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Induction Heat Treatment - Phase I - Technology to Produce Monolithic Gradient Hardness Steel Armor

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13. ABSTRACT *(Maximum 200 words)*

This report details the results of Phase I of the Dual Hard Steel Armor Program funded by the PM, Survivability, U.S. Army Tank-Automotive Command (TACOM). This report investigates the use of an induction heat-treating process to produce a gradient hardness monolithic steel armor to complement MIL-A-46099, Armor Plate, Steel, Rolled-Bonded, Dual-Hardness, for thicknesses of approximately 0.5 in.

Results of this investigation indicate that a conventionally heat-treated steel armor plate (tempered to a hardness range of Rc 42-52; induction-hardened to approximately Rc 60 and induction tempered to approximately Rc 50 with a high hardness thickness of approximately 40%) will provide acceptable ballistic results when compared to the ballistic requirements of MIL-A-46099. Future efforts (Phase II) will include optimization of the composition, hardness levels, and thickness gradients. Production-size plates will also be processed to ensure that the technology can be transitioned from the laboratory to production.

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1. OBJECTIVE

The objective of the Induction Heat Treatment Program is to improve the current technology of processing metallic armor materials by using induction heat-treating equipment. Phase I of the program is to produce monolithic gradient hardness armor steel using the induction heat-treating process to complement MIL-A-46099[1] (i.e., prove the principle that induction hardening and tempering can produce a monolithic gradient hard steel armor plate that can satisfy the ballistic requirement of MIL-A-46099).

Future efforts to complete the Induction Heat Treatment Program will have the following objectives: (1) Phase II of the Program will attempt to determine optimum alloy composition and hardness profiles in the 5/16- to 1-in thickness range that provide the highest ballistic performance while maintaining the plate's integrity with respect to armor piercing (AP) threats. Phase II will also extend the technology to production-size plates. (2) Phase III of the Program will investigate the development of ductile skins on ultrahard armor materials. (3) Phase IV will extend the technology to other materials, such as titanium.

Under a Cooperative Research and Development Agreement (CRDA), TOCCO, Inc,[2] will transfer the technology to industry. The potential of applicability in the civilian sector (commercial applications) is unlimited.

2. BACKGROUND

In 1989, the U.S. Army Research Laboratory/Materials Directorate (ARL/MD) (formerly Materials Technology Laboratory) purchased an Audio Frequency/Radio Frequency (AF/RF) Induction Unit from TOCCO, Inc., and modified in-house for selected use in developing improved armor steel plate. The research was aimed at developing procedures to obtain various hardness gradients within the steel armor monolithic structure. The equipment was installed (in Building 43), modified, and tested for proper operation during 1990. Research began shortly thereafter. However, with the announcement of the closure and the cleanup of the ARL/MD site (Watertown, MA), research stopped. Building 43 was one of the first buildings to be cleaned, so the Induction Unit was disconnected, crated, and stored in

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[1] Department of Defense. Armor Plate, Steel, Rolled-Bonded, Dual-Hardness. Military Specification MIL-A-46099, Revision C, 14 September 1987.

[2] Cooperative Research and Development Agreement (CRDA), Induction Heat Treatment of Steel Armor, between the U.S. Army Research Laboratory/Materials Directorate (ARL/MD) and TOCCO, Inc., May 1993.

Building 37. The expense of reassemble and hookup to an operating status was determined not to be cost effective in light of the remaining time ARL/MD would be operational at the Watertown site. In an effort to use the equipment between 1993 and 1997 (relocation date/new facility completed at the APG, MD) and to keep the equipment in working condition, a Cooperative Research and Development Agreement was established between ARL/MD and TOCCO, Inc. The equipment was crated and shipped to TOCCO, Inc. (Madison Heights, MI), on 31 May 1993.

The operational setup of the equipment at TOCCO, Inc., encountered delays due to component breakage in shipping and handling. Modification of various components of the equipment was also required. The equipment became operational through the combined efforts of TOCCO, Inc. personnel and Mr. Raymond A. Cellitti, President, R. C. Associates, Hinsdale, IL. Photographs of the equipment (at TOCCO, Inc.) are shown in Appendix A.

During this timeframe, Jessop Steel (producer of rolled bonded dual hard armor steel) was contacted for samples of dual hard material. This material was ballistically tested at ARL/MD and analyzed for hardness profiles (thickness of the individual rolled bonded plates and the hardness levels of each). The results are discussed in future sections of this report.

Prior induction heat treat processing work was performed at the U.S. Naval Ordnance Laboratory in White Oaks, MD. Two reports were generated from this work, namely, "Studies on a Steel Gradient Hardened Armor," D. Goldstein and W. J. Buehler, 30 July 1969, Report No. NOLTR 69-129; and "Scaling-Up Studies on Steel Gradient Hardened Armor - Part 1," D. Goldstein, 31 July 1970, Report No. NOLTR 70-106. A classified patent was filed on 1 July 1971 by D. Goldstein, Case No. 50346. Due to the changes in the Security Classification Guide, declassification of this patent is in progress.

3. INTRODUCTION

This is the first report documenting the results from using induction heat treatment to produce improved gradient hardened armor steel. The focus of this research effort is to investigate the feasibility of various methods to produce monolithic gradient hardness armor steel to complement MIL-A-46099.

Induction heating is an extremely versatile method for hardening steel. Uniform or localized surface hardening, through-hardening, and tempering of hardened plates may all be performed by induction heating. The heating of a steel plate is accomplished by placing the plate within a magnetic field generated by a high-frequency alternating current. The high-frequency current is carried in a water-cooled copper coil called an inductor. The rapidly alternating magnetic field established within the loop of the coil induces current (I) within the steel. The induced current then generates heat (H) according to the relationship, $H = I^2 * R$, where R is the electrical resistance of the steel. The depth of heating produced by induction is inversely related to the frequency of the alternating current. The higher the frequency the thinner, or more shallow, the heating. Therefore, surface hardening is achieved by high frequencies, while through-hardening is produced by using lower frequencies.

There are two methods that can be used to produce monolithic dual hardness gradient material. One is induction tempering and the other is induction rehardening. The induction tempering method will produce a plate in which the change of hardness from high to low will be more drastic than the induction rehardening method. When an induction tempering method is used, the tempering temperatures will affect the level of the hardness gradient of the back face (softer side). A tempering temperature of 925° F as compared to 425° F will produce a hardness profile that more closely represents the gradient in a standard rolled bonded dual hard armor steel.

It is anticipated that the successful completion of Phase I and Phase II will generate a material and process to complement conventional dual hard armor steels for use as an applique armor on light- to medium-weight military vehicles (high-mobility, multipurpose wheeled vehicle [HMMWV]; light assault vehicle [LAV]; Bradley class) as applique armor.

4. PROCEDURE

The following procedure was developed in this study:

<u>Phase I</u>

1. Obtain and characterize rolled bonded material from Jessop Steel Company (JSC).
2. Ballistically test the material.
3. Determine the problem areas of rolled bonded material.

4. Determine the thickness percentage of hard material vs. soft material in JSC-produced dual hard material.

5. Produce heats (at ARL/MD) with the same chemical composition.

6. Produce monolithic dual hard material using the induction heat-treating equipment (TOCCO).

7. Ballistically test the monolithic material.

8. Compare results.

9. Adjust parameters (chemical composition) and produce more ARL/MD in-house heats. Modify the procedures using the TOCCO Unit. Return to Step 7.

5. RESULTS/DISCUSSION

Dual hard steel armor plate from JSC was received and characterized. The hardness profiles were determined on six plates as a reference point for processing the monolithic plate (see Figures 1 and 2). The thickness of the hard side (~Rc 58) of the rolled bonded plate, not including the transition zone, ranged from 36 to 44% with an average and also a median of 40%. Plates from JSC (conventional rolled bonded material) were ballistically tested at ARL/MD with the 0.30-cal. AP M2 and 0.50-cal. AP M2 projectiles according to MIL-A-46099. The results are listed in Table 1. Table 1 also contains some ballistic data from the Heiss-IsenStaht (H-S) Ballistic Laboratory, Detroit, MI (Nongovernment range). Plates ballistically tested with the 0.30-cal. AP M2 projectile exhibited no outstanding problems. Problems, however, were encountered with those plates that were ballistically tested with the 0.50-cal. AP M2 projectile. Photographs (see Appendix B) were taken of the plates after they were shot. As can be seen from the pictures, three out of four plates that were tested at ARL/MD against the 0.50-cal. AP M2 projectile shattered. The plates delaminated between the hard and soft interface. This condition provides no multihit capability against the 0.50-cal. AP M2 threat. The armor plate thickness range for the 0.50-cal. AP M2 projectile per MIL-A-46099 is 0.3126–0.625 in. Delamination within this thickness range is the problem area that this study will be focused on.

In-house heats were produced for processing as listed in Table 2. Plates from heat 4353 were used to develop the best settings. Four trials were preformed.* Using the best trial, four plates were induction

* The processing parameters for producing the desired hardness gradient are intentionally left out of this report due to its proprietary significance to the U.S. Government.

tempered: two plates with a 725° F body temper and two plates with a 825° F body temper. The results of the ballistic testing (tested in accordance with MIL-A-46099) are listed in Tables 3 and 6.

A hardness profile thickness of approximately 40% was attempted. The hardness level was approximately Rc 55. Due to the lower-than-normal carbon content of this heat, the hardness level was limited. This heat was used only for trial and error in developing the required induction unit processing controls for developing monolithic armor plate with approximately the same characteristics of the rolled bonded material. Ballistically, the four plates did not meet the specification; however, the plates did not shatter as did the rolled bonded material against the 0.50-cal. AP M2 projectile. Photographs of the ballistically tested plates are shown in Appendix C. Multihit capability is evident.

The second heat to be processed was Z-62A first pour. Its carbon level was 0.56% (see Table 2 for the complete chemistry), and therefore, a higher hardness could be obtained. The first seven plates of the heat were induction tempered: two plates with a 425° F body temper, two plates with a 825° F body temper, and three plates with a 950° F body temper. The hardness profiles were varied for each plate and are plotted in Figures 3, 4, and 5. The results of the ballistic test are listed in Tables 4 and 6. Appendix D shows photographs of the ballistically tested plates. Multihit capability is again evident. The cracks on some of the plates were due to the holding fixture adding excessive stress to the plate. The ballistic test for plate No. 2B was terminated because complete penetrations as low as 2,660 ft/s were occurring. As can be seen from Figure 3, the hardness profile is suspect.

Table 6 indicates that an armor plate with approximately a 40% front face at Rc 60, a back face of approximately Rc 51, and a tempering temperature of 425° F gave results comparable to conventional rolled bonded dual hard armor plate.

