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Metals, Ceramics,
and Materials

MASTER

PENETRATION TESTS (U)

W. T. Carey

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UNION CARBIDE CORPORATION
NUCLEAR DIVISION
OAK RIDGE Y-12 PLANT

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Nuclear Division

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W. T. Carey

Oak Ridge, Tennessee

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ABSTRACT

A test has been developed to evaluate the ability of materials to resist penetration by a small-diameter penetrator. The test was developed for use in evaluating high-strength materials. The test results and limitations of the test are presented in this report.

CONTENTS

INTRODUCTION	5
SUMMARY	6
PENETRATION TESTS	7
Equipment and Procedure	7
Material Penetration	10
PENETRATION TEST DATA	13
Sample Criteria	13
Test Results	13
CONCLUSIONS	18

INTRODUCTION

In the course of a development study at Y-12, it was necessary to perform some tests on certain metal samples in order to evaluate their ability to resist penetration. The test consisted of punching a small hole through these samples which ranged in thickness from 0.20 to 0.025 inch.

It was decided to use a commercial explosive-actuated gun to drive commercial fasteners through the samples. This report describes the penetration test, presents the test data, and discusses the limitations of the test and the data. The application of these data to the evaluation of sample materials for their ultimate use is outside the scope of this report.

SUMMARY

A test has been developed to evaluate the ability of materials to resist penetration. The tests are simple and can be quickly made using commercial equipment. However, with the present commercial equipment, the test results are indicative of the resistance to penetration of only relatively thin samples.

The test consisted of using an explosive-actuated gun to drive fasteners through metal samples. For samples pierced by the penetrator, the results indicate that the relative absorbed energy is higher for the stronger materials tested. It also appears that the relative energy is independent of the specimen thickness.

PENETRATION TESTS

EQUIPMENT AND PROCEDURE

The penetration test was conducted using a HILTI^(a) Model DX-100L rapid-fastener gun to drive either a screw (HILTI E-836-DX) or a nail (HILTI NK-30-DK) through a sample and into a stack of 1/8-inch-thick, Type 1100 aluminum sheets. The test setup is illustrated in Figure 1; the driver gun, its actuating hammer, and the penetrators are shown in Figure 2.

Figure 1. PENETRATOR TEST SETUP.

(a) HILTI, Incorporated, 360 Fairfield Avenue, Stamford, Connecticut.

Figure 2. MODEL DX-100L GUN WITH ACTUATING HAMMER AND PENETRATORS.

The nail and screw, which are illustrated in Figure 3, are 0.145 inch in diameter and 1 and 1/2 inches long, respectively. They are made of tool steel hardened to R_c 54. Figure 4 is a magnification of a micro-hardness test taken on a sectioned penetrator.

Figure 3. NAIL AND SCREW PENETRATORS BEFORE DRIVING.

The gun is actuated by a hammer blow which ignites an explosive cap containing a propellant such as gun powder. Three powers of caps are available: "strong" (HILTI 150), "medium" (HILTI 120), and "light" (HILTI 75). The expanding gas drives the plunger which in turn drives the penetrator. A practice operation of this driver indicated that the energy delivered was uniform within each cap size. Since the point of the penetrator was resting on the surface of the sample, the action of the gun was much like a hammer blow.

Figure 4. MICRO-HARDNESS TEST OF A SECTIONED PENETRATOR (10X)

The test was based upon two calibration penetrations: the first drove a penetrator with each cap size into a stack of Type 1100 aluminum sheets; the second drove a penetrator with each cap size into a 1/2-inch-thick, Type SAE-1020, hot-rolled steel plate. The results of these calibration penetrations are reported in Table 1. The steel plate with the three calibration penetrators in it is shown in the foreground of Figure 5: the "strong" cap sample on the left (through the plate and contacting on the washer), the "medium" cap sample on the right, and the "light" cap sample to the rear. In the background are the three aluminum calibration penetration samples: the "strong" cap sample on the left (the washer tight on the top—the two extra 1/8-inch plates represent assumed additional penetration if the penetrator had not been stopped), the "medium" cap sample in the center, and the "light" cap sample on the right.

