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Ballistic Performance and Adiabatic Shear Behavior of AerMet® 100 Steel

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13. ABSTRACT *(Maximum 200 words)*

Results from our experiments indicate that AerMet® 100 Steel is very well suited for applications which require both load-bearing capability and ballistic tolerance. For applications where ballistic tolerance is the primary design criterion, we demonstrate that an alternate heat treatment of AerMet® 100 can produce markedly improved ballistic performance while retaining adequate toughness for use in less demanding structural applications. Our findings also indicate that as hardness is increased, concomitant increases in fracture toughness will be required to advance the performance capabilities of steels used for ballistic applications against small caliber projectiles.

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Background

The most desired property for an armor material is high hardness, because hardness is the only measurable mechanical property which consistently correlates well with ballistic performance. Increased hardness levels, however, can result in plate shattering. Thus, for structural components which require ballistic tolerance, the material used must also possess adequate fracture toughness.

For many years, the Army has used low and medium carbon alloy steels for applications on ground vehicles and helicopters which require ballistic tolerance. A component is said to be ballistically tolerant when it can continue to perform its function even after sustaining impacts from kinetic energy penetrators (bullets and fragments). Quenched and tempered (Q&T) grades such as AISI 4340 steel can be heat treated to ultrahigh strength levels while retaining toughness adequate for use in ballistically tolerant components.

To achieve improved ballistic performance requires increasing the hardness of quenched and tempered steels. Since maximum hardness is a function of carbon content, the only way to increase hardness would be to move to a higher carbon alloy steel. Although increasing carbon content will produce a higher hardness steel, fracture toughness diminishes and ballistic tests reveal a greater propensity towards plate shattering beyond carbon levels of approximately 0.40 to 0.50 weight percent (wt%). It is unlikely, therefore, that we can achieve significant improvements in the ballistic performance of Q&T steels. Rather, we must turn our attention to other grades of steel.

One possibility which has received only limited attention is the use of secondary hardening steels such as HY-180, AF1410, and AerMet®* 100. These secondary hardening steels derive their incremental hardness from precipitated carbides in a fine martensitic lath microstructure. The hardness of some precipitation hardening grades is increased further through addition of more nickel and cobalt for solid solution strengthening. Cobalt also provides recovery resistance and raises the martensite start (M_s) temperature of iron based alloys, permitting the addition of more nickel (that lowers the M_s temperature). Nickel also improves cleavage resistance, thus enhancing fracture toughness.

Speich researched the physical metallurgy of HY-180 Steel and established that strength and toughness of these steels could be simultaneously increased through dissolution of M_3C carbides and the precipitation of M_2C carbides.[1] This research laid the foundation for the development of AF1410 in the mid seventies and AerMet 100 in the late eighties.

* AerMet is a registered trademark of Carpenter Technology Corporation

Table 1 provides information on the chemistry and typical mechanical properties for HY-180, AF1410, and AerMet 100. When processed using the standard heat treatment, the hardness of AerMet 100 is equivalent to that of 4340 with a typical fracture toughness of more than twice that of 4340.[2] Since the standard heat treatment for AerMet 100 is not the peak hardened condition but rather an overaged condition, it should be possible to alter the heat treatment to increase hardness while retaining adequate fracture toughness for use as an armor material. For our purposes, "adequate" fracture toughness means equal to or greater than 50 ksi$\sqrt{in.}$--the average toughness of 4340 used for ballistic applications. The oportunity to increase hardness without greatly compromising fracture toughness is the reason we chose AerMet 100 for use in this study.

Table 1. Properties of three precipitation hardening steels

Steel	HY 180	AF 1410	AerMet 100
US Patent Number	3,502,462	4,076,525	5,087,415
Patent Issue Date	March 24, 1970	February 28, 1978	February 11, 1992
Fracture Toughness (ksi$\sqrt{in.}$) typical	185	150	120
Hardness (HRC) typical	43	49	53
Ultimate Tensile Strength (ksi) typical	205	250	290

Experimental Approach

Our objective was to determine if alternative processing could be used to improve the ballistic performance of AerMet 100. The approach was to develop processing curves showing hardness as a function of solution treatment temperatures and ageing temperatures. The intent was to optimize hardness, since it generally correlates with ballistic performance. In addition, resistance to shear localization was also measured. Earlier work on VAR 4340 steel has shown the relationship of shear localization behavior to armor performance (for thin plates of high strength steel), and the dependance of hardness and shear localization on the fine scale microstructure.[3] This approach provides the opportunity to study the influence of small scale microstructural features on ballistic performance and the underlying deformation mechanisms.

Material Processing

The Materials Directorate of the U.S. Army Research Laboratory (ARL•MD) purchased the AerMet 100 alloy (bar stock and plates) used for this study from

Carpenter Technology Corporation (CarTec).[4] CarTec supplied ARL•MD with material from Heat Number 89557 (see Tables 2, 3, and 4). The alloy was double vacuum melted, first as a 24-in. diameter vacuum induction melted (VIM) electrode, second as a 30-in. diameter vacuum arc remelted (VAR) ingot. Prior to VAR, electrodes were stress relieved at 1250°F for four to 16 hours and air cooled. After VAR, the material was homogenized at 2150°F for six to ten hours. The ingot was bloomed to a cross section of 5 in. by 50 in. and the plate was cross-rolled to final thickness. After rolling, CarTec overage-annealed the plates at 1250°F for 16 hours to a hardness of 39 Rockwell C (HRC). Samples measuring 12 inch square were then cut from the plates.

Table 2. Chemical analysis of Heat 89557 by weight percent

C	0.24	P	0.003	Al	0.009
Co	13.4	S	0.001	O	< 0.001
Ni	11.07	Mn	0.01	N	< 0.001
Cr	3.09	Si	0.01	P + S	0.004
Mo	1.17	Ti	0.012		

Table 3. AerMet 100 chemistry requirements from AMS Specification 6532

C	0.21 - 0.25	P (max)	0.008	Al (max)	0.015
Co	13 - 14	S (max)	0.005	O	< 0.002
Ni	11 - 12	Mn (max)	0.1	N	< 0.015
Cr	2.9 - 3.3	Si (max)	0.1	P + S (max)	0.01
Mo	1.1 - 1.3	Ti (max)	0.015		

Table 4. Manufacturer's certified properties for Heat 89557

Yield Strength (0.20%)	253 ksi
Tensile Strength	276 ksi
Elongation	13% in 2 inches
Hardness	52 HRC

Development of Ageing Curves

Novotny detailed heat treatment of the alloy over a very broad range of solution treatments and ageing temperatures.[5] Novotny's study focused on ageing times of one, three, five and eight hours at various temperatures after a solution treatment temperature of 1625°F. These data provided us with important background information for our study.

Our objective was to determine the maximum hardness capability of AerMet 100 and then proceed to determine the alloy's ballistic and mechanical properties when peak hardened. First, we developed data for Rockwell C hardness as a function of solution treatment temperature. This data provided the one hour solution treatment temperature which produced the maximum as-cooled hardness. Next, we determined the ageing response for two ageing temperatures at times ranging from one minute to sixteen hours. Whereas Novotny's study dealt with a broad range of solution treatment temperatures and tended to favor examination of overaged microstructures this study focused on a more detailed study of a narrower range of time-temperature combinations for the explicit purpose of optimizing the best combination of hardness, fracture toughness, and ballistic performance.

For our solution treatment and ageing treatment studies, we sectioned pieces measuring approximately one half inch cubed from the bar stock which measured five inches wide by two inches thick by eighteen inches long. The orientation of each cube relative to the parent stock was marked on each face. The specimens used for the solution treatment study were all heat treated in air for one hour at temperature and air cooled. Upon arrival at room temperature, the specimens were cut in half using a Buehler Isocut Plus cutoff saw equipped with a type 11-4207 blade rotating at 3500 rpm under an applied load of 250 grams with circulating coolant. After sectioning, the outside face opposite the cut face was ground to remove decarburization and scale. Rockwell C measurements were then taken on the cut face of each specimen. At least eight measurements were taken on each specimen. The resulting averaged data is presented in Figure 1.

