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ADDITIONAL FRACTURE AND STRENGTH TEST RESULTS FOR A723 STEEL AND 38644 TITANIUM

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Four types of additional mechanical test results are described for high strength steel and titanium alloys, as a continuation of previous work.

1. The effects of elevated temperature on the circumferential orientation tensile properties of titanium and steel cylinders are described.

2. A comparison is presented of strength and fracture toughness results from two titanium ingots.

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3. The fatigue lives of notched bend specimens of titanium are measured and compared with calculated fatigue lives for steel.

4. The effects of elevated temperature cycles and a plasma spraying process on the strength of steel are presented. (Keywords) — >

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INTRODUCTION

In previous work (ref 1), a variety of strength and fracture properties of a high strength steel and a high strength titanium alloy were reported. This report is a continuation of that work. In the earlier work, measurements of elastic modulus, Poisson's ratio, yield and ultimate strengths, stress relaxation, and fracture toughness were made at various temperatures with a maximum range of -54° to +482°C. The application was for compound cylinders of steel and titanium subjected to temperatures primarily above, but also below, room temperature.

The results described in this report continue some of the tests of the previous work related to advanced-jacketed cannon applications. The additional results are of four types:

1. The effects of elevated temperature on the circumferential orientation tensile properties of titanium and steel cylinders are described.
2. A comparison is presented of strength and fracture toughness results from two titanium ingots.
3. The fatigue lives of notched bend specimens of titanium are measured and compared with calculated fatigue lives for steel.
4. The effects of elevated temperature cycles and a plasma spraying process on the strength of steel are presented.

The first two sets of results are of obvious use with cannon, where both high strength and high toughness are desired. The third area, fatigue behavior of notched specimens, is required for the design of titanium cylinders

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[1] J. H. Underwood, R. R. Fujczak, and R. G. Hasenbein, "Elastic, Strength, and Stress Relaxation Properties of A723 Steel and 38644 Titanium for Pressure Vessel Applications," Proceedings of 1986 Army Symposium on Solid Mechanics, US Military Academy, 7-9 October 1986.

containing fastener holes or other stress risers. The fourth area addresses the effects of an aluminum plasma spraying process on the properties of the steel. Since the temperature of the plasma spraying and subsequent hot isostatic pressing (HIP) process are in the range of the steel tempering temperature, the effects on the steel are of interest.

MATERIALS

The two materials taken from the previous work (ref 1) are described as follows:

The alloy steel was purchased as remelt-process forging preforms with the following nominal chemical composition in weight percent: 2.6 Ni, 1.0 Cr, 0.5 Mo, 0.6 Mn, 0.34 C, 0.10 V, 0.008 max. P, and 0.004 max. S. It was rotary forged and heat treated to a nominal yield strength of 1090 MPa. It conforms to ASTM Standard A723, Grade 2.

The titanium alloy was purchased as remelt-process extrusions from two ingots with nominal yield strength of 1100 MPa. It is commonly referred to as 38644 titanium and has a nominal chemical composition in weight percent of: 3.0 Al, 8.0 V, 6.0 Cr, 4.0 Mo, and 4.0 Zr.

TESTS AND RESULTS

Circumferential Tensile Strength

Table I lists the results of elevated temperature tests of steel and titanium in the circumferential orientation. A 5.1 mm by 6.4 mm cross section, 64 mm overall length specimen was used (ref 1). Tests were performed at 316°C, a

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[1] J. H. Underwood, R. R. Fujczak, and R. G. Hasenbein, "Elastic, Strength, and Stress Relaxation Properties of A723 Steel and 38644 Titanium for Pressure Vessel Applications," Proceedings of 1986 Army Symposium on Solid Mechanics, US Military Academy, 7-9 October 1986.

higher temperature than that used in the previous work which had equipment limitations. The steel results at 316°C agree within 6 percent with estimates from the prior work. The titanium results at 21°C agree within 4 percent with the mean of prior results; the titanium results at 316°C agree within 1 percent with estimates from the previous work. In general, the results from both steel and titanium showed the expected decrease in strength due to elevated temperature. In addition, the titanium results gave an initial comparison between ingots #1 and #2, with no indication of a significant difference.