The next series of tests included 16 plates from the same heat, i.e., Z-62A, first pour (see Table 5). Two tempering temperatures, 925° F and 425° F, were used. Tempering temperatures will affect the level/type of the highness gradient of the back face (softer side). Various gradients with respect to depth were produced, ranging from 31 to 48% for the front face. The hardness of the front face was held at approximately Rc 60. The hardness of the back face was varied from Rc 42.6 to Rc 52.5. The results of these 16 plates are summarized in Table 7. Four acceptable (with respect to the ballistic requirements of MIL-A-46099) plates were observed. The hardness profiles of these 16 plates are plotted in Figures 6, 7, 8, and 9. Photographs of the ballistically tested plates are shown in Appendix E with the multihit capability again being evident.

An attempt was undertaken to determine why 4 plates passed and 12 plates failed the ballistic requirements. However, a detailed explanation could not be documented. One thing is known, however—the higher hardness (front face) must be consistent across the face for a certain thickness. This thickness will vary in accordance with several factors, such as the actual hardness level of the front face, the gradient of the softer side (back face), and the level of hardness of the back face. If the hardness gradient of the back face is the same hardness and consistent (as in the case of a plate tempered at 925° F), then the thickness of the front face must be greater than a plate that has a back side gradient that increases in hardness over the width of the back side thickness. This can be seen in plate No. 14. The opposite of this is also true. That is, if the back side has an increasing hardness gradient (425° F temper), then the thickness of the front face can be reduced, as in the case of plate No. 15. The problem that exists is that all the plates that were processed and tested do not have a "black-and-white" phenomenon that can explain why certain plates pass and others fail the ballistic test. Such is the case with plate Nos. 20 and 15. The hardness levels, the hardness gradient for both the front face and the back face, the plate thickness, and the processing (same temper) were approximately the same for both plates. However, the ballistic results of the 2 plates vary by 181 ft/s.

Further testing is required and will be accomplished in Phase II. Phase I demonstrated that induction heat treating is a viable method for producing monolithic gradient hard armor steel plate that can complement standard dual hard rolled bonded steel armor.

6. CONCLUSIONS

(1) Phase I efforts have demonstrated that the technique of induction heat treating can produce a monolithic steel armor plate with a hardness gradient that passes the ballistic requirements of MIL-A-46099.

(2) Based on the results obtained in Phase I, the following chemical composition should be used as a starting point for Phase II:

Carbon ~= 0.58% - 0.60%
Manganese ~= 0.44%
Silicon ~= 0.35%
Nickel ~= 3.28%
Chromium ~= 0.61%
Molybdenum ~= 0.45%

7. RECOMMENDATIONS

(1) Based on the ballistic data obtained in Phase I, it is recommended that the Induction Heat Treat Program continue with Phase II.

(2) The heats developed during Phase I (see Table 2) but not utilized along with six other heats that are currently being produced should be utilized in Phase II. Phase II will optimize the chemical composition, the hardness levels, the thickness of these hardness levels (front face and back face), and the gradient of the back face. The gradient of the front face will be held constant (i.e., the hardness level of the front face will be the same across the front face thickness).

Table 1. Ballistic Testing of Rolled Bonded Dual Hard Material

Jessop Plate No.	Firing Record	Thickness (in)	Obliquity	V_{50} (ft/s)
Threat: 0.50-cal. AP M2				
K2230-8	040-94	0.382	0	2,305
K2221-4	037-94	0.528	0	2,365
K2221-3	H-S Lab	0.528	0	2,446
K2230-8	041-94	0.382	30	2,560
K2230-7	H-S Lab	0.382	30	2,595
K2221-4	042-94	0.528	30	2,776
Threat: 0.30-cal. AP M2				
K2216-4	044-94	0.267	0	2,342
SDH No. 1	020-94	0.335	0	2,283
K2216-3	043-94	0.269	30	3,080
SDH No. 2	021-94	0.342	30	3,263

Table 2. Chemistries of In-House Heats

Heat No.	C	Mn	SI	NI	Cr	Mo	P	S
4353	0.530	0.89	0.30	1.99	0.83	0.25	0.002	0.002
Z-60A/1	0.597	0.33	0.30	3.24	0.97	0.52	0.007	0.018
Z-60A/2	0.629	0.44	0.45	3.12	0.62	0.49	0.014	0.010
Z-60A/3	0.638	0.35	0.36	3.51	0.58	0.48	0.006	0.012
Z-61A/1	0.622	1.42	1.34	2.47	0.82	0.53	0.011	0.003
Z-61A/3	0.663	1.48	1.34	2.56	0.93	0.57	0.006	0.008
Z-61A/4	0.622	1.29	1.19	2.57	0.84	0.56	0.009	0.011
Z-62A/1	0.560	0.44	0.35	3.28	0.61	0.45	0.007	0.003
Z-62A/2	0.554	0.35	0.32	3.00	0.53	0.43	0.010	0.013

Table 3. Ballistic Testing of Monolithic Dual Hard Material Heat No. 4353

Threat: 0.50-cal. AP M2					
ARL/MD Plate No.	Temper (° F)	Firing Record	Thickness (in)	Obliquity	V_{50} (ft/s)
53-1	725	067-94	0.543	30	2,908
53-2	725	070-94	0.554	0	2,292
53-3	825	069-94	0.550	0	2,425
53-4	825	068-94	0.549	30	2,910

Table 4. Ballistic Testing of Monolithic Dual Hard Material Heat No. Z-62A/1

Threat: 0.50-cal. AP M2					
ARL/MD Plate No.	Temper (° F)	Firing Record	Thickness (in)	Obliquity	V_{50} (ft/s)
Z-62-1A	425	0118-94	0.536	30	2,956
Z-62-1B	425	0122-94	0.523	30	2,851
Z-62-2A	950	0123-94	0.546	30	2,930
Z-62-2B	950	0121-94	0.518	30	No Test[a]
Z-62-2C	950	0120-94	0.531	30	2903
Z-62-3A	825	0119-94	0.538	30	2902
Z-62-3B	825	0117-94	0.539	30	2847

[a] Test was terminated due to all complete penetrations as low as 2,660 ft/s. See discussion for an explanation.

Table 5. Ballistic Testing of Monolithic Dual Hard Material Heat No. Z-62A/1

Threat: 0.50-cal. AP M2					
ARL/MD Plate No.	Temper (° F)	Firing Record	Thickness (in)	Obliquity	V_{50} (ft/s)
Z-62-5	925	0161-94	0.546	30	2,924
Z-62-6	925	0164-94	0.522	30	2,909
Z-62-15	425	0158-94	0.532	30	3,033
Z-62-17	425	0159-94	0.531	30	3,002
Z-62-18	425	0160-94	0.523	30	3,025
Z-62-22	425	0162-94	0.523	30	2,914
Z-62-23	425	0163-94	0.517	30	2,875
Z-62-13	925	0167-94	0.523	30	2,901
Z-62-7	925	0165-94	0.530	30	2,860
Z-62-21	425	0166-94	0.529	30	2,927
Z-62-19	425	0168-94	0.529	30	2,877
Z-62-20	425	0169-94	0.533	30	2,852
Z-62-11	925	0170-94	0.530	30	2,900
Z-62-1	925	0171-94	0.530	30	2,888
Z-62-8	925	0172-94	0.541	30	2,879
Z-62-14	925	0173-94	0.519	30	2,962

Table 6. Hardness Profile vs. Ballistics (0.50-cal. AP M2)[a]

Heat and Plate No.	Temper (° F)	Thck (in)	Front Face - Rc[b]	% of Front Face	Back Face - Rc[b]	V_{50} (ft/s)	Pass/ Fail (ft/s)
4353-1	725	0.543	55.5	38%	46.5	2,908	−86
4353-2	725	0.554	55.5	38%	46.5	2,292	−247
4353-3	825	0.550	55.5	38%	45.5	2,425	−100
4353-4	825	0.549	55.5	38%	44.0	2,910	−108
Z-62A/1-1A	425	0.536	60.3	40%	51.4	2,956	−11
Z-62A/1-1B	425	0.523	61.9	37%	50.7	2,851	−65
Z-62A/1-2A	950	0.546	60.1	29%	45.0	2,930	−76
Z-62A/1-2B	950	0.518	65.0	17%	44.5	—	Test Stopped
Z-62A/1-2C	950	0.531	62.1	37%	44.8	2,903	-45
Z-62A/1-3A	825	0.538	61.8	44%	51.1	2,902	−73
Z-62A/1-3B	825	0.539	61.6	37%	48.7	2,847	−132

[a] All ballistic tests were performed at 30° obliquity, except for heat plate Nos. 4353-2 and 4353-3, which were performed at 0° obliquity. Also, the pass/fail values used for these two plates were calculated by using a mil handbook.

[b] Hardness values are an average of all hardness readings taken at 0.01-in interval.

Table 7. Hardness Profile vs. Ballistics (0.50-cal. AP M2) at 30° Obliquity

Heat and Plate No.	Temper (° F)	Thck (in)	Front Face - Rc[a]	% of Front Face[a]	Back Face - Rc	V_{50} (ft/s)	Pass/ Fail (ft/s)
Z-62A/1-5	925	0.546	59.6	38	43.1	2,924	−82
Z-62A/1-6	925	0.522	59.2	31	42.6	2,909	−3
Z-62A/1-15	425	0.532	59.5	32	51.5	3,033	+77
Z-62A/1-17	425	0.531	60.9	43	50.8	3,002	+50
Z-62A/1-18	425	0.523	60.1	38	52.5	3,025	+109
Z-62A/1-22	425	0.523	62.4	35	51.8	2,914	−2
Z-62A/1-23	425	0.517	61.9	36	51.3	2,875	−17
Z-62A/1-13	925	0.523	59.6	48	44.4	2,901	−15
Z-62A/1-7	925	0.530	62.1	42	44.5	2,860	−84
Z-62A/1-21	425	0.529	59.9	37	51.5	2,927	−13
Z-62A/1-19	425	0.529	59.4	42	50.7	2,877	−63
Z-62A/1-20	425	0.533	60.3	31	51.4	2,852	−104
Z-62A/1-11	925	0.530	60.8	34	45.5	2,900	−44
Z-62A/1-1	925	0.530	60.3	31	45.7	2,888	−56
Z-62A/1-8	925	0.541	60.0	33	43.2	2,879	−109
Z-62A/1-14	925	0.519	61.4	43	45.1	2,962	+63

[a] Hardness values are an average of all hardness readings taken at 0.01-in interval.