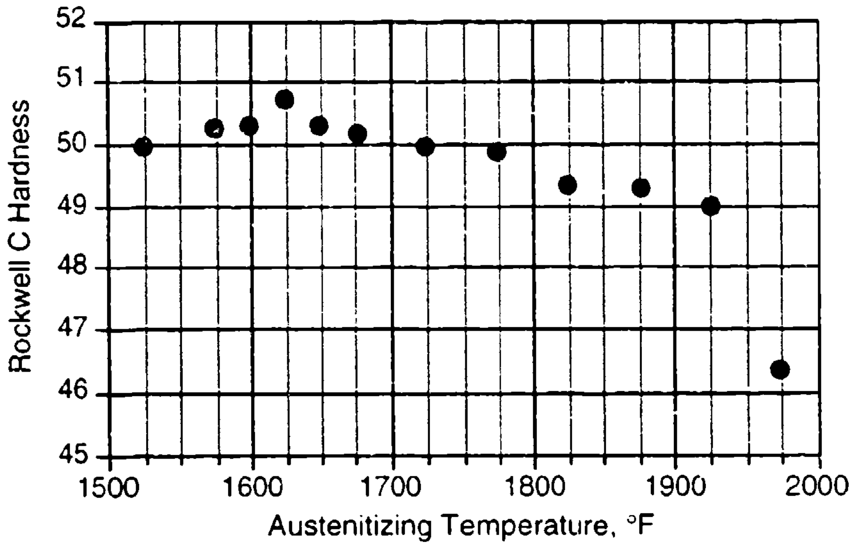

Figure 1. Effect of solution treatment temperature on the as-cooled hardness of AerMet 100.

Based upon these solution treatment results, we selected a solution treatment temperature of 1625°F for use throughout the remainder of this study. Carpenter Technology recommends this temperature for solution treatment of AerMet 100 and it is also the solution temperature used by Novotny.

Ageing temperatures of 900°F and 875°F were selected for use in our ageing study. Several factors influenced our selection of these two temperatures. At temperatures in excess of 900°F, the austenite content in the microstructure increases, leading to reduced hardness.[5] Below 875°F, the toughness of tne steel is adversely affected by the presence of significant M_3C in the microstructure. Although M_2C can precipitate below 875°F, the resultant kinetics do not allow the development of adequate toughness after a five hour age.

The same specimen preparation and measurement techniques used for the solution treatment study were also used for the ageing study. For ageing times less than 30 minutes, specimens were aged in molten lead to ensure proper control over ageing time. The typical temperature deviation in the lead pot was ±3°F. Specimens aged for 30 minutes and longer were heated in a conventional laboratory furnace with a maximum deviation of ±10°F. The surface temperature of each specimen was monitored with a thermocouple during ageing. The ageing curves are shown in Figure 2.

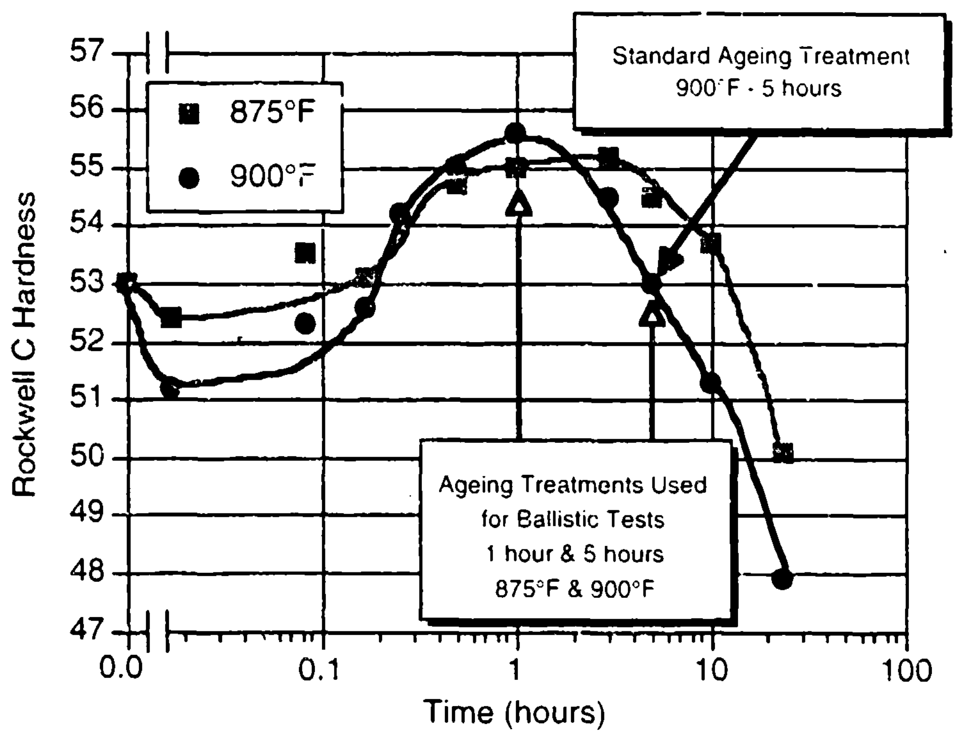

Figure 2. AerMet 100 ageing study.

Heat Treatment of Ballistic Plate

The ageing curves shown in Figure 2 was used to select heat treatments for the ballistic plate material. Since our objective was to produce the hardest material possible, we first selected a temperature of 900°F and time of one hour to produce a hardness of 55.5 to 56 HRC. At 875°F, it was not clear which time produced the peak aged (peak hardness) microstructure. We selected a time of one hour, which represents a condition of near peak aged. For comparison to other ballistic tests conducted on AerMet 100, we heat treated plates at 900°F for five hours (the standard heat treatment) and at 875°F for five hours (to produce a slightly overaged microstructure).[6] First, all of the plates were solution treated together at 1625°F for one hour at temperature in an L&L specialty furnace equipped with a recirculator using an argon blow-by atmosphere. Although it does not produce a completely neutral atmosphere, the argon blow-by minimizes scale and decarburization. Microhardness measurements on corner sections taken from each plate indicated that significant decarburization was limited to between 0.010 inch and 0.020 inch below the surface. Table 5 shows a summary of the treatments we selected, the average hardness measured on the surface of the plates, and the anticipated microstructure. The measured hardness values are somewhat lower than anticipated based on the data shown in Figure 2. These lower hardness values may have resulted from the surface preparation technique applied to the plates.

Table 5. Heat treatments selected for ballistic plate

Temperature (°F)	Time (hours)	Hardness (HRC)	Microstructure
900	5	52 - 53	overaged
900	1	55.5 - 56	peak aged
875	5	53	slightly overaged
875	1	54	slightly underaged

After heat treatment, the plates were ground on a Blanchard grinder using a 36 to 40 grit alumina wheel and a soluble oil coolant to remove the decarburized layer and scale that often influence the results of ballistic testing. First, the plates were ground to produce parallel surfaces to within 0.015 inch, and then further ground to remove at least 0.020 inch from the impact side to ensure complete removal of the decarburized layer. This surface preparation technique inherently produces machining marks on the plate surface.

<u>Shear Instability Tests</u>

Shear instability measurements were made on each microstructure selected for ballistic testing. Quasi-static tests using a double-linear shear specimen were performed to determine the shear instability strain, γ_i, which is defined as the maximum uniform strain achieved in shear before gross localization of the strain occurs. The sample design and test have been described in detail previously.[7,8]

The results from shear testing are shown in Figures 3 and 4. Figure 3 compares the different AerMet 100 microstructures (heat treatments, including the type of product--plate stock or extruded stock). Figure 4 compares the shear instability strain of AerMet 100 to a number of other high strength steels. While it is evident that AerMet 100 shows superior resistance to unstable shear compared to many high strength steels, these results demonstrate the sensitivity (0.4 to 1.6) of this alloy to the treatments studied.

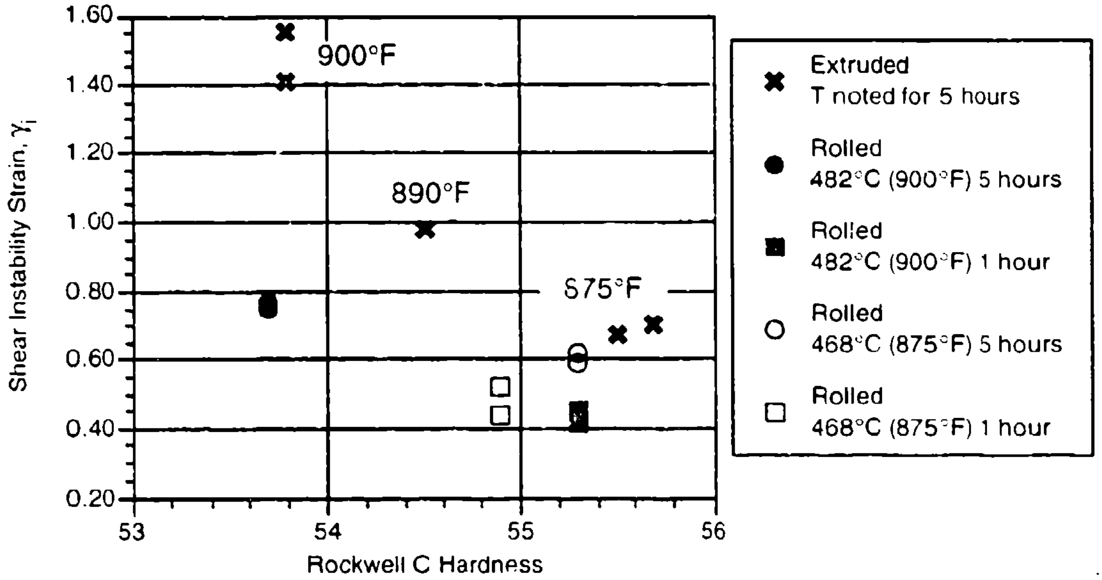

Figure 3. Shear instability strains for AerMet 100 for various ageing treatments.