TABLE I. CIRCUMFERENTIAL ORIENTATION TENSILE PROPERTIES OF TITANIUM AND STEEL AT +21°C AND +316°C

Material	Temperature °C	Measured Strength 0.1% Yield MPa	Measured Strength Ultimate MPa	Strength From Ref. 1 0.1% Yield MPa	Strength From Ref. 1 Ultimate MPa
Steel	+316°C	918	1049	Est: 870	1060
Titanium	+21°C	1056	1235	Mean: 1094	1216
		(Ingot #2)		(Ingot #1)	
	+316°C	945	1090	Est: 950	1100

Strength and Toughness From Two Ingots

Table II lists the results of tests performed to directly measure any difference in mechanical properties of the two titanium ingots. Longitudinal tensile specimens (ref 1) and arc bend, chord-support fracture specimens (refs 1,2)

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[2] J. H. Underwood, J. A. Kapp, and M. D. Witherell, "Fracture Testing With Arc Bend Specimens," *Fracture Mechanics: Seventeenth Volume*, *ASTM STP 905*, (J. H. Underwood, et al., eds.), American Society for Testing and Materials, Philadelphia, 1986, pp. 279-296.

were used for strength and fracture toughness tests, respectively. The mean yield stress of ingot #2 at 21°C was 3 percent lower; the mean ultimate strength of ingot #2 at 21°C was 2 percent higher. Therefore, there appears to be no significant difference in strength between the ingots.

TABLE II. COMPARISON OF STRENGTH AND FRACTURE TOUGHNESS RESULTS FROM TWO TITANIUM INGOTS

	Test Temperature °C	Yield Strength; 0.1% Offset L Orientation MPa	Ultimate Strength L Orientation MPa	Fracture Toughness C-R Orientation MPa $m^{1/2}$		
				n	mean	std. dev.
Ingot #1	+21°	1035, 1035	1117, 1124	3	50.8	3.0
	-54°	1269, 1276	1304, 1331	3	46.9	5.5
Ingot #2	+21°	973, 1035	1111, 1159	3	59.8	4.6
	-54°	-	-	3	50.4	1.7

The fracture toughness of ingot #2 at +21°C was 18 percent higher; the toughness of ingot #2 at -54°C was 7 percent higher. Considering that the standard deviation of toughness is as high as 12 percent of the mean, the higher indicated toughness of ingot #2 may be partly due to scatter.

Since the overall levels of strength and toughness of ingot #2 are similar to that of ingot #1, the concern addressed in the previous work (ref 1) - "A carefully considered fracture control plan will be necessary for safe use of the titanium" - still applies. This is graphically illustrated by the result of the burst test of the first titanium-jacketed cylinder. Figure 1 shows the 1 m long test cylinder after testing with the titanium jacket portion on the right.

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[1] J. H. Underwood, R. R. Fujczak, and R. G. Hasenbein, "Elastic, Strength, and Stress Relaxation Properties of A723 Steel and 38644 Titanium for Pressure Vessel Applications," Proceedings of 1986 Army Symposium on Solid Mechanics, US Military Academy, 7-9 October 1986.