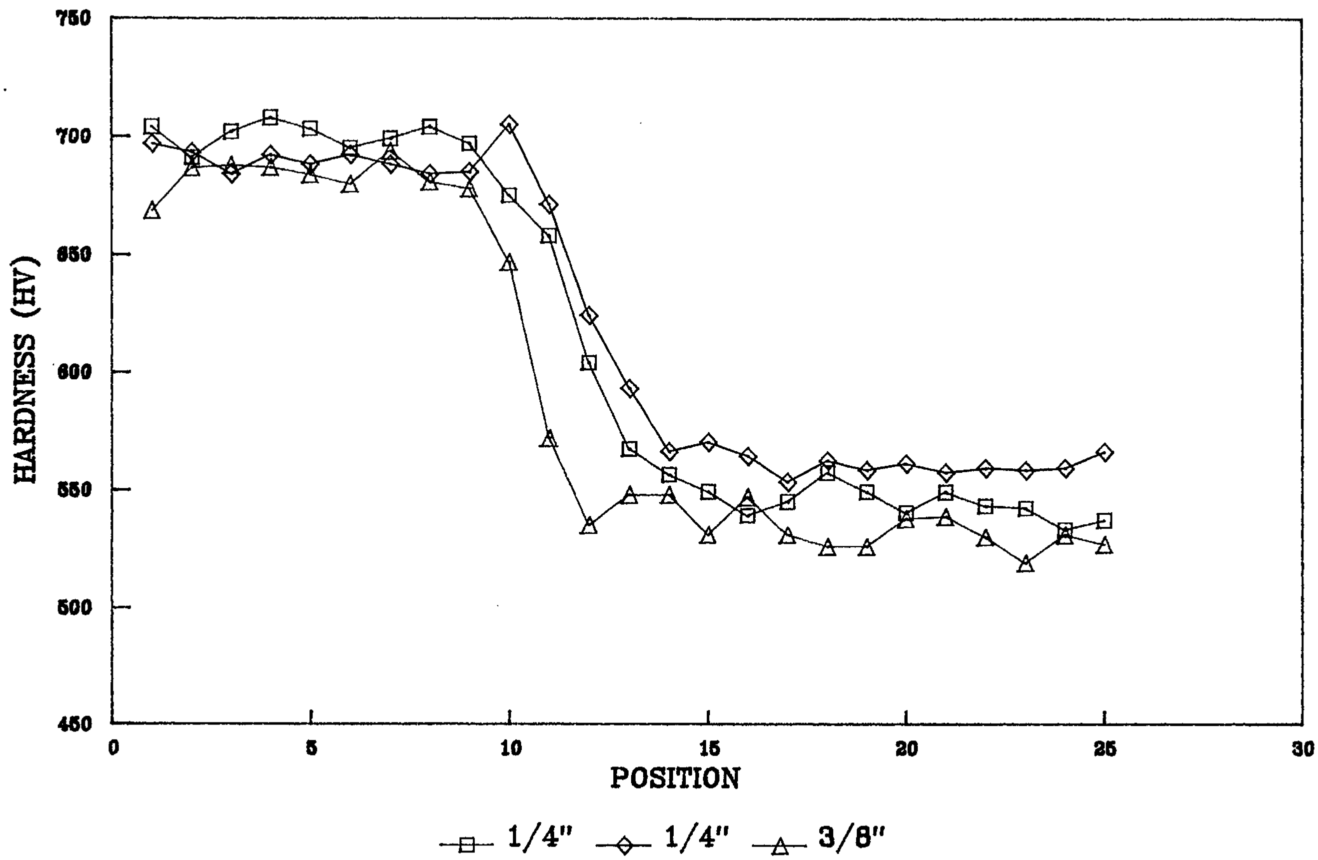

Figure 1. Standard dual hard Jessop steel.

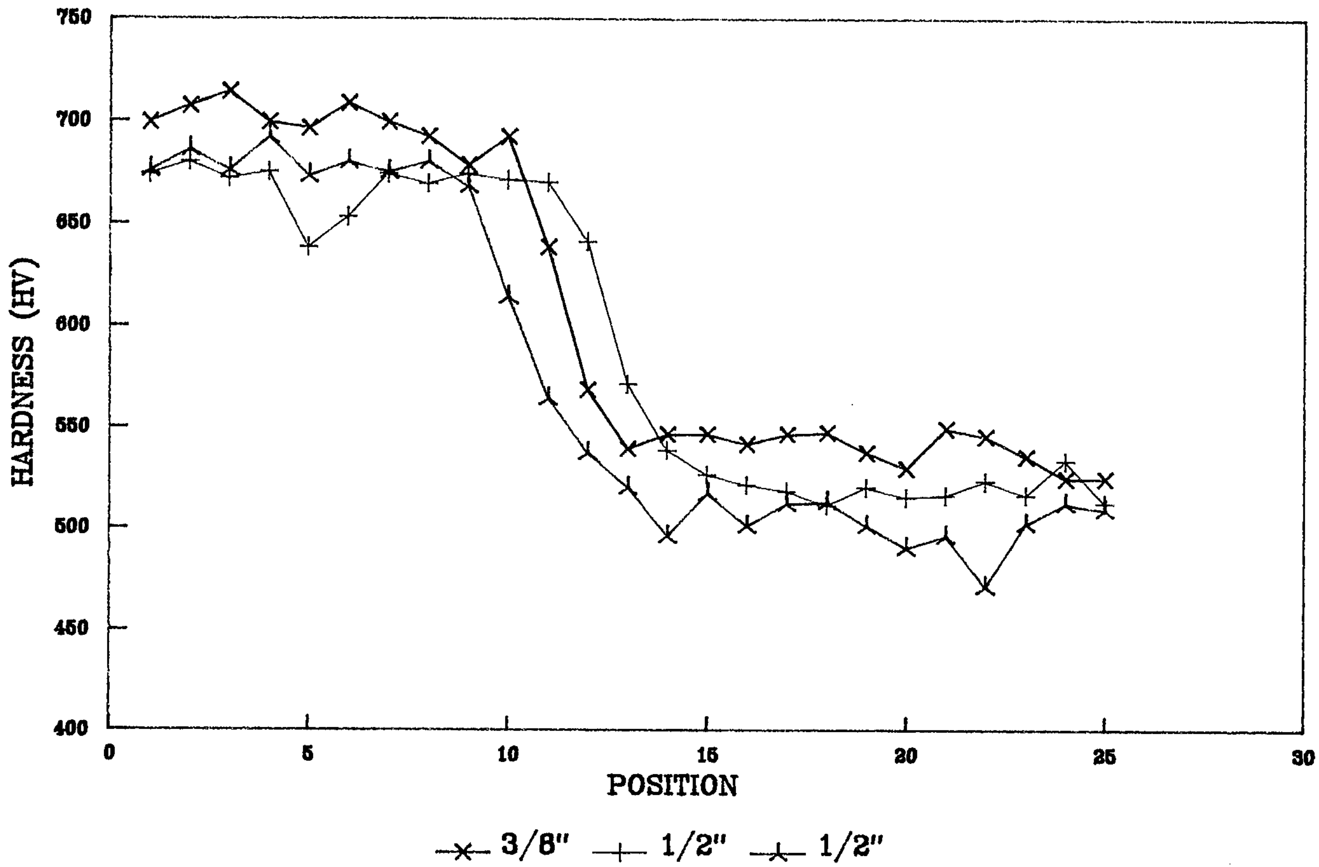

Figure 2. Standard dual hard Jessop steel.

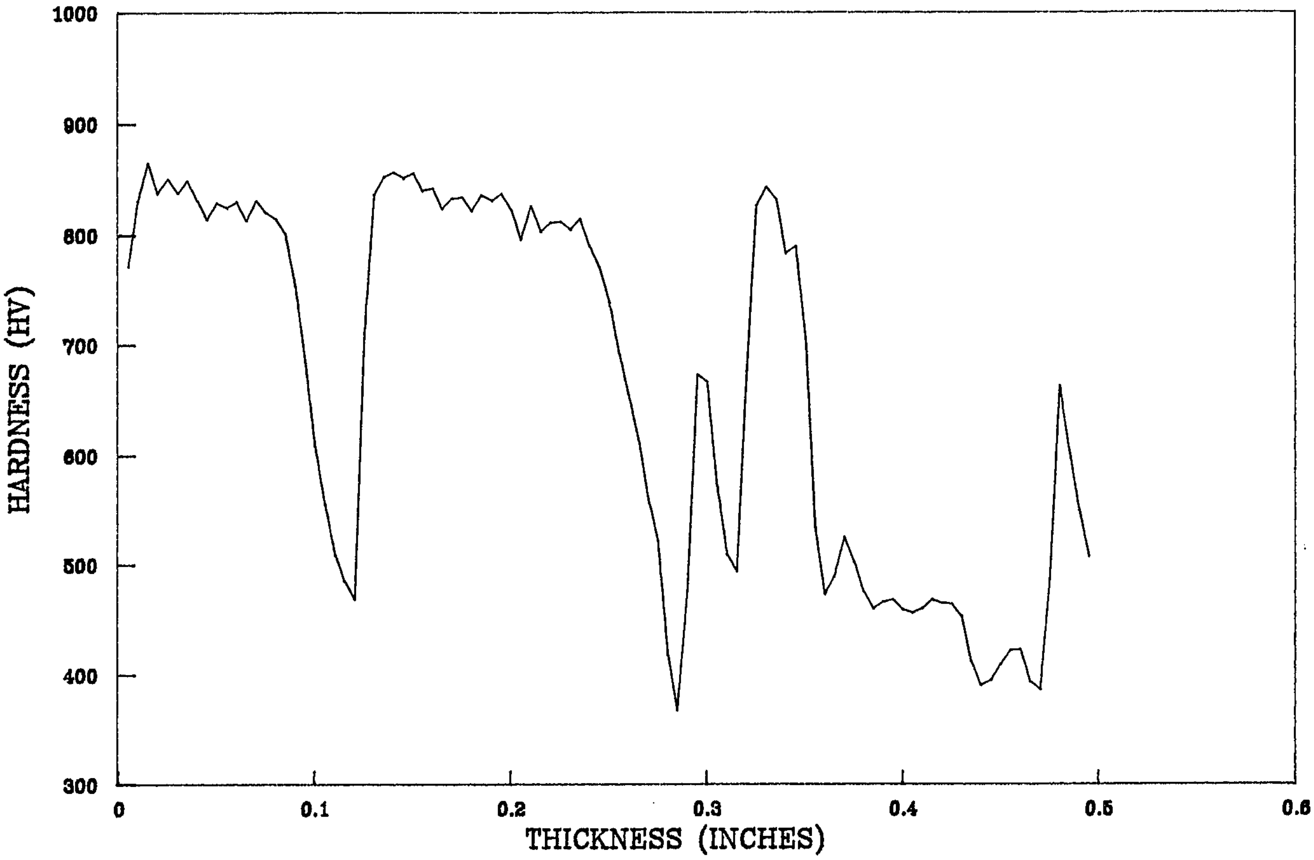

Figure 3. Heat No. Z-62A first pour - plate No. 2B.