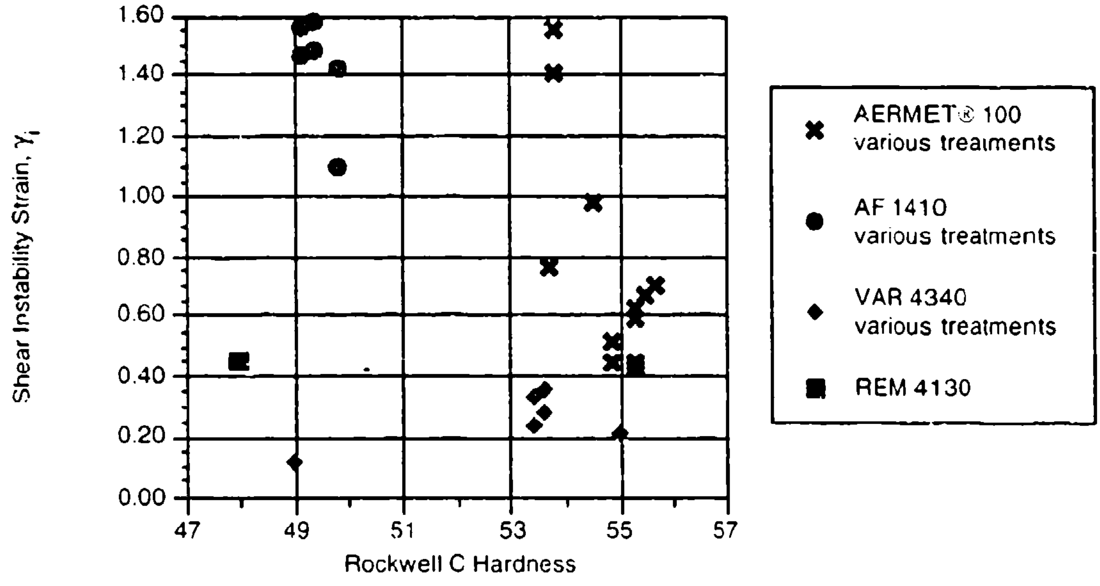

Figure 4. Comparison of shear instability strains for various high strength steels and AerMet 100.

Ballistic Tests

Ballistic tests were conducted in accordance with MIL-STD-662E, *V_{50} Ballistic Test for Armor.*[9] Two different small arms projectiles were selected for ballistic testing: the U.S. .30 caliber armor piercing (AP) M2 and the U.S. .50 caliber AP M2. The 12-inch square ballistic test plates were mounted to the test fixture by clamping each corner with a C clamp. The ballistic test fixture consists of a steel frame with an opening measuring 10 inches square. For the .50 caliber tests a Browning barrel was used; for the .30 caliber tests, a standard service barrel was used. For the .50 caliber tests, the barrel muzzle end was located approximately 20 feet from the target. Projectile velocity was determined using paper break screens spaced 10 feet apart and time counters which recorded the time lapse to the nearest microsecond. For the .30 caliber tests, the barrel muzzle end was located approximately 10 feet from the target. Projectile velocity was measured using paper break screens spaced two feet apart with the same timing mechanism used for the .50 caliber tests.

Ballistic Test Results

Results from tests of AerMet 100 versus the .30 caliber armor piercing M2 projectile are shown in Figure 5. The pair of numbers near each symbol indicate the number of test firings used to calculate the V_{50} Protection Ballistic Limit (PBL). For example, '5 & 5' means that velocities from five complete penetrations and five partial penetrations were used to calculate the V_{50} These data show that plates heat treated at peak and near peak hardness have a V_{50} PBL approximately 400 feet per second (fps) greater than the plates processed using the standard heat treatment. All of the plates showed excellent multiple hit capability. In two cases, more than 25 rounds were fired at a single target. Photographs of the front and rear face of each plate are shown in the Appendix.

Results for AerMet 100 versus the .50 caliber armor piercing M2 projectile are shown in Figure 6. During these tests, two of the peak aged plates showed a tendency to crack during ballistic impact. These cracks typically emanated on or near the impact hole and were coincident with machining marks on the surface of the plate.

Although some of the peak hardened plates were found to have higher V_{50} velocities than the 900°F five hour age baseline plates, the increase was not as dramatic as found for the .30 caliber threat. For all but the 900°F one hour plate which shattered, the increase was usually within the scatter accepted for a V_{50} PBL Test--approximately 100 fps.

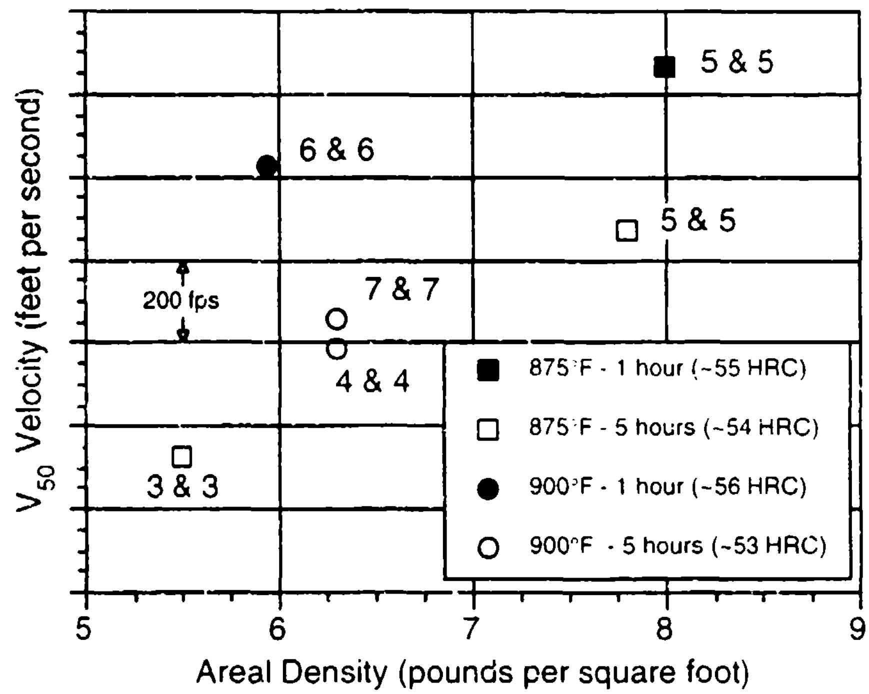

Figure 5. Results of .30 caliber AP M2 Ballistic Tests of AerMet 100.

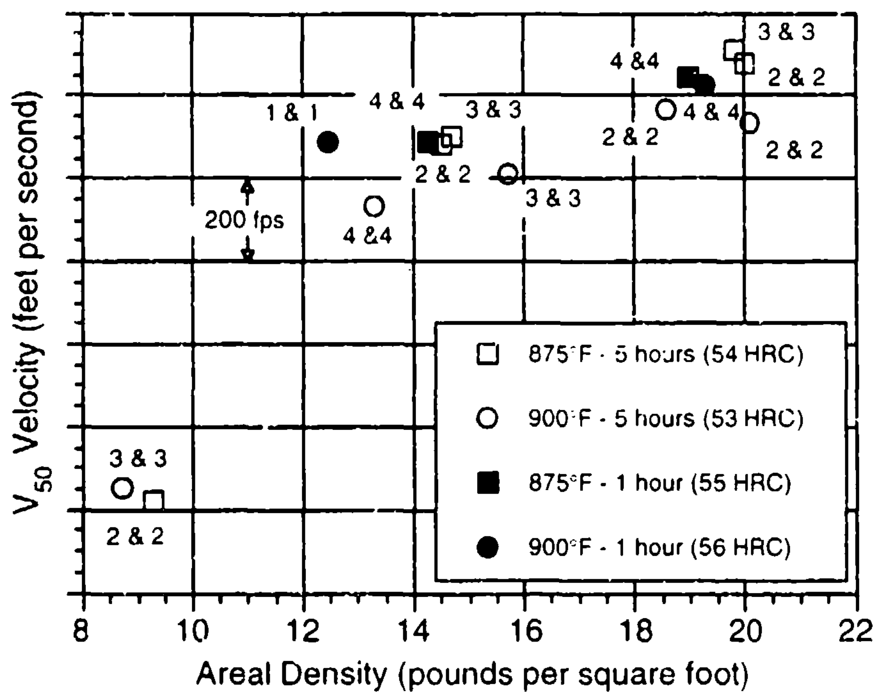

Figure 6. Results of .50 caliber AP M2 Ballistic Tests of AerMet 100.