Table 1
PENETRATION TEST CALIBRATION

Cap Size	Aluminum Samples		Steel Samples	
	Penetration ⁽¹⁾ (inches)	Displaced Energy ⁽²⁾ (in lbs)	Penetration ⁽¹⁾ (inches)	Displaced Energy ⁽³⁾ (in lbs)
Strong	1 1/8 ⁽⁴⁾	180	7/16 ⁽⁵⁾	210
Medium	7/8	140	1/4	170
Light	1/2	80	3/16	90

(1) A 0.145-inch-diameter nail.

(2) Assumed average yield strength - 10,000 psi.

(3) Assumed average yield strength - 40,000 psi.

(4) Estimated because the nail head and washer contacted the top of the aluminum, stopping the penetration.

(5) Penetrator went through the sample and into the aluminum but was stopped by the washer.

Figure 5. ALUMINUM AND STEEL TEST SAMPLES.

MATERIAL PENETRATION

The penetrator was stopped in each case by: (1) the energy required to displace the sample metal, (2) the friction to move the penetrator past the displaced sample metal, (3) the energy required to distort the penetrator, and (4) by the compaction of the washer if it contacted the surface of the sample. The energy required to displace the metal can be estimated by multiplying the approximate volume of the metal displaced by the yield stress for the sample metal. The displaced metal can be readily estimated; the yield stresses are assumed to be 10,000 psi for aluminum and 40,000 psi for steel. The calculated energies for these calibration tests are also listed in Table 1. This energy is proportional to the penetration. The friction effect probably increased more than proportionally to the penetration but is not readily calculable. The penetrator either pierced the samples with very little

distortion or it failed to enter because it shattered or collapsed. When the washer contacted the sample, the driving piston was stopped and the energy absorbed could only be estimated from the appearance. The steel and aluminum calibration tests gave better agreement than expected. For these simple tests, therefore, only the displacement energy was used to give a numerical calculation to the penetration of each sample. Knowing the size of the cap used and the amount of aluminum penetrated after passing through the sample, the amount of displacement energy absorbed during this test can be calculated using Figure 6.

Figure 6. ENERGY ABSORBED BASED UPON THE THICKNESS OF THE ALUMINUM PENETRATED.

To obtain the basic property of the metal in a sample somewhat independent of its thickness, a relative energy was calculated by multiplying the sample energy by the factor necessary to make the product sample thickness times the factor equal one inch (eg, for a 0.20-inch thickness, the factor is 5). This factor has been plotted so that the relative energy can be obtained from Figure 7 using the sample thickness and absorbed energy for any specific test.

Figure 7. RELATIVE ENERGY AS A FUNCTION OF THE SAMPLE ENERGY AND THICKNESS.

PENETRATION TEST DATA

SAMPLE CRITERIA

The materials in Table 2 were supplied for the penetration tests on the basis of a prior evaluation of their properties and in terms of their ultimate application. The samples were two inches in diameter with as-heat-treated surfaces. (The samples were heat treated to give a tough, high-strength structure.) The materials tested

Table 2

SAMPLES FOR PENETRATION

Type of Steel	Approximate Heat Treatment	Sample Thickness (inch)			
		0.20	0.10	0.05	0.025
4340	1100° F Temper	4 ⁽¹⁾	4	4	4
4340	1000° F Temper	4	4	4	4
4340	800° F Temper	4	4	4	4
S-2	800° F Temper	4	4	4	4
18% Maraging	250 ksi 900° F	4	4	4	4

(1) Number of samples. All samples were not tested.

were Type AISI-SAE-4340 steel hardened and tempered at 1100, 1000, and 800° F; Type S-2 tool steel^(b) hardened and tempered to R_c 60/62; and 18% maraging steel (250 ksi) hardened at 900° C. The approximate strengths of these materials are given in Table 3 and the approximate compositions are given in Table 4.