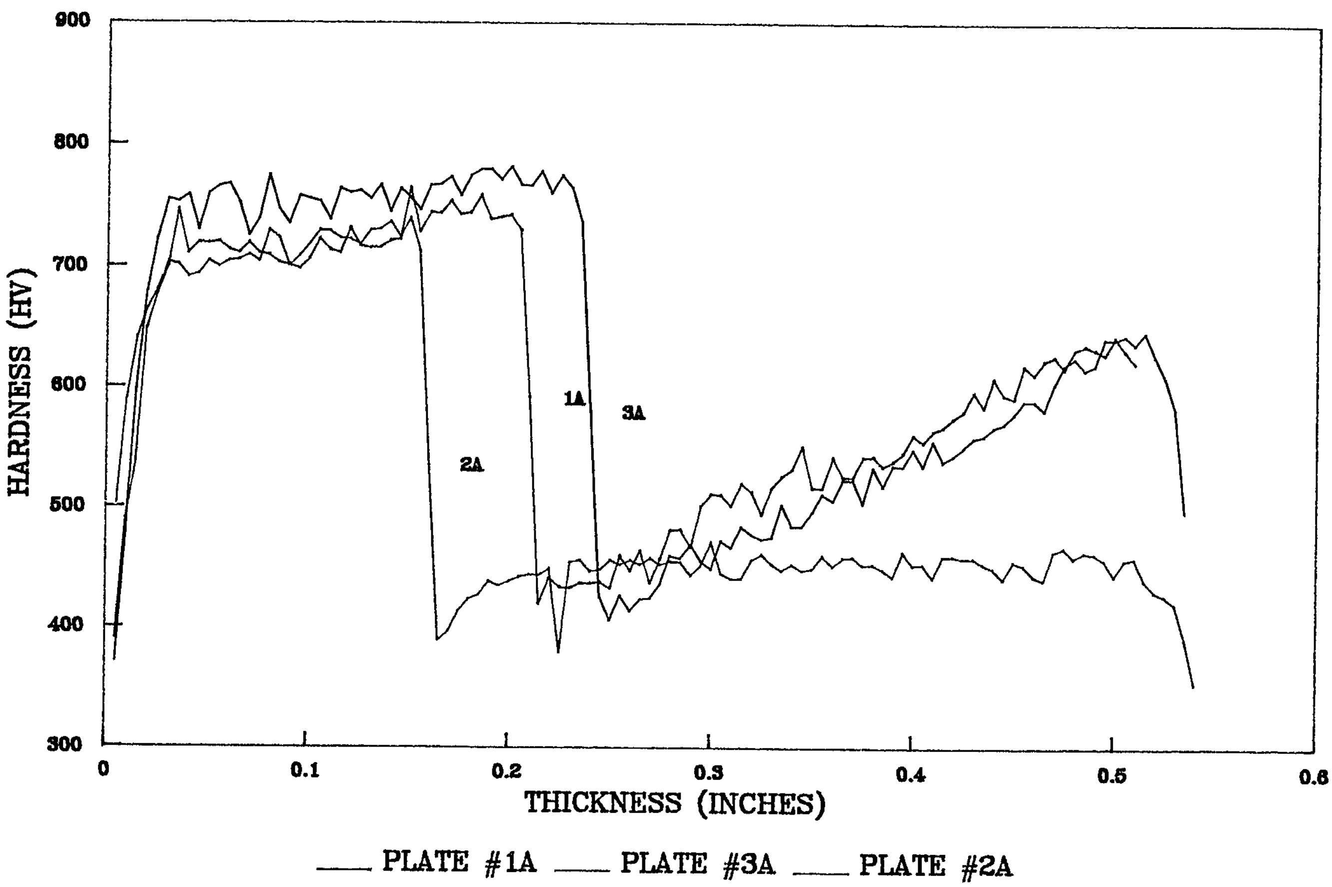

Figure 4. Heat No. Z-62A first pour - plate Nos. 1A, 2A, and 3A.

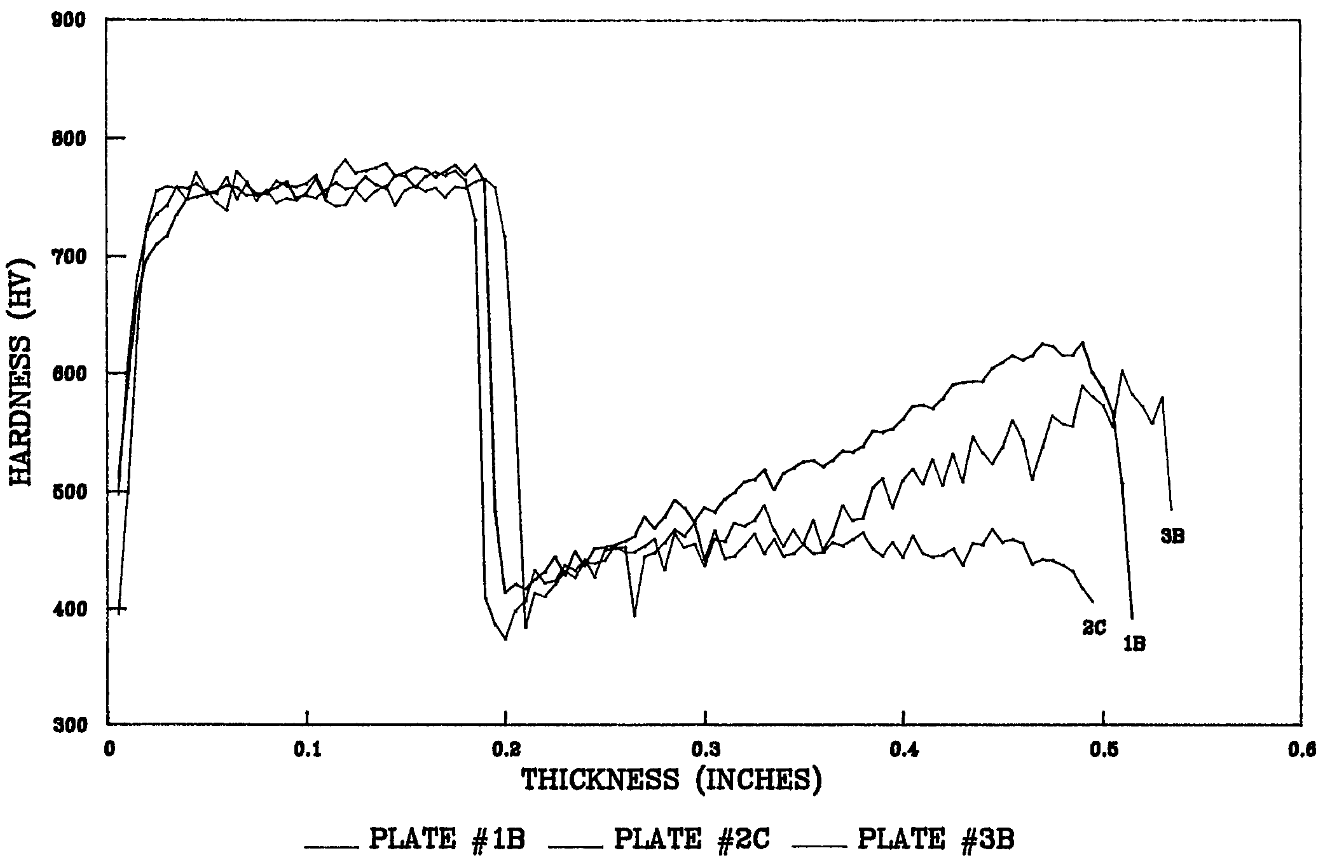

Figure 5. Heat No. Z-62A first pour - plate Nos. 1B, 2C, and 3B.

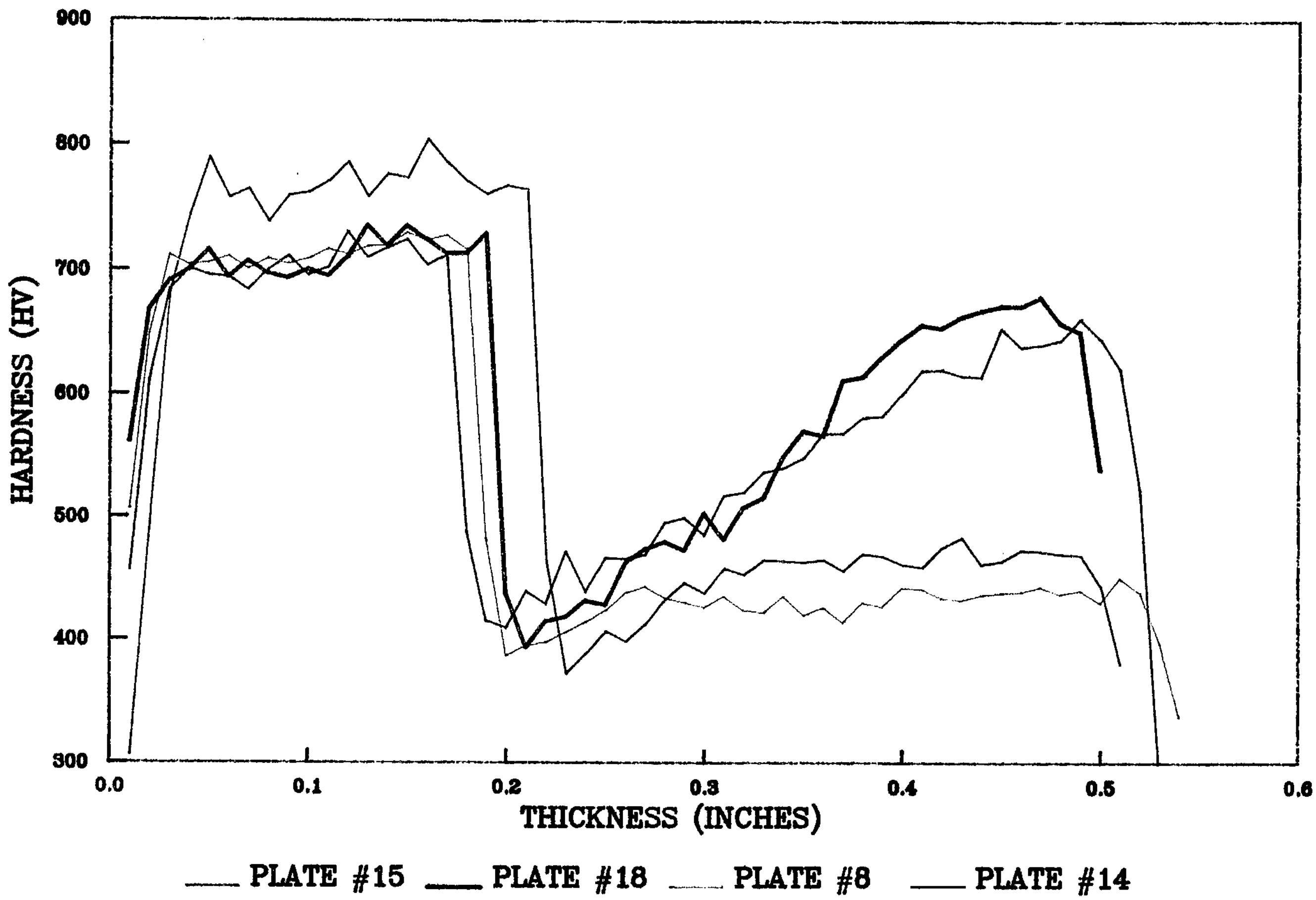

Figure 6. Heat No. Z-62A first pour - plate Nos. 15, 18, 8, and 14.