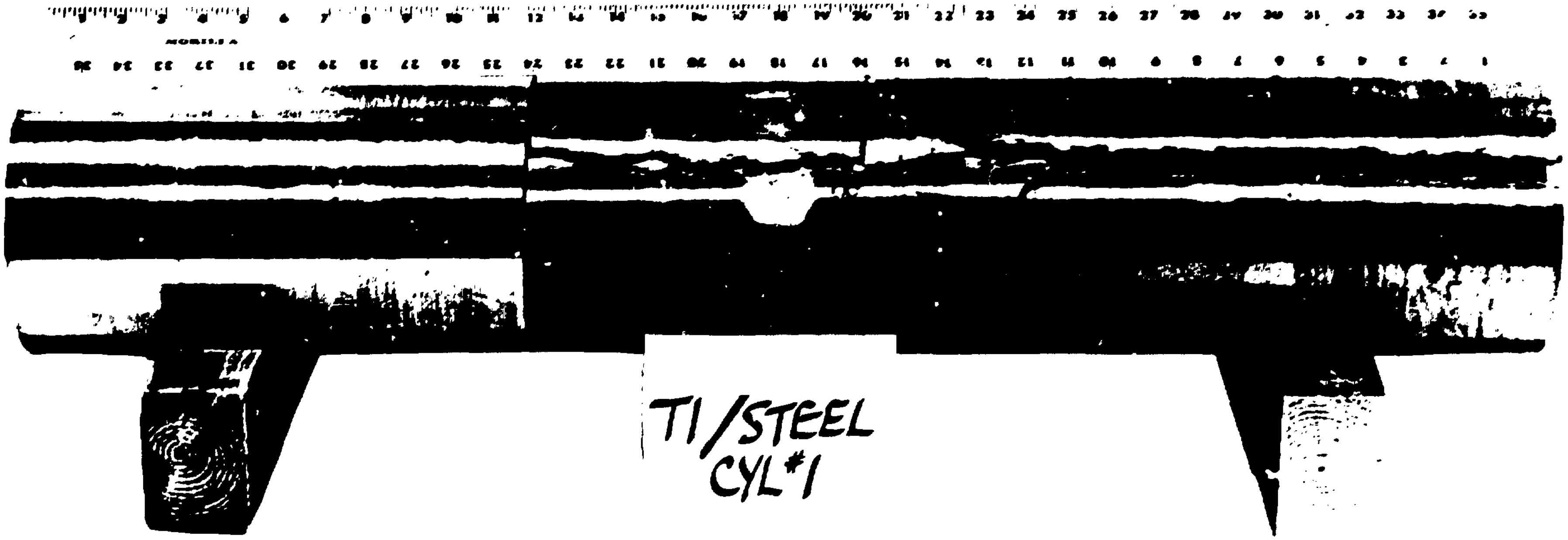

Figure 1. Photograph of titanium-jacketed cylinder after burst test.

It is clear that the burst occurred by a fast fracture running the length of the jacket and with some fragmentation. It should also be emphasized that the burst occurred at several times the highest possible service pressure of the tube. Therefore, if this type of failure were ever to occur in service, it could only occur due to the presence of a significant notch or other preexisting defect.

Fatigue Life Tests

Figure 2 and Table III outline the tests to obtain a measure of notched fatigue life for titanium. If fastener holes were used, for example, it would be important to have fatigue life information. This is particularly true, considering the nature of the burst test results of the previous section.