Short-Range Order Experiments

Schmidt and Gore reported that post ageing treatments applied to AF1410 steel produced a hardness increase of over 20 Diamond Pyramid Hardness (DPH).[10] They attributed the observed behavior to possible short-range ordering. If short-range ordering is indeed responsible for the increased hardness, we also expect to see a corresponding increase in tensile properties.

To determine if AerMet 100 displayed similar behavior, we conducted a post-age tre tment at 700°F to determine any variations in both hardness and mechanical property data as a function of time. Prior to the post-age treatment, all specimens were heat treated using the standard practice of 1625°F, one hour, air cool; -100°F, one hour, air warm; 900°F, five hours, air cool. The results of those experiments are graphed in Figure 7. Although an increase in Vickers Hardness (DPH) of between 20 and 40 points was observed, tensile properties showed no dramatic influence from the post-age treatment. Rockwell C Hardness (HRC) measurements (not shown) were also taken and showed no discernible change in hardness level as a function of ageing time. Because the DPH test is much finer in scale than the HRC test, the variation in DPH measurements are more likely related to local microstructural differences.

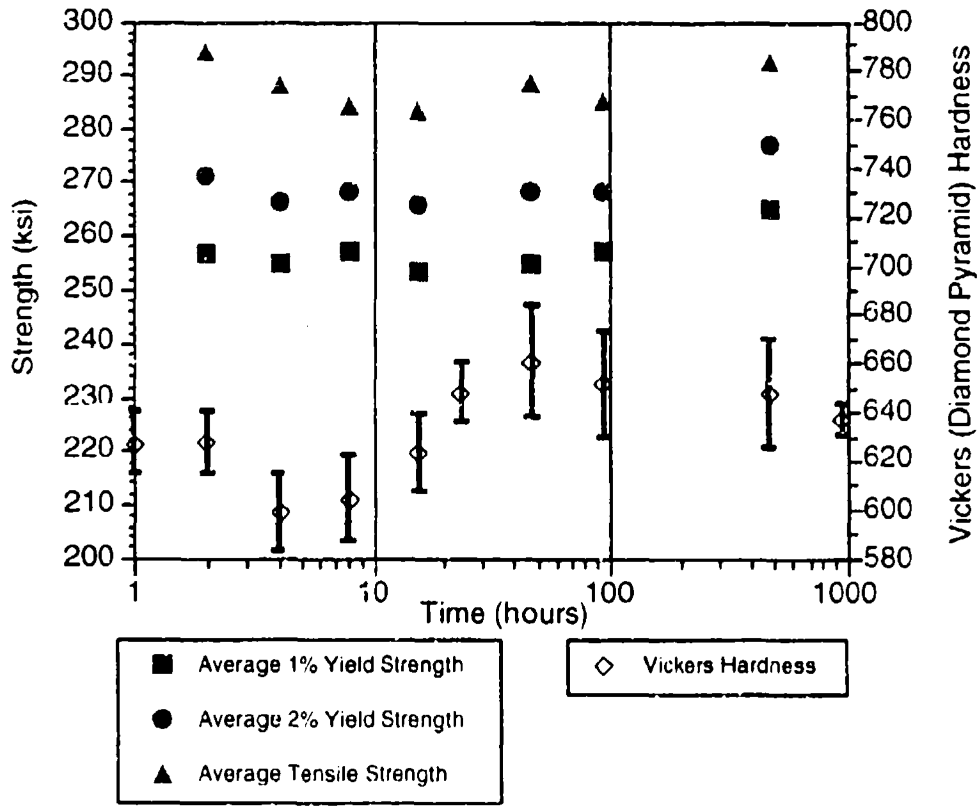

Figure 7. Hardness and strength as a function of ageing time for a two step ageing treatment.

Discussion

The use of alternative heat treatments to increase the hardness of AerMet 100 provided exceptional results for one of the two small arms projectiles used for this study. The difference in performance of the same material against these two different threats will be the topic of future study. It may be that the thinner plates tested versus the .30 caliber threat were probably in a different stress state than the thicker plates tested versus the .50 caliber threat during the ballistic impact event.

From a microstructural standpoint, elimination of M_3C carbides while precipitating M_2C carbides in this class of armor steel is preferred. The former reduce toughness and tend to promote brittle fracture, while the latter have the dual benefit of improving strength by impeding dislocation flow and increasing toughness through better interfacial cohesion with the matrix. These microstructural features are important to ballistic performance because they determine--in part--the tendency of the plate to fail by brittle fracture and its resistance to localized adiabatic shear.

The improved shear resistance of these secondary hardening steels (compared to that of quenched and tempered steels of the same hardness) is the key factor in providing improved ballistics at equivalent hardnesses. This improvement is achieved by delaying the onset of adiabatic shear bands, which play an important role in initiating the plugging mechanism of armor failure. The interaction of the fine scale microstructure (M_3C and M_2C precipitates in this case) with shear localization phenomena is not yet fully understood. Cowie demonstrated that the carbide-size/carbide-separation-distance ratio was the controlling factor at quasi-static strain rates in VAR 4340 steel.[11] However, at higher strain rates the same relationship does not hold, though the carbides still play an important role.[12] The unusually high instability strains measured for the extruded AerMet 100 show promise for obtaining even better ballisitc performance through processing and microstructural control.

The ballistic performance of AerMet 100 heat treated to achieve different microstructures provides valuable knowledge for use in future efforts to design high performance armor steels for specialized applications. Even if combinations of hardness greater than 55 HRC with toughness greater than 50 ksi$\sqrt{in.}$ can be achieved, special care must be taken to ensure that the microstructure is contributing as much hardness as possible without introducing undesireable effects such as brittle fracture.

Although the peak hardened condition of AerMet 100 is not the optimum microstructure for toughness limited applications, it has mechanical properties at least as good as 4340 steel and superior ballistic performance against one of the small arms projectiles. Our future efforts should be directed at producing a slightly overaged microstructure with optimized hardness. To this end, ARL•MD funded an effort with Northwestern University to design an armor steel which possesses both the desired mechanical properties and a microstructure of overaged M_2C carbides.[13] Ballistic tests of the new armor steel are scheduled for the Fall of 1993.

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Specimen Machining & Preparation - Leonard Bucciarelli
Photographs - Jeffrey Loughlin

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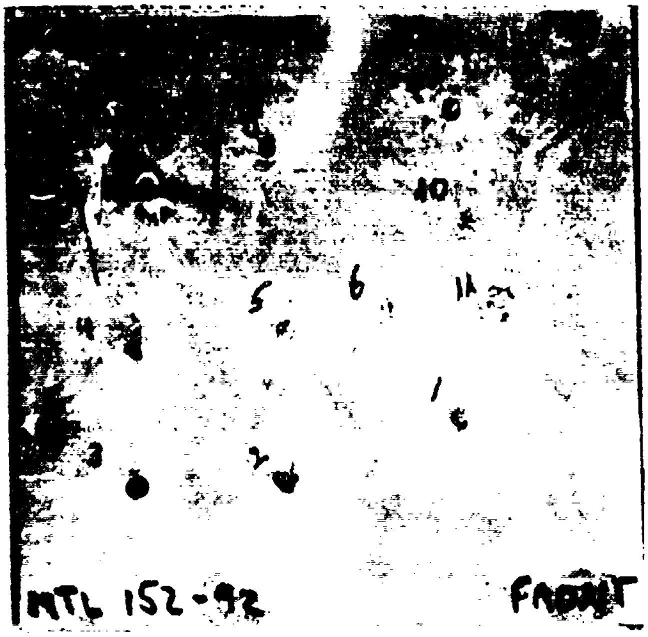
Appendix

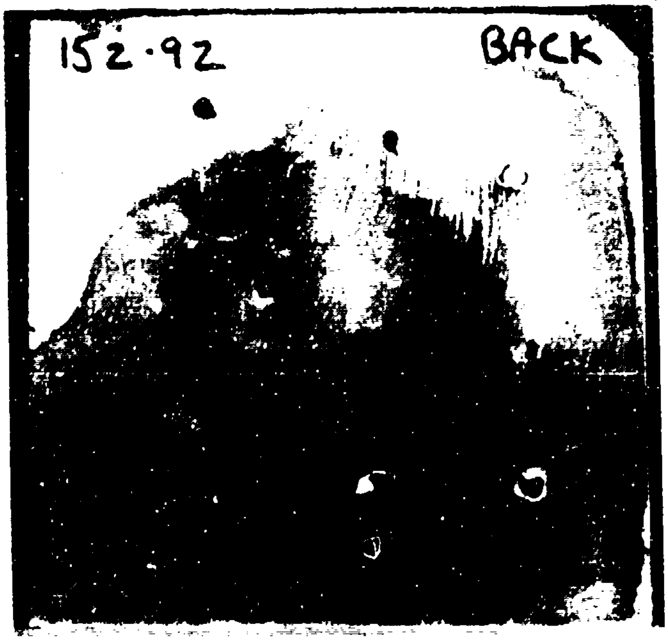
ARL•MD Ballistic Test Number 151-92. Front Side.
0.156 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile.
(Austenitized @ 1625°F, 1 hour, oil quench;-100°F, 1 hour, air warm; Aged @ 875°F, 5 hours air cool.)

