297 K).

Figure 3b. Crossplot of load versus strain for specimen No. A-3.

Figure 4a. Output of load and strain versus time for specimen No. B-3 (D6AC steel, $\dot{\epsilon}_2 = 137 \text{ sec}^{-1}$, 297 K).

Figure 4b. Crossplot of load versus strain for specimen No. B-3.

Figure 5. Yield strength versus test temperature for 9-4-20.

Figure 14. Yield strength versus fracture toughness (K_{IC}) for several candidate penetrator structural alloys.

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