Table 3

APPROXIMATE TENSILE STRENGTH OF THE SAMPLE MATERIAL

Type of Steel Sample	Hardness (R _c)	Strength (psi)
4340 (1100° F)	34	160,000
4340 (1000° F)	37	175,000
4340 (800° F)	43	210,000
S-2	60	> 300,000
18% Maraging	50	250,000

TEST RESULTS

The penetration results for the test samples are listed in Table 5. The codes for interpreting the data in this table are listed in Table 6; the relative energies of these

(b) Vanango Special, Universal-Cyclops Steel Corporation.

Table 4
CHEMICAL COMPOSITION OF THE SAMPLE MATERIALS
(All Values in Weight Percent)

Type S-2 Steel		
Carbon	0.68	Molybdenum 0.55
Manganese	0.55	Sulfur and Phosphorus - Low
Silicon	1.15	Remainder - Iron
Vanadium	0.2	
Type AISI-SAE 4340 Steel		
Carbon	0.38 - 0.43	Molybdenum 0.20 - 0.30
Manganese	0.60 - 0.80	Sulfur 0.025 (max)
Nickel	1.65 - 2.00	Silicon 0.20 - 0.35
Chromium	0.70 - 0.90	Phosphorus 0.025 (max)
18% Maraging Steel (250 ksi)		
Carbon	0.03 (max)	Molybdenum 4.6 - 5.10
Titanium	0.3 - 0.5	Boron 0.000 - 0.003
Aluminum	0.05 - 0.15	Silicon 0.05 (max)
Nickel	17 - 19	Sulfur 0.01 (max)
Cobalt	7.0 - 8.5	Phosphorus 0.01 (max)

materials are listed in Table 7 in decreasing order of strength. It appears that above 200,000 psi strength, the relative energy absorbed is constant; below 200,000 psi, it decreases with the strength. Figure 8 shows typical samples that have been pierced by the penetrator; Figure 9 indicates that the relative energy appears to be independent of the specimen thickness.

Figure 8. SAMPLES WHICH THE PENETRATOR PIERCED.

When the specimens were over a minimum thickness, the penetrator shattered or bent rather than pierced the sample (Figure 10). These samples are listed as "no test" (NT) and cannot be used in calculating the test data.

Table 5
PENETRATION TEST DATA
(See Table 6 for Code Meanings)

Test Number	Test Specimen			Penetration Test			Absorbed Energy of Sample (in lbs)	
	Type of Steel	Heat Treatment (° F)	Thickness (inch)	Cap Strength	Penetrator	Results	Total	Relative
1	4340	110C	0.20	S	Nail	Nail Buckled	NT	-
2			0.20	S	Screw	Screw Started and Buckled	NT	-
3			0.10	S	Screw	5/16" Al Penetrated	125	1250
4			0.10	M	Nail	Nail Buckled	NT	-
5			0.05	M	Nail	9/16" Al Penetrated	50	1000
6			0.05	L	Nail	1/8" Al Penetrated	60	1200
7			0.05	M	Nail	1/2" Al Penetrated	60	1200
8			0.025	L	Nail	5/16" Al Penetrated	30	1200
9	4340	100C	0.20	S	Screw	Screw Buckled	NT	-
10			0.10	S	Screw	Screw Buckled	NT	-
11			0.10	S	Screw	Screw Buckled	NT	-
12			0.10	M	Screw	Penetrated and Buckled	NT	-
13			0.10	S	Screw	Screw Buckled	NT	-
14			0.05	L	Nail	3/16" Al Penetrated	50	1000
15			0.05	M	Nail	5/16" Al Penetrated	90	1800
16			0.05	S	Nail	3/4" Al Penetrated	60	1200
17			0.025	L	Nail	5/16" Al Penetrated	30	1200
18			0.025	M	Nail	5/8" Al Penetrated	40	1600
19	4340	80C	0.10	S	Screw	Screw Shattered	NT	-
20			0.10	S	Screw	Screw Buckled	NT	-
21			0.05	M	Nail	3/8" Al Penetrated	120	2400
22			0.025	L	Nail	3/16" Al Penetrated	50	2000
23	S-2	-	0.10	S	Screw	Screw Shattered	NT	-
24			0.05	M	Nail	Nail Shattered	NT	-
25			0.05	M	Screw	1/8" Al Penetrated	120	2400
26			0.025	M	Nail	1/2" Al Penetrated	60	2400
27			0.025	L	Nail	3/16" Al Penetrated	50	2000
28	Maraging (250 ksi)	90C	0.10	S	Screw	Screw Shattered	NT	-
29			0.05	M	Nail	Nail Shattered	NT	-
30			0.05	M	Screw	1/8" Al Penetrated	120	2400
31			0.025	L	Nail	3/16" Al Penetrated	50	2000