ARL•MD Ballistic Test Number 151-92. Back Side.
0.156 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile.
(Austenitized @ 1625°F, 1 hour, oil quench;-100°F, 1 hour, air warm; Aged @ 875°F, 5 hours air cool.)

Appendix

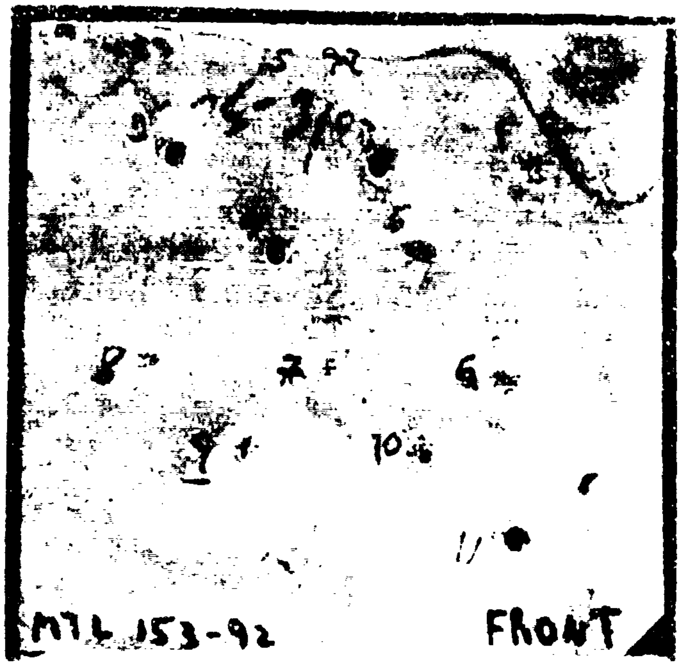


ARL•MD Ballistic Test Number 152-92. Front Side.
0.230 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile.
(Austenitized @ 1625°F, 1 hour, oil quench; -100°F 1 hour, air warm; Aged @ 900°F 5 hours, air cool.)



ARL•MD Ballistic Test Number 152-92. Back Side.
0.230 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile.
(Austenitized @ 1625°F, 1 hour, oil quench; -100°F, 1 hour, air warm; Aged @ 900°F 5 hours, air cool.)

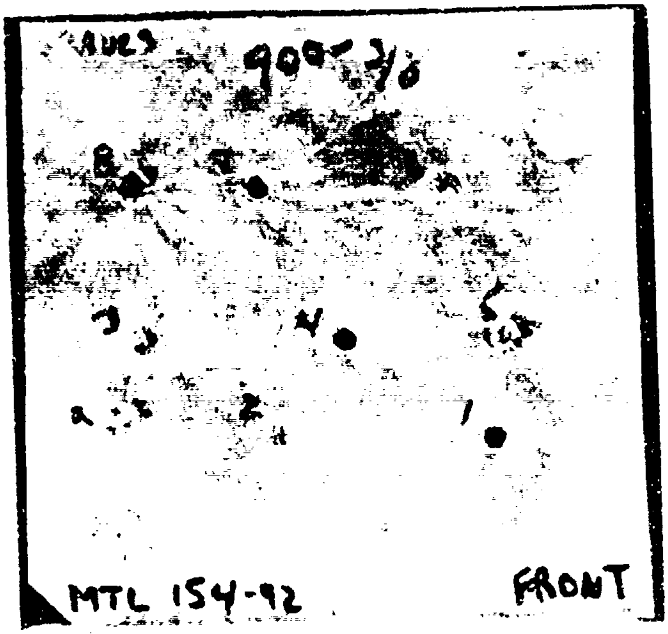
Appendix



ARL•MD Ballistic Test Number 153-92. Front Side.
0.350 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile.
(Austenitized @ 1625°F. 1 hour, oil quench; -100°F. 1 hour, air warm; Aged @ 875°F. 5 hours, air cool.)

ARL•MD Ballistic Test Number 153-92. Back Side.
0.350 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile.
(Austenitized @ 1625°F. 1 hour, oil quench; -100°F. 1 hour, air warm; Aged @ 875°F. 5 hours, air cool.)

Appendix A



ARL•MD Ballistic Test Number 154-92. Front Side.
0.375 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile
(Austenitized @ 1625°F, 1 hour, oil quench; -100°F, 1 hour, air warm; Aged @ 900°F 5 hours air cool.)

ARL•MD Ballistic Test Number 154-92. Back Side.
0.375 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile.
(Austenitized @ 1625°F, 1 hour, oil quench; -100°F, 1 hour, air warm; Aged @ 900°F, 5 hours, air cool.)

Appendix

ARL•MD Ballistic Test Number 155-92. Front Side
0.483 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile
(Austenitized @ 1625°F. 1 hour. oil quench. -100°F 1 hour. air warm: Aged @ 875°F 5 hours air cool.)

ARL•MD Ballistic Test Number 155-92. Back Side.
0.483 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile.
(Austenitized @ 1625°F. 1 hour. oil quench: -100°F. 1 hour. air warm. Aged @ 875 F 5 hours air cool.)

Appendix

ARL•MD Ballistic Test Number 156-92. Front Side.
0.488 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile
(Austenitized @ 1625°F 1 hour, oil quench; -100°F, 1 hour, air warm; Aged @ 900°F 5 hours air cool)

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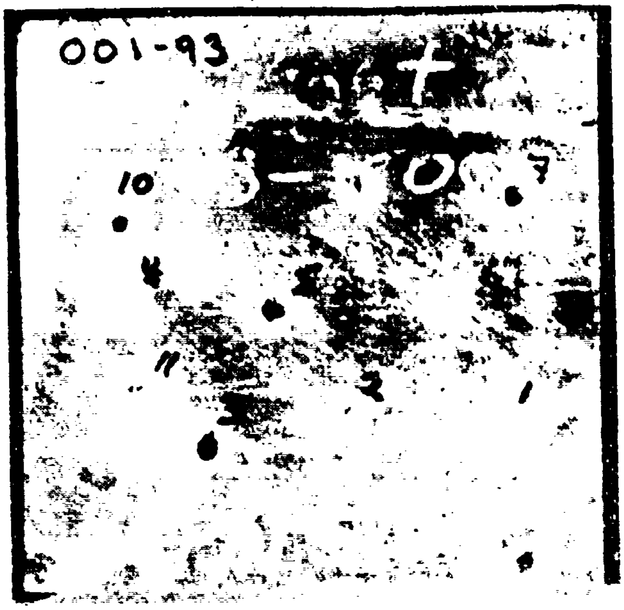
0.488 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile.
(Austenitized @ 1625°F, 1 hour, oil quench; -100°F, 1 hour, air warm; Aged @ 900°F 5 hours air cool)