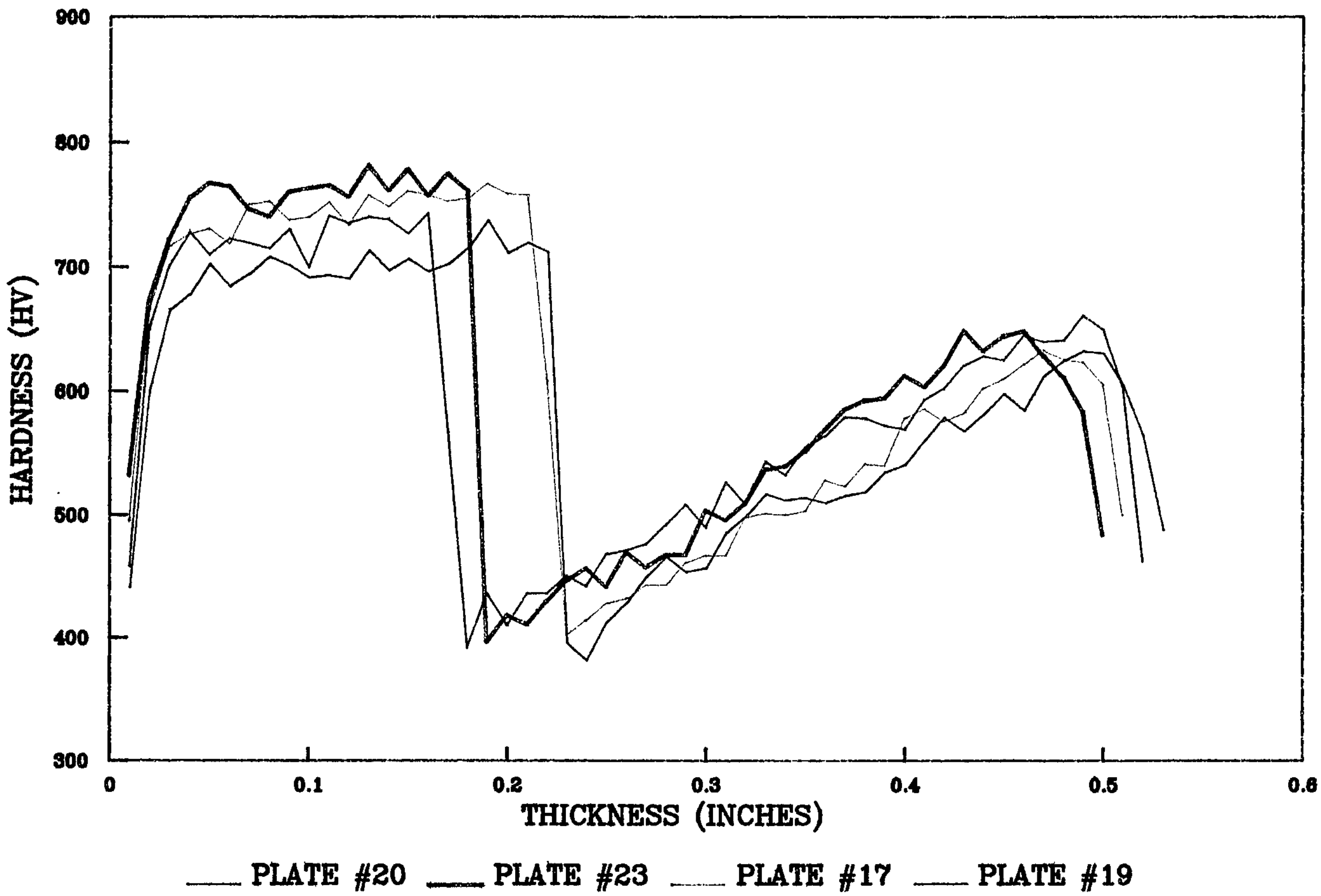

Figure 7. Heat No. Z-62A first pour - plate Nos. 20, 23, 17, and 19.

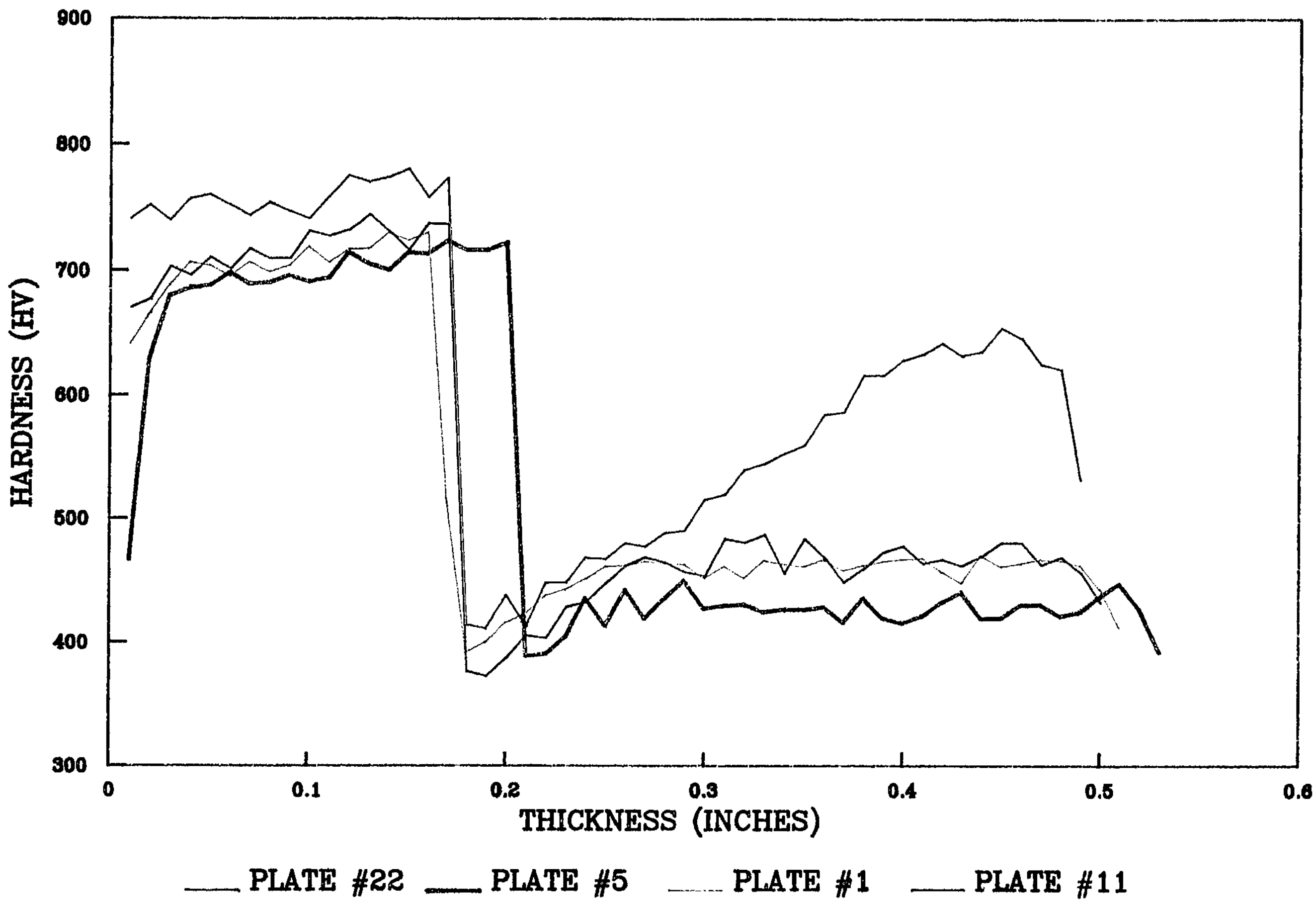

Figure 8. Heat No. Z-62A first pour - plate Nos. 22, 5, 1, and 11.