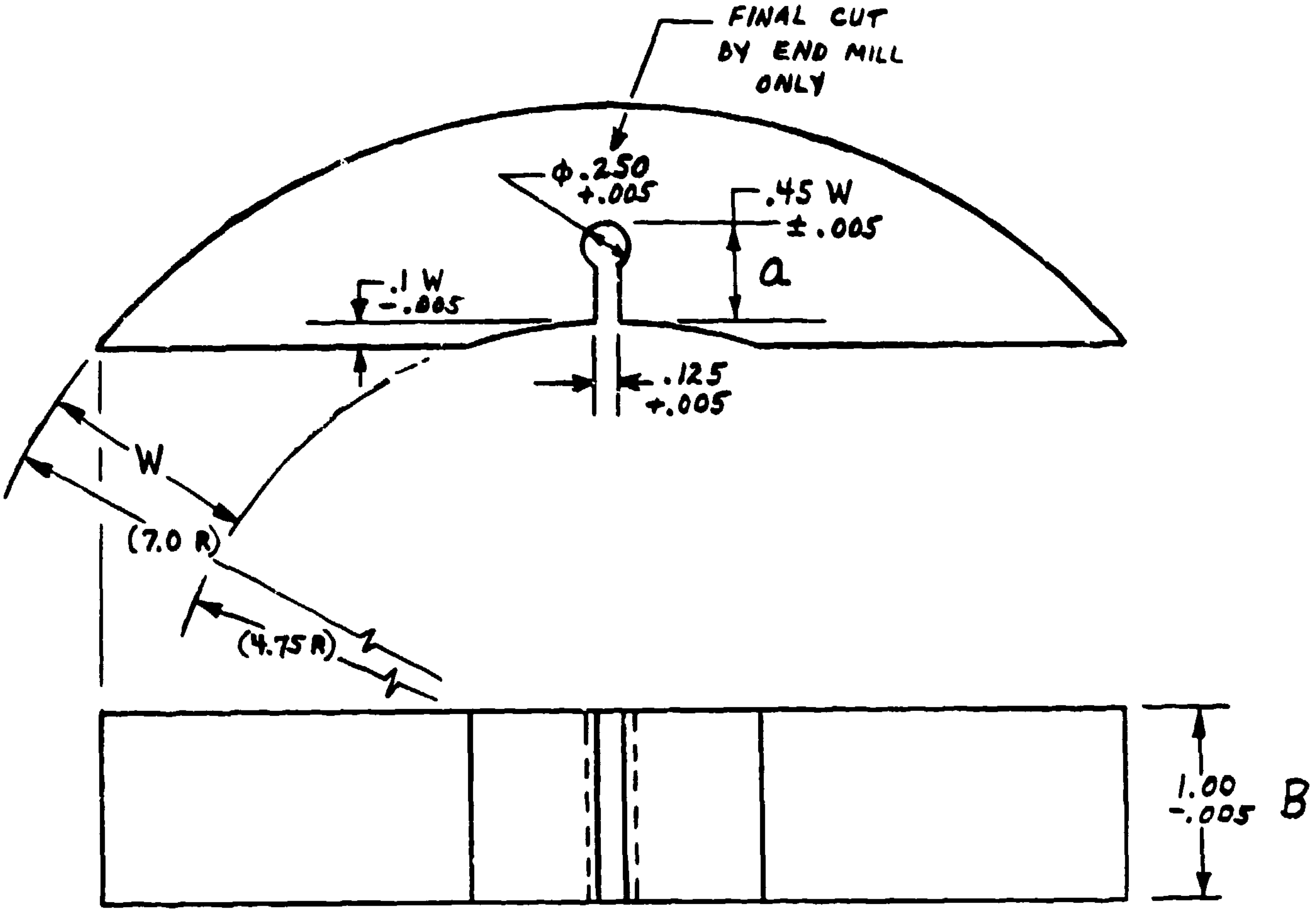

Figure 2. Sketch of fatigue crack initiation specimens for titanium.

Figure 2 shows the arc bend, chord-support specimen (ref 2), similar to that used for fracture toughness tests. The test plan was simply to cyclically load the specimens to failure and compare the life to that obtained from similar steel specimens in prior testing (ref 3). Table III shows the test results and the comparison. Four repeat tests were performed at each of two loads, which correspond to the stress intensity factor range, ΔK, calculated as follows:

$$\Delta K = \frac{\Delta P \, (S/W) \, Y}{(1-a/W)^{3/2} \, B \, W^{1/2}} \tag{1}$$

in which ΔP is the load range (from Table III); S/W is the span-to-wall thickness ratio (4.0 for these tests); and Y is the dimensionless K parameter for this specimen geometry (from ref 2). Using $W = 28$ mm and values of a and B shown in Figure 2, the ΔK values are 48 and 33 MPa $m^{1/2}$. The fatigue lives, N, mean, N_m, and standard deviation, N_{sd}, are compared with results from a fracture mechanics representation of steel fatigue results (ref 3)

$$N_{steel} = \text{function} \left[\frac{1.12 \, \Delta K}{\rho^{1/2} \, \sigma_y} \left(1 + \frac{\rho}{\rho_0}\right) \right] \tag{2}$$

Using the ΔK values from Eq. (1); root radius, $\rho = 3.1$ mm; yield strength, $\sigma_y =$ 1035 MPa; and $\rho_0 = 10$ mm (ref 3), the calculated lives for steel are shown in Table III. The measured lives for titanium are lower than those for steel by more than a factor of three for the high load tests.

---

[2] J. H. Underwood, J. A. Kapp, and M. D. Witherell, "Fracture Testing With Arc Bend Specimens," Fracture Mechanics: Seventeenth Volume, ASTM STP 905, (J. H. Underwood, et al., eds.), American Society for Testing and Materials, Philadelphia, 1986, pp. 279-296.

[3] J. H. Underwood, "Fatigue Life Analysis and Tensile Overload Effects With High Strength Steel Notched Specimens," High Pressure in Science and Technology, Part II, Elsevier, New York, 1984, pp. 209-214.

TABLE III. FATIGUE LIVES OF NOTCHED BEND SPECIMENS OF TITANIUM COMPARED WITH CALCULATED LIVES OF STEEL

Tests with $\Delta K = 48$ MPa $m^{1/2}$ $P_{max} = 24.5$ kN; $P_{min} = 2.45$ kN						Tests with $\Delta K = 33$ MPa $m^{1/2}$ $P_{max} = 16.9$ kN; $P_{min} = 1.69$ kN			
	N	N_m	N_{sd}	N_{steel}		N	N_m	N_{sd}	N_{steel}
#1	20,500	18,600	2,000	61,000	#5	71,000	112,000	52,000	163,000
#2	19,900				#6	63,700			
#3	18,700				#7	193,300			
#4	15,400				#8	122,000			

Plasma Spray and HIP Process Tests

Tables IV and V and Figure 3 outline the tests and results related to the effects of the aluminum plasma spray and HIP processes on the strength properties of steel. Table IV gives the temperature versus time cycle which was used as a nominal HIP cycle to be applied to longitudinal tensile specimens of steel.