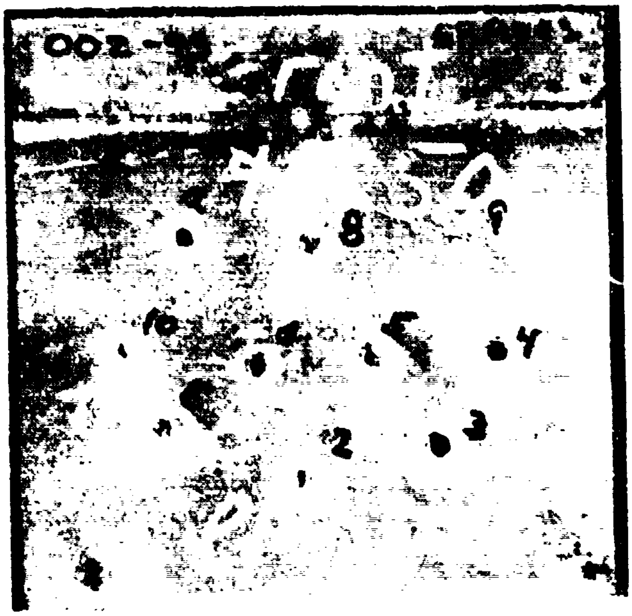
Appendix



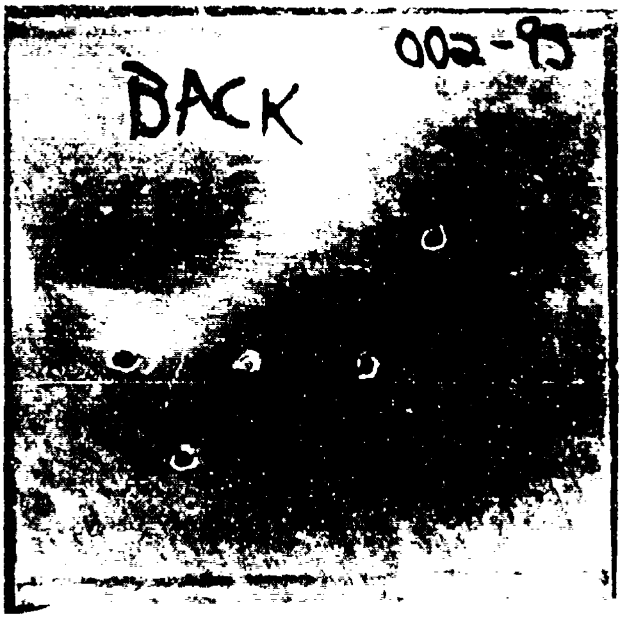
ARL•MD Ballistic Test Number 001-93. Front Side.
0.453 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile
(Austenitized @ 1625°F, 1 hour, air cool; -100°F, 1 hour, air warm; Aged @ 900°F 5 hours, air cool.)

ARL•MD Ballistic Test Number 001-93. Back Side.
0.453 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile.
(Austenitized @ 1625°F, 1 hour, air cool; -100°F, 1 hour, air warm; Aged @ 900°F 5 hours, air cool.)

Appendix

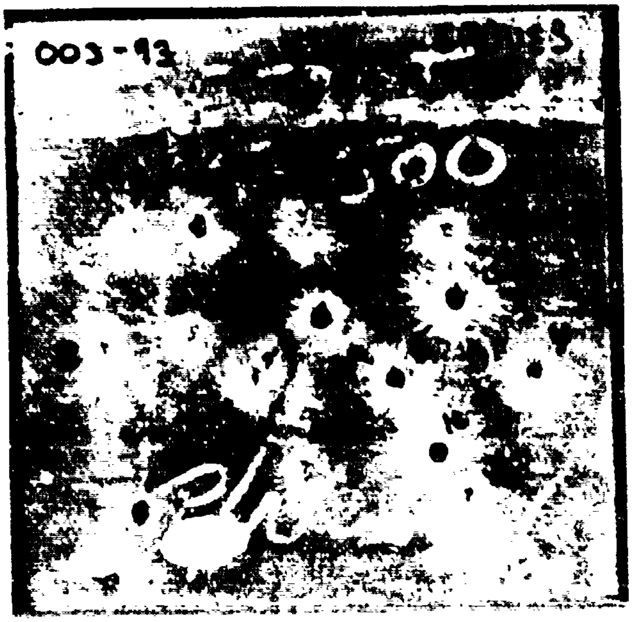


ARL•MD Ballistic Test Number 002-93. Front Side
0.481 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile
(Austenitized @ 1625°F, 1 hour, air cool, -100°F 1 hour, air warm, Aged @ 875°F 5 hours air cool)

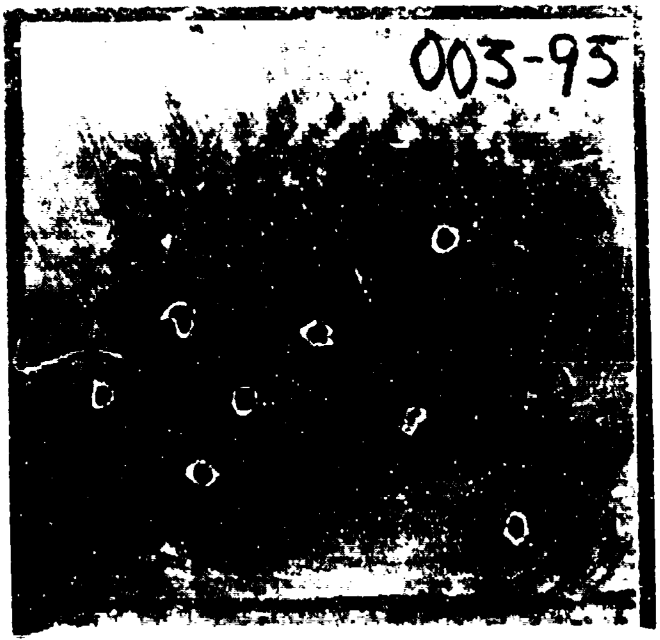


ARL•MD Ballistic Test Number 002-93. Back Side.
0.481 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile
(Austenitized @ 1625°F, 1 hour, air cool, -100°F, 1 hour air warm; Aged @ 875°F 5 hours air cool)

Appendix

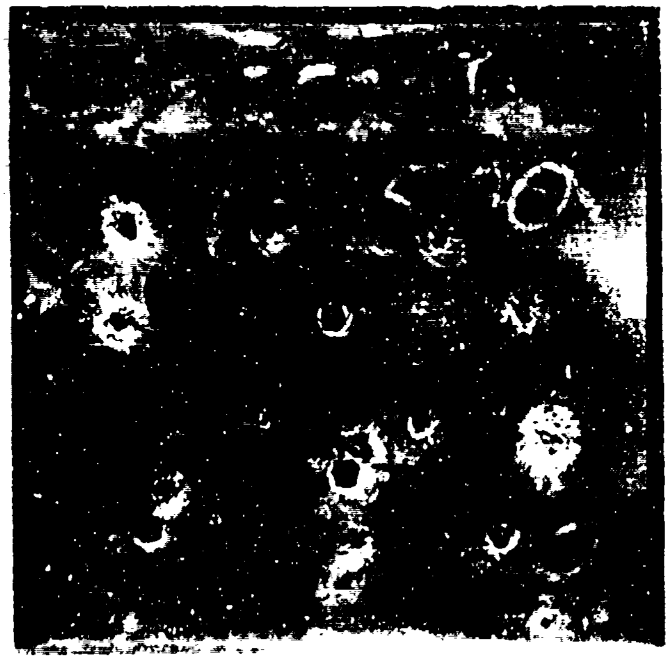


ARL•MD Ballistic Test Number 003-93. Front Side
0.470 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile.
(Austenitized @ 1625°F, 1 hour, air cool; -100°F, 1 hour, air warm. Aged @ 900°F, 1 hour, air cool.)

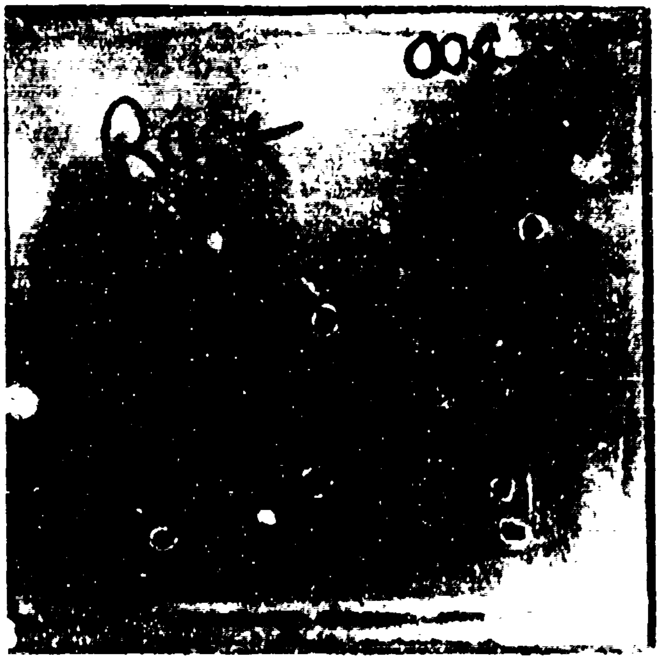


ARL•MD Ballistic Test Number 003-93. Back Side.
0.470 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile.
(Austenitized @ 1625°F, 1 hour, air cool, -100°F, 1 hour, air warm. Aged @ 900°F, 1 hour, air cool.)

Appendix



ARL•MD Ballistic Test Number 004-93. Front Side.
0.467 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile
(Austenitized @ 1625°F, 1 hour, air cool, -100°F, 1 hour, air warm; Aged @ 875°F 1 hour air cool.)