Table 6
CODE FOR DATA IN TABLE 5

<u>Caps (for HILTI Penetrator Gun, DX 100-L)</u>			
S for Strong - HILTI 150			
M for Medium - HILTI 120			
L for Light - HILTI 75			
<u>Penetrator (for HILTI Penetrator Gun DX 100-L)</u>			
Nail - 0.145" D x 1" L (HILTI NK-30-DX)			
Screw - 0.145" D x 1/2" L (HILTI E-836-DX)			
<u>Materials</u>			
"4340" for AISI-SAE 4340			
"S-2" for oil hardening steel			
"Maraging" for 18" maraging steel (250 ksi)			
<u>Heat Treatment</u>			
1100, 1000, and 800° F tempering temperature			
250 for 250,000 UTS, ~ 900° F			
<u>Results</u>			
"Shattered" - Point collapsed under the blow			
"Buckled" - Column failure in bending or shearing			
"9/16" Al Penetration" etc - The length of penetration through the sample			
<u>Total Energy Absorbed</u>			
Energy absorbed by the sample based on Figure 6			
NT means the test was not effective (no test)			
<u>Relative Energy</u>			
Energy absorbed by the same material if it were one-inch thick (Figure 7)			

Table 7
RELATIVE ENERGY ABSORBED BY THE SAMPLE MATERIAL

Type of Steel	Heat Treatment (° F)	Ultimate Tensile Strength (psi)	Average Energy Absorbed (in lbs)
S-2	-	> 300,000	2200
Maraging (250 ksi)	900	250,000	2300
4340	800	210,000	2200
4340	1000	175,000	1400
4340	1100	160,000	1200

Figure 9. RELATIVE ENERGY PER SAMPLE THICKNESS AND MATERIAL.

Figure 10. SAMPLES WHICH THE PENETRATOR FAILED TO PIERCE.

CONCLUSIONS

The penetration tests described are simple and can be quickly made using commercial equipment and little operator skill. However, with the present commercial penetrators, the test results are indicative of the resistance to penetration of only relatively thin samples. The test could be improved to give more meaningful information by making stronger penetrators. A material study indicates that small improvements in punch strength could be expected. The effect of multiple blows, in starting the hole with a short punch continuing with a smaller, longer punch, could be investigated.

Where the penetrator pierced the sample of the materials tested, the relative absorbed energy was higher for the stronger materials. Although the samples were hard enough to be considered brittle, they were all pierced with the displaced material being moved uniformly away from the penetrator leaving only a small lip.

The thicker the specimen the greater the absorbed energy required to pierce it. It appears that it will be extremely difficult to pierce a small hole in samples of the three strongest of these materials if they are 0.100 inch or thicker.

While not demonstrated per se as part of these tests, it would be difficult to punch a small, neat hole in these samples if they were not firmly supported or if the penetrator angle were not perpendicular to the sample surface. The unsupported sample would bend inward and absorb much of the energy; a long, thin penetrator would buckle. If the penetrator angle were not reasonably square with the surface, the penetrator point would be deflected and would shatter or bend.

The diameter of the penetrator could be increased with respect to the sample thickness, and sufficient energy could be used to drive the penetrator through the sample, but the result would be a battering blow that would punch out a large hole and inject metal into the opposite surface backing up the sample plate.