TABLE IV. TEMPERATURE VERSUS TIME CYCLE APPLIED TO STEEL TENSILE SPECIMENS

Elapsed Time Minutes	Temperature °C	Elapsed Time Minutes	Temperature °C
0	370	130	620
15	460	160	620
30	520	175	605
45	530	190	595
60	560	205	505
75	580	220	460
90	595	235	425
105	605	250	395

TABLE V. EFFECT OF ELEVATED TEMPERATURE AND PLASMA-SPRAYED ALUMINUM ON THE STRENGTH OF STEEL

Temperature Cycle	Maximum Temperature °C	Plasma Spray -	Specimen Number -	0.1% Yield Strength MPa	Ultimate Strength MPa
None	-	None	1	1104	1221
			2	1111	1228
			3	1104	1235
			Mean	1106	1228
			Std. Dev.	3	6
Table IV	620°	None	4	1076	1194
			5	1056	1159
			6	1056	1166
			Mean	1063	1173
			Std. Dev.	9	15
None	-	Yes	7	1090	1228
			8	1179	1242
			Mean	1135	1235
Table IV	620°	Yes	9	1179	1228
			10	1125	1228
			Mean	1152	1228
Similar to Table IV	565°	None	11	1104	1221
			12	1111	1214
			Mean	1108	1218

This cycle was applied to two of the specimen groups listed in Table V and a modification of the cycle (lower maximum temperature) was applied to another specimen group. Plasma spraying by an outside contractor (AVCO) was performed on two of the specimen groups. It should be noted in Figure 3 that the adherence of the plasma-sprayed aluminum layer to the steel tensile specimen was generally poor. Note the separation in Figure 3.

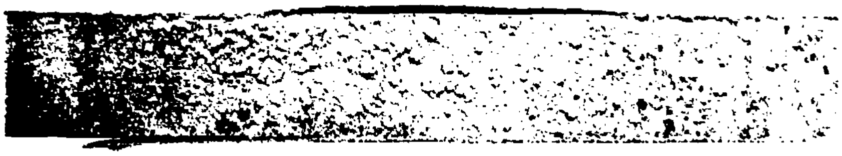

Figure 3. Photograph of plasma-sprayed steel tensile specimen (3X).

Yield and ultimate tensile strengths are listed in Table V for the various test conditions, with standard deviations shown for the two cases with three repeat tests. The most important result is the significantly lower yield and intimate strengths, 4 and 5 percent respectively, of specimens 4 through 6 compared with specimens 1 through 3. Considering that the largest standard deviation in these two groups of data is only about 1 percent, this loss in strength due to the temperature cycle is significant. No other significant effects on strength, due to the test conditions, are readily apparent.

SUMMARY

The one significant difference in mechanical properties noted in these tests is an increase in the fracture toughness of the titanium ingot #2 over that of ingot #1. However, the increase in toughness will not eliminate the possibility of fast, unstable fracture of titanium jackets due to overpressurization or the presence of notches or defects.

The notched fatigue life of titanium is less than that of steel for the same strength level and other test conditions. The poorer fatigue behavior of titanium becomes more noticeable at higher load levels.

A 620°C (1150°F) temperature cycle used, to simulate a HIP cycle, causes a 5 percent decrease in strength of 1100 MPa yield steel. The decrease is believed to be due to a retempering effect on the steel.

REFERENCES

1. J. H. Underwood, R. R. Fujczak, and R. G. Hasenbein, "Elastic, Strength, and Stress Relaxation Properties of A723 Steel and 38644 Titanium for Pressure Vessel Applications," Proceedings of 1986 Army Symposium on Solid Mechanics, US Military Academy, 7-9 October 1986.
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3. J. H. Underwood, "Fatigue Life Analysis and Tensile Overload Effects With High Strength Steel Notched Specimens," High Pressure in Science and Technology, Part II, Elsevier, New York, 1984, pp. 209-214.

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