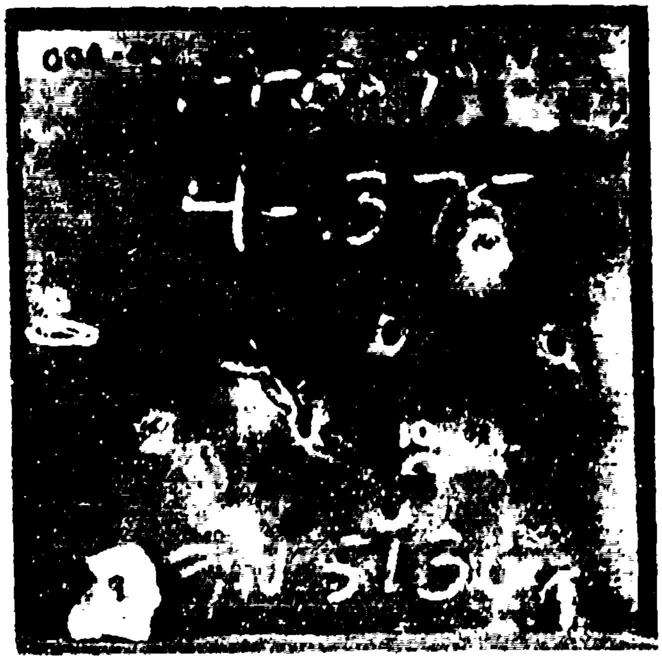
ARL•MD Ballistic Test Number 004-93. Back Side.
0.467 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile.
(Austenitized @ 1625°F, 1 hour, air cool; -100°F, 1 hour, air warm, Aged @ 875°F 1 hour air cool.)

Appendix

ARL•MD Ballistic Test Number 005-93. Front Side.
0.330 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile
(Austenitized @ 1625°F, 1 hour, air cool; -100°F, 1 hour, air warm; Aged @ 900°F 5 hours, air cool.)

ARL•MD Ballistic Test Number 005-93. Back Side
0.330 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile
(Austenitized @ 1625°F, 1 hour, air cool; -100°F, 1 hour, air warm; Aged @ 900°F 5 hours, air cool.)

Appendix



ARL•MD Ballistic Test Number 006-93. Front Side
0.364 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile
(Austenitized @ 1625°F, 1 hour, air cool; -100°F, 1 hour, air warm; Aged @ 875°F 5 hours air cool.)

ARL•MD Ballistic Test Number 006-93. Back Side.
0.364 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile.
(Austenitized @ 1625°F, 1 hour, air cool; 100°F, 1 hour, air warm; Aged @ 875°F, 5 hours air cool.)

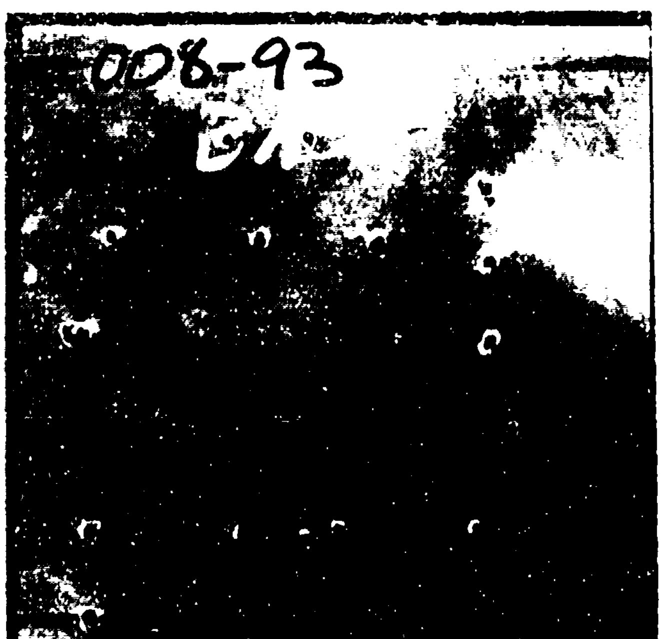
Appendix

ARL•MD Ballistic Test Number 007-93. Front Side.
0.309 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile
(Austenitized @ 1625°F, 1 hour, air cool; -100°F, 1 hour air warm; Aged @ 900°F 1 hour air cool.)

ARL•MD Ballistic Test Number 007-93. Back Side.
0.309 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile.
(Austenitized @ 1625°F, 1 hour, air cool; -100°F, 1 hour, air warm; Aged @ 900°F, 1 hour air cool.)

Appendix

ARL•MD Ballistic Test Number 008-93. Front Side.
0.156 inch thick AerMet 100™ Steel versus U.S. 0.30 caliber AP M2 projectile.
(Austenitized @ 1625°F, 1 hour, air cool; -100°F, 1 hour, air warm; Aged @ 900°F 5 hours, air cool.)



ARL•MD Ballistic Test Number 008-93. Back Side.
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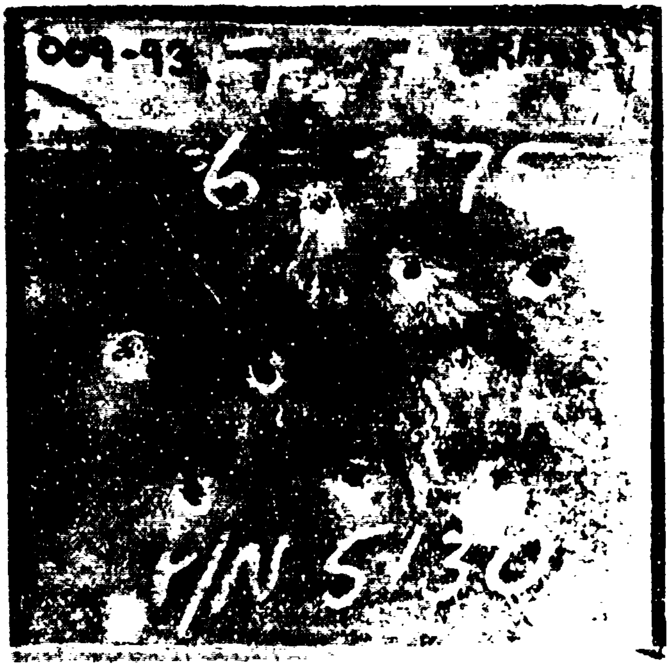
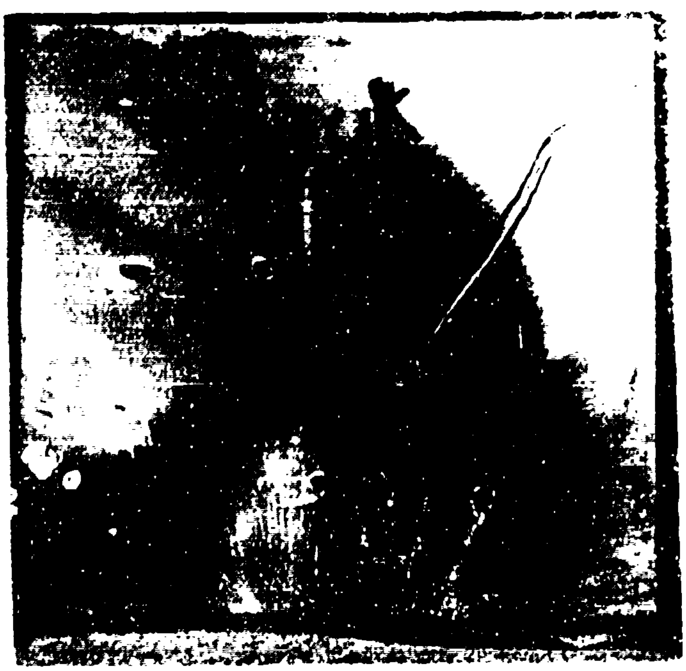
(Austenitized @ 1625°F, 1 hour, air cool; -100°F, 1 hour, air warm; Aged @ 900°F 5 hours, air cool.)

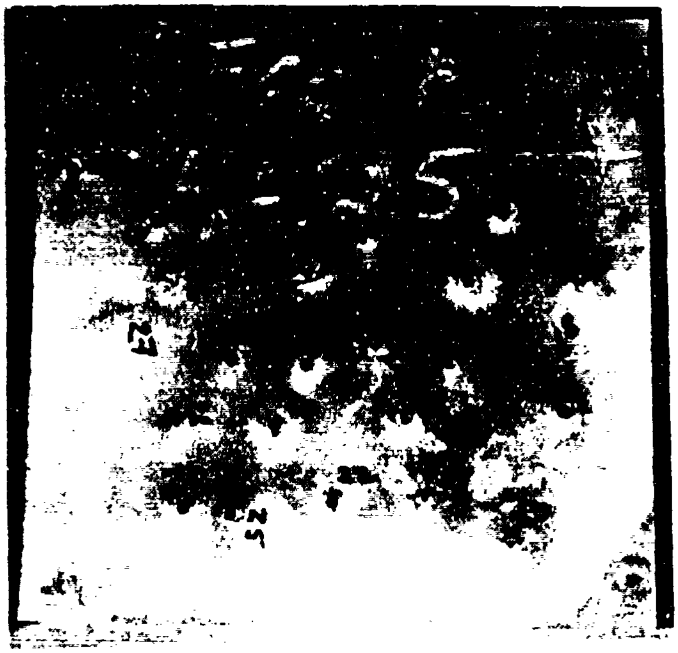


ARL•MD Ballistic Test Number 009-93. Front Side.
0.355 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile.
(Austenitized @ 1625°F, 1 hour, air cool; -100°F, 1 hour, air warm; Aged @ 875°F, 1 hour, air cool.)