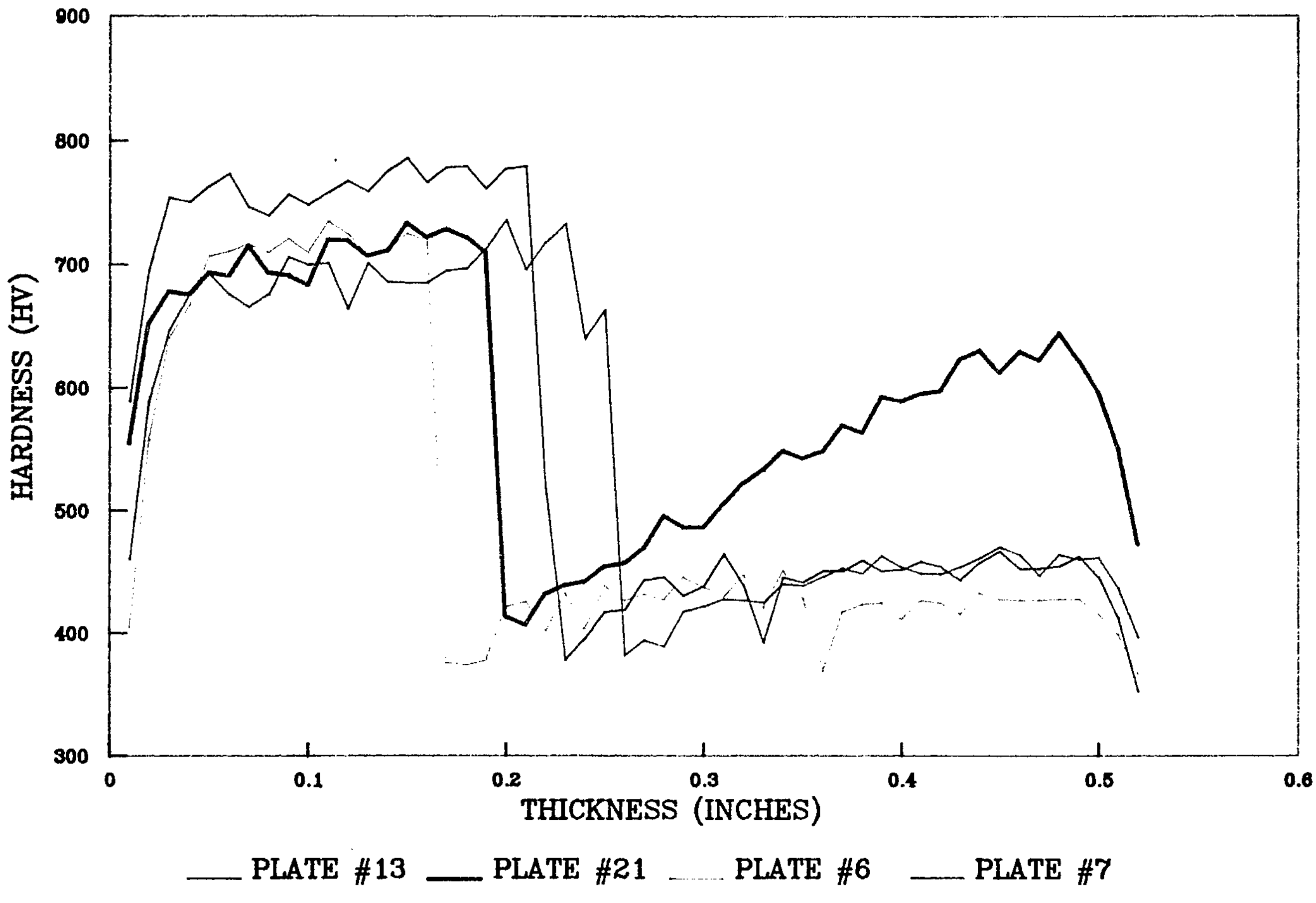

Figure 9. Heat No. Z-62A first pour - plate Nos. 13, 21, 6, and 7.

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APPENDIX A:

EQUIPMENT PHOTOGRAPHS

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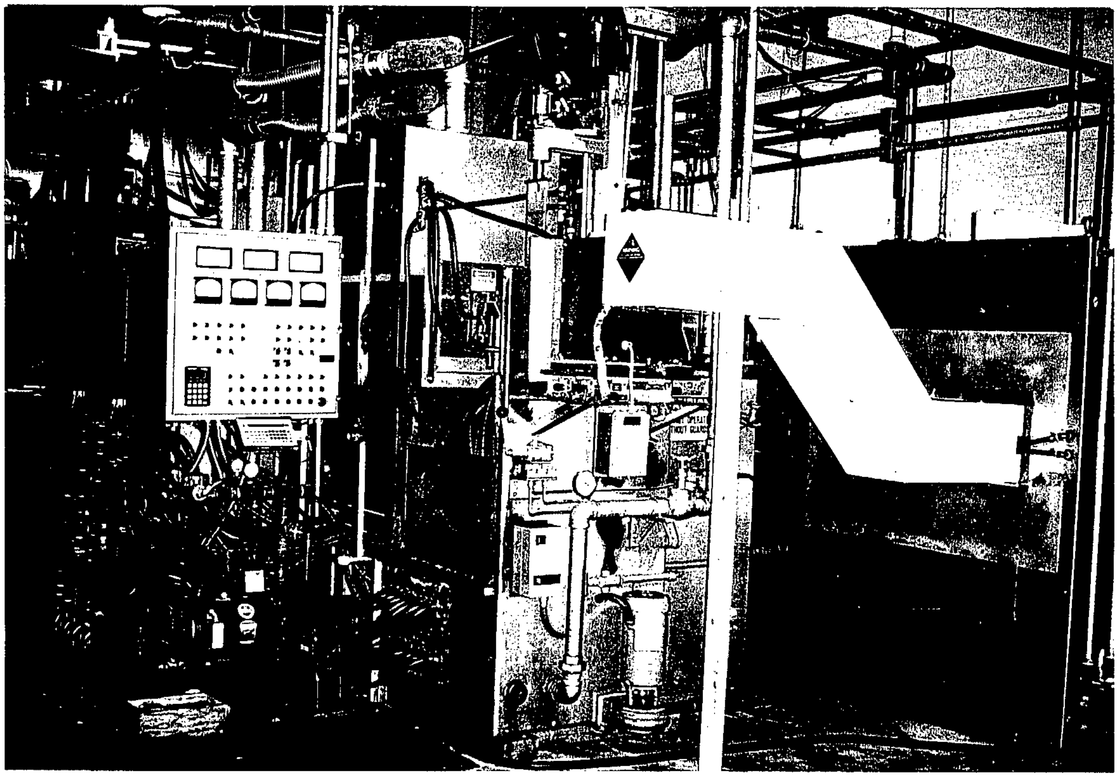

Figure A-1. Overall view of work station and controls with quench system and RF transformer.

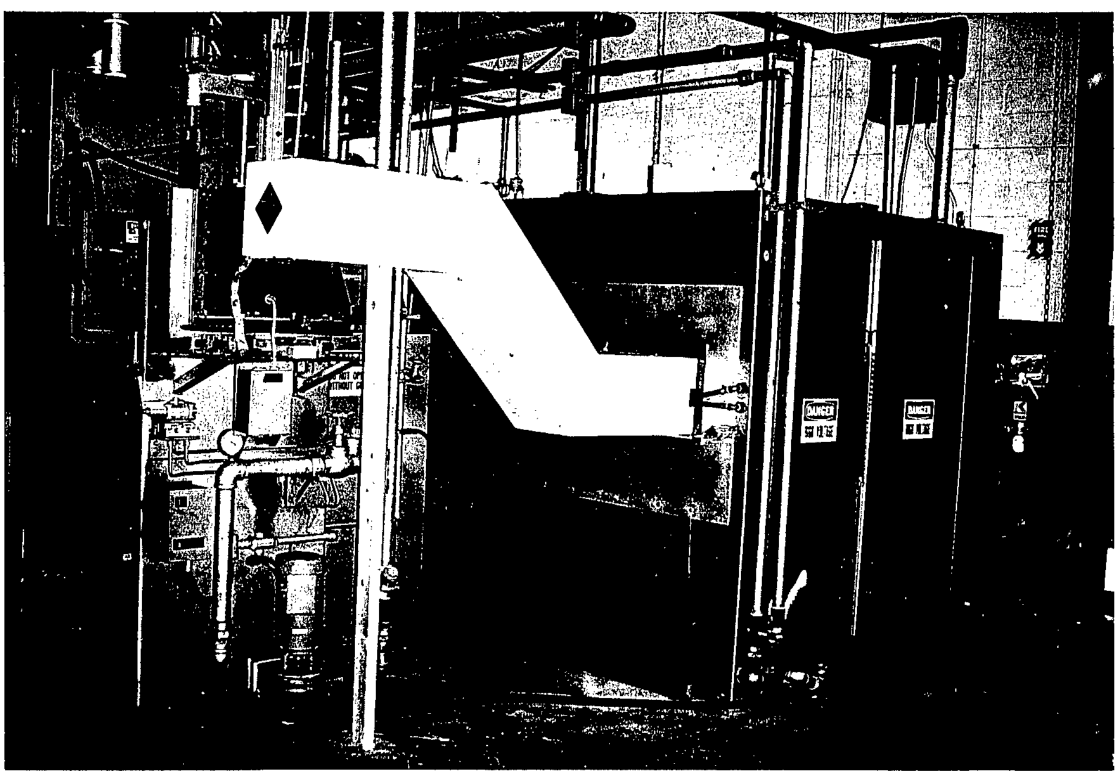

Figure A-2. RF power supply and RF transformer.

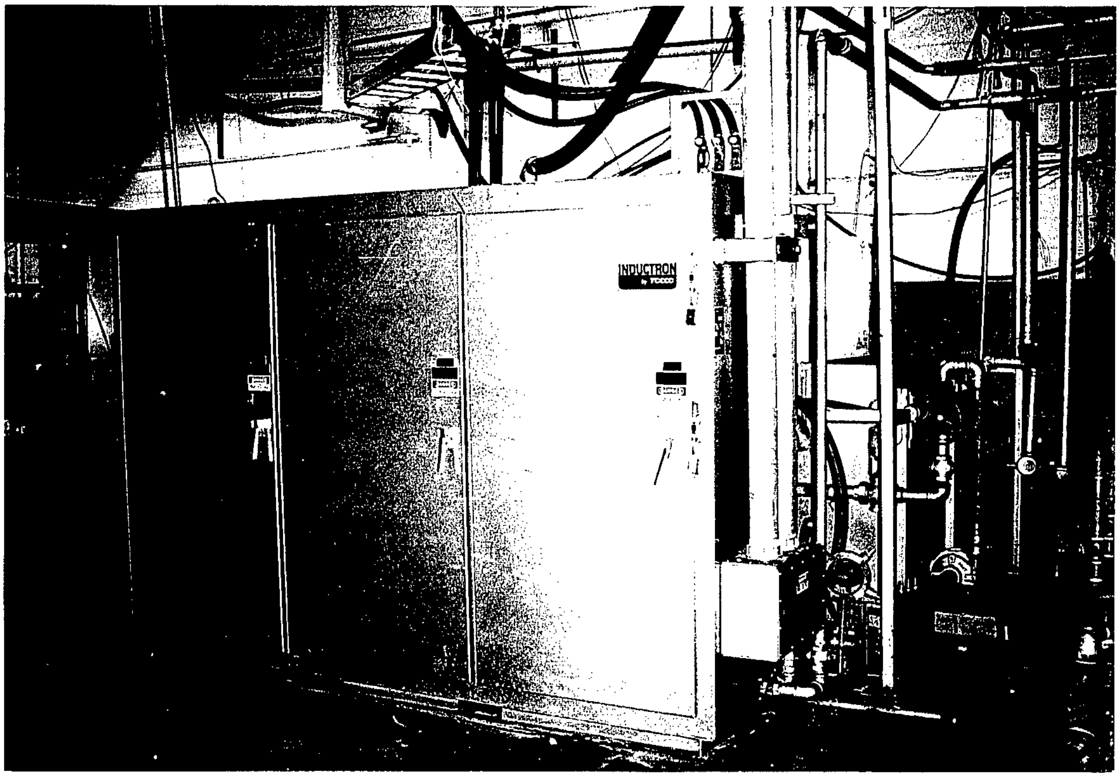

Figure A-3. AF power supply that feeds into the AF transformer.