ARL•MD Ballistic Test Number 009-93. Back Side.
0.355 inch thick AerMet 100™ Steel versus U.S. 0.50 caliber AP M2 projectile.
(Austenitized @ 1625°F, 1 hour, air cool; -100°F, 1 hour, air warm; Aged @ 875°F, 1 hour, air cool.)

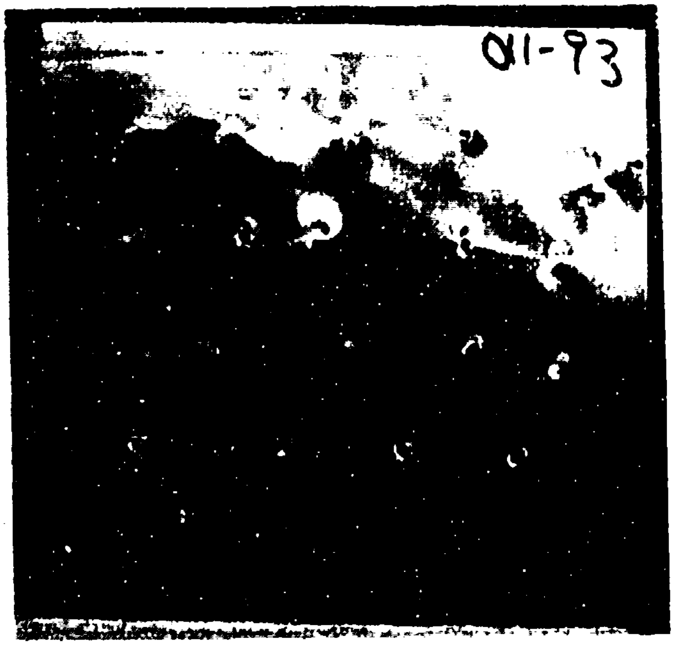
Appendix



ARL•MD Ballistic Test Number 010-93. Front Side.
0.135 inch thick AerMet 100™ Steel versus U.S. 0.30 caliber AP M2 projectile
(Austenitized @ 1625°F, 1 hour, air cool; -100°F, 1 hour, air warm; Aged @ 875°F, 5 hours, air cool.)

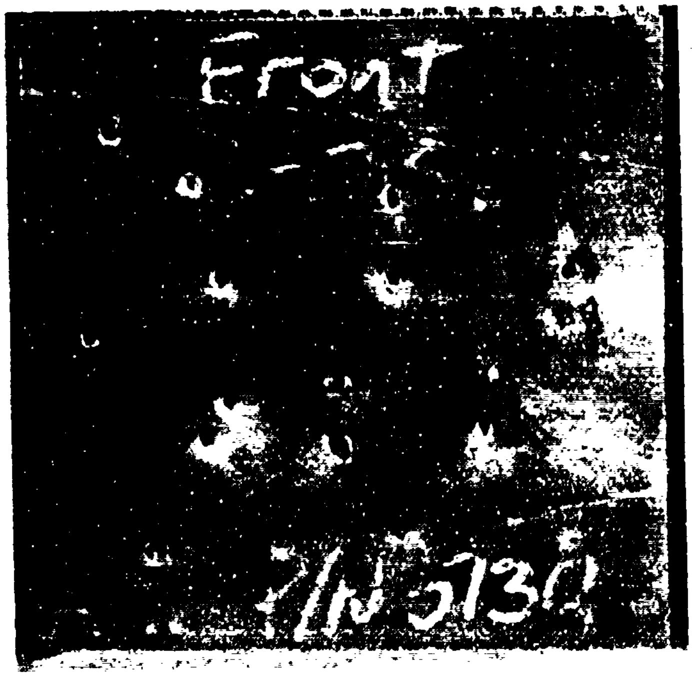
ARL•MD Ballistic Test Number 010-93. Back Side.
0.135 inch thick AerMet 100™ Steel versus U.S. 0.30 caliber AP M2 projectile
(Austenitized @ 1625°F, 1 hour, air cool; -100°F, 1 hour, air warm; Aged @ 875°F, 5 hours, air cool.)

ARL•MD Ballistic Test Number 011-93. Front Side.
0.146 inch thick AerMet 100™ Steel versus U.S. 0.30 caliber AP M2 projectile
(Austenitized @ 1625°F 1 hour, air cool; -100°F, 1 hour, air warm; Aged @ 900°F, 1 hour air cool.)



ARL•MD Ballistic Test Number 011-93. Back Side.
0.146 inch thick AerMet 100™ Steel versus U.S. 0.30 caliber AP M2 projectile.
(Austenitized @ 1625°F, 1 hour, air cool; -100°F, 1 hour, air warm; Aged @ 900°F, 1 hour, air cool.)

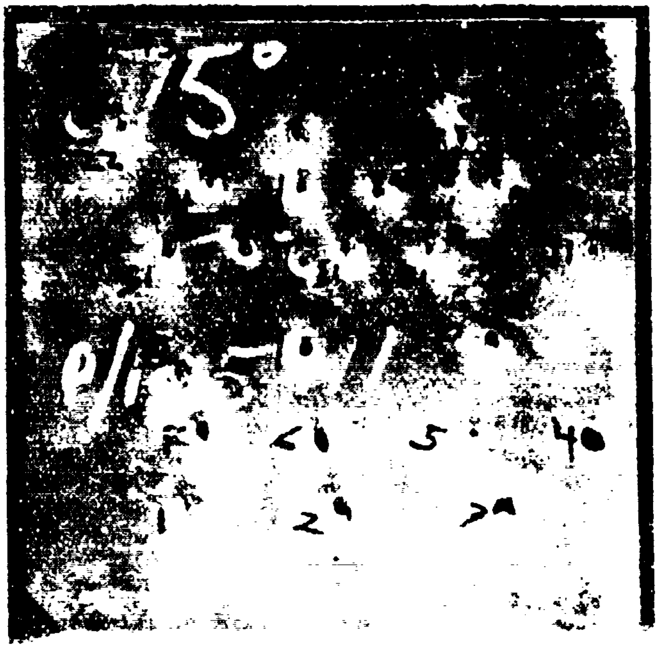
Appendix



ARL•MD Ballistic Test Number 012-93. Front Side.
0.197 inch thick AerMet 100™ Steel versus U.S. 0.30 caliber AP M2 projectile.
(Austenitized @ 1625°F, 1 hour, air cool; -100°F, 1 hour, air warm; Aged @ 875°F 1 hour air cool.)

ARL•MD Ballistic Test Number 012-93. Back Side.
0.197 inch thick AerMet 100™ Steel versus U.S. 0.30 caliber AP M2 projectile.
(Austenitized @ 1625°F, 1 hour, air cool; -100°F, 1 hour, air warm; Aged @ 875°F, 1 hour air cool.)

Appendix



ARL•MD Ballistic Test Number 013-93. Front Side.
0.191 inch thick AerMet 100™ Steel versus U.S. 0.30 caliber AP M2 projectile
(Austenitized @ 1625°F, 1 hour, air cool; -100°F, 1 hour, air warm; Aged @ 875 F 5 hours air cool.)

ARL•MD Ballistic Test Number 013-93. Back Side.
0.191 inch thick AerMet 100™ Steel versus U.S. 0.30 caliber AP M2 projectile.
(Austenitized @ 1625°F, 1 hour, air cool; -100°F, 1 hour, air warm; Aged @ 875°F, 5 hours air cool.)

Appendix

ARL•MD Ballistic Test Number 014-93. Front Side.
0.155 inch thick AerMet 100™ Steel versus U.S. 0.30 caliber AP M2 projectile.
(Austenitized @ 1625°F. 1 hour, air cool; -100°F. 1 hour, air warm; Aged @ 900°F. 5 hours, air cool.)

ARL•MD Ballistic Test Number 014-93. Back Side.
0.155 inch thick AerMet 100™ Steel versus U.S. 0.30 caliber AP M2 projectile.
(Austenitized @ 1625°F. 1 hour, air cool; -100°F. 1 hour, air warm; Aged @ 900°F. 5 hours, air cool.)

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