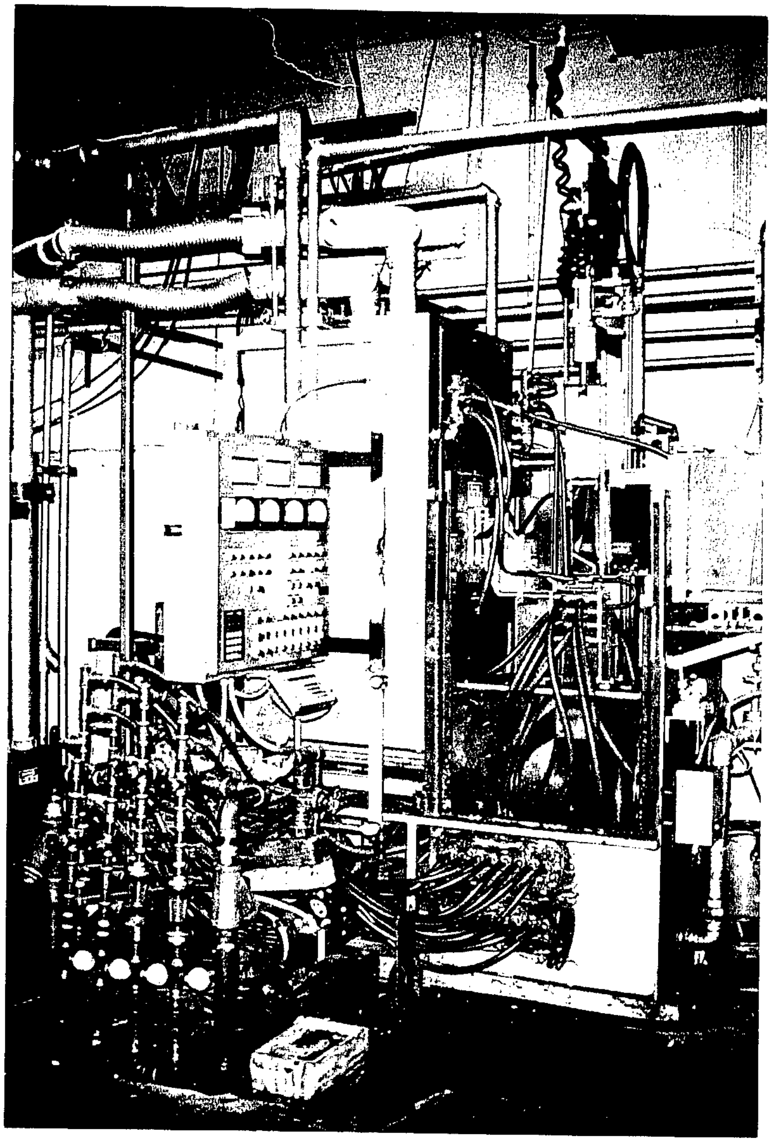

Figure A-4. AF transformer housing, station controls, and quench system.

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APPENDIX B:

PHOTOGRAPHS OF JESSOP STEEL CONVENTIONAL ROLLED BONDED MATERIAL

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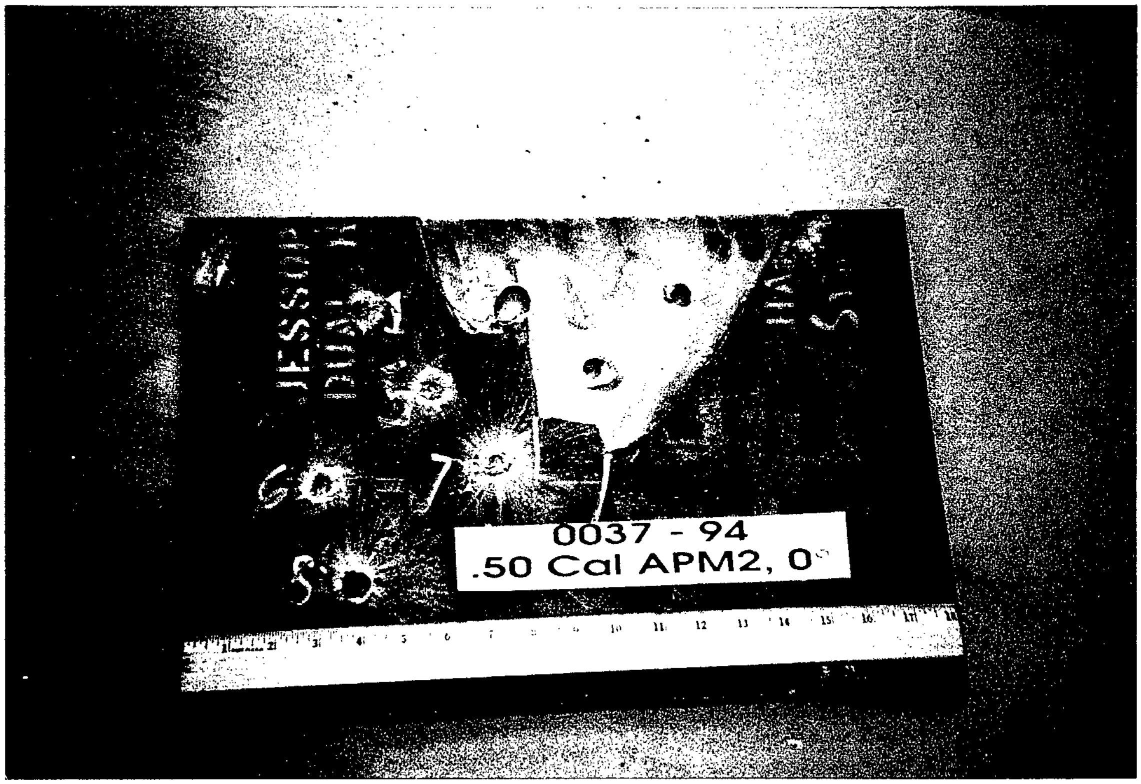
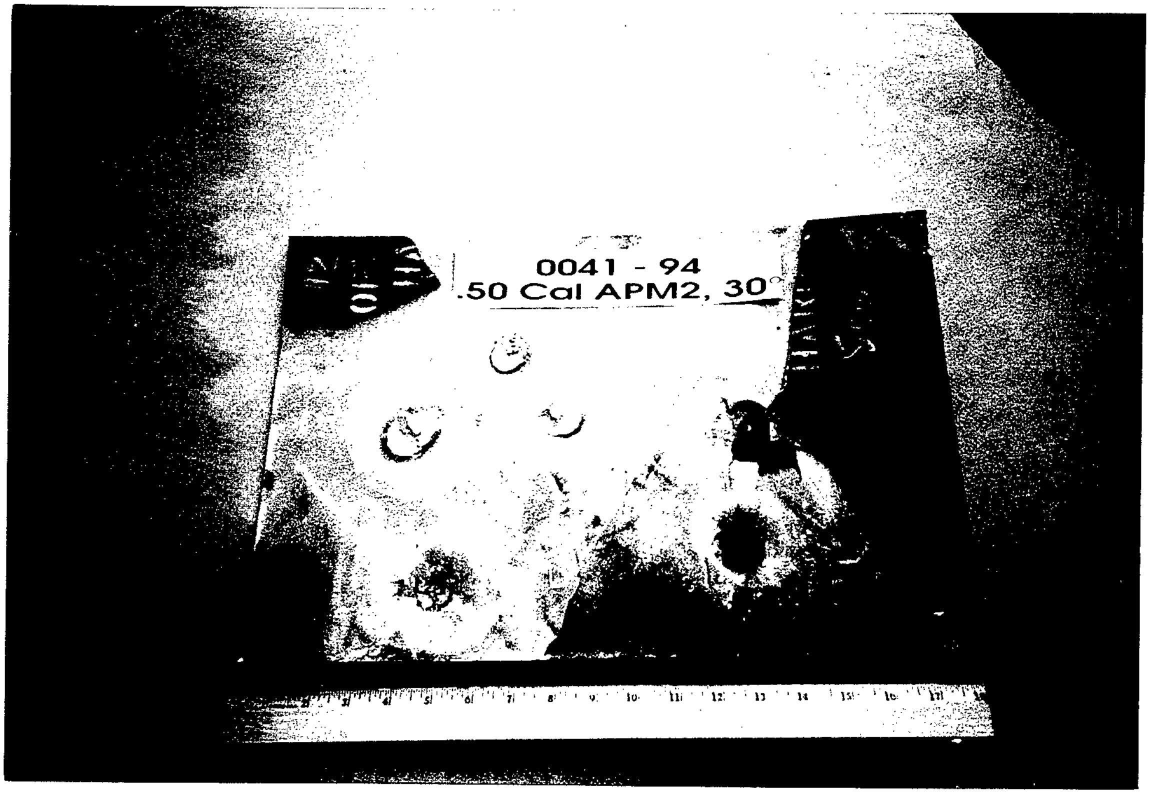

0037 - 94
.50 Cal APM2, 0°


0040 - 94
.50 Cal APM2, 0°


0041 - 94
.50 Cal APM2, 30°


0042 - 94
.50 Cal APM2, 30°

APPENDIX C:

PHOTOGRAPHS OF HEAT NO. 4353

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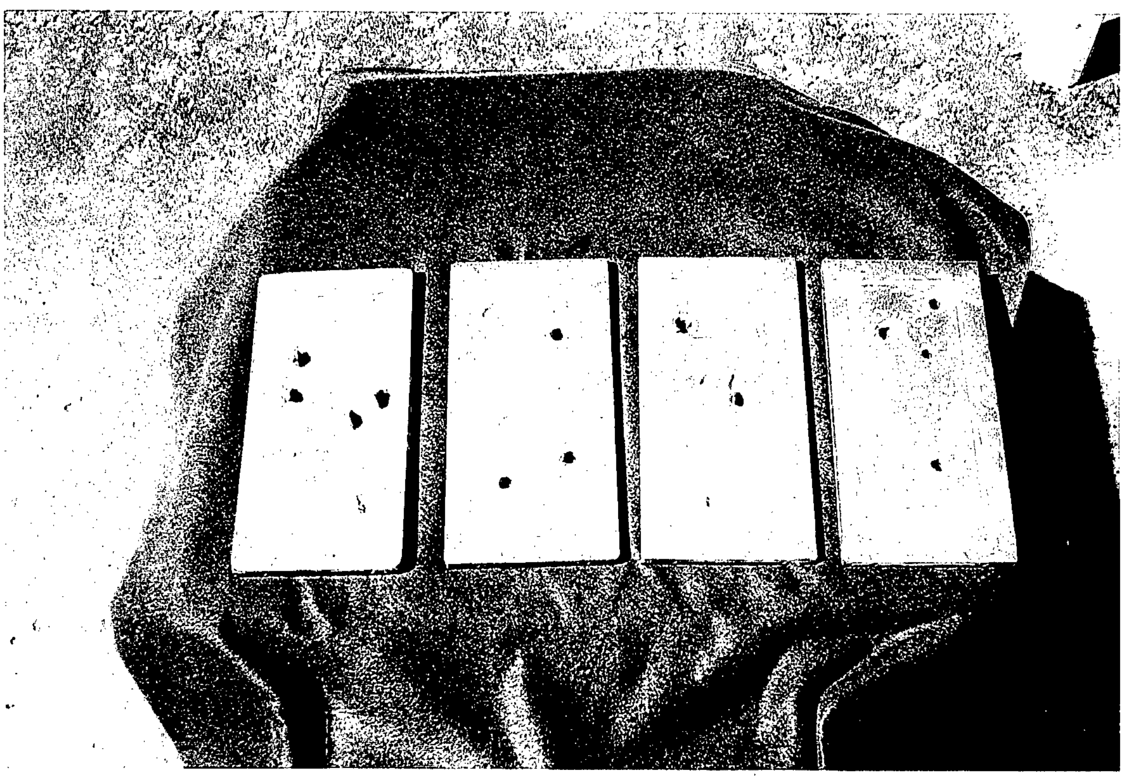

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APPENDIX D:

PHOTOGRAPHS OF HEAT NO. Z-62A 1ST POUR

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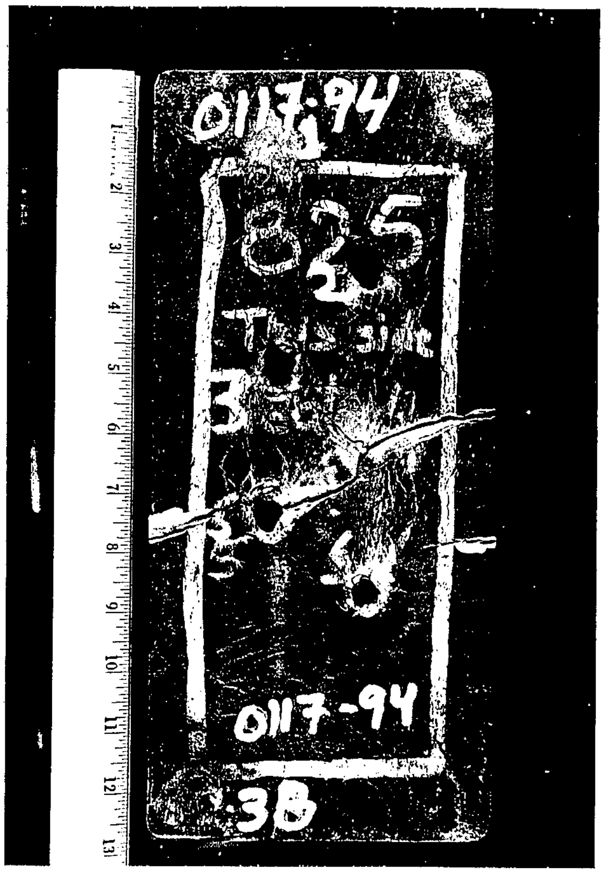
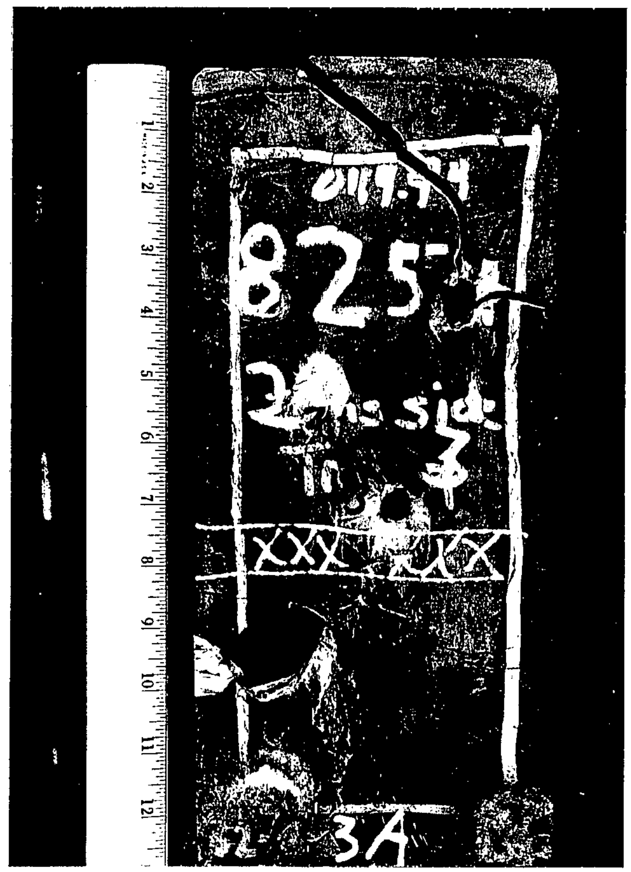
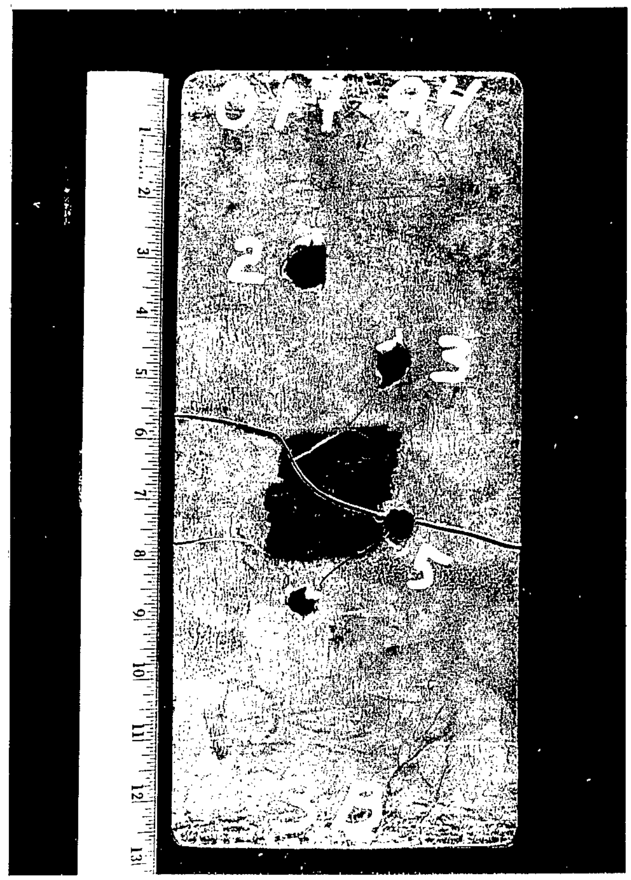
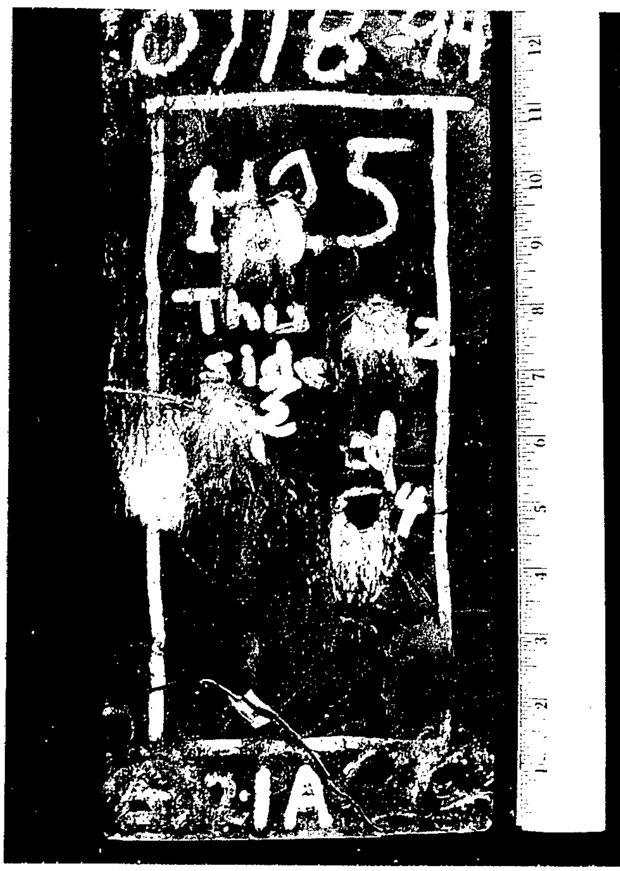
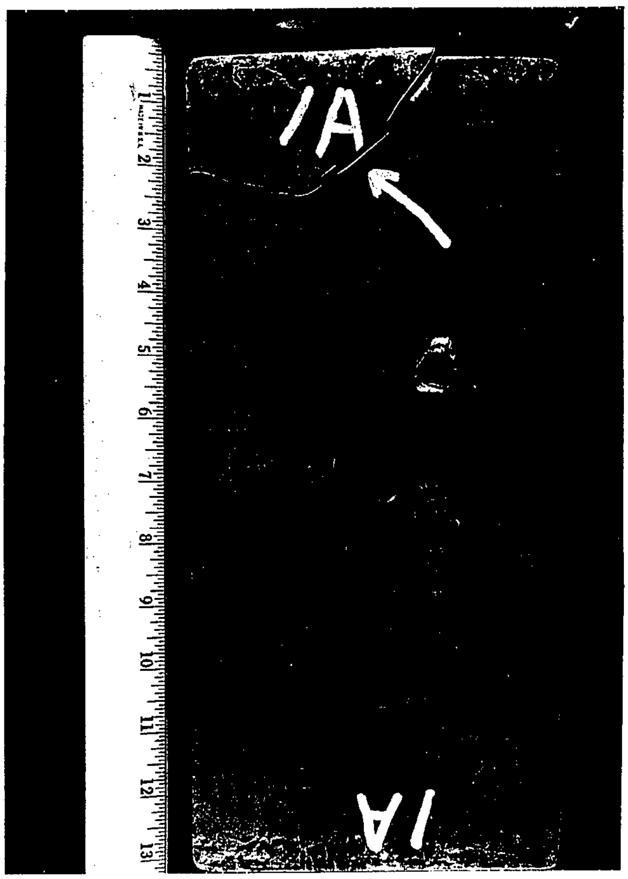

0117-94
825
0117-94
3B


825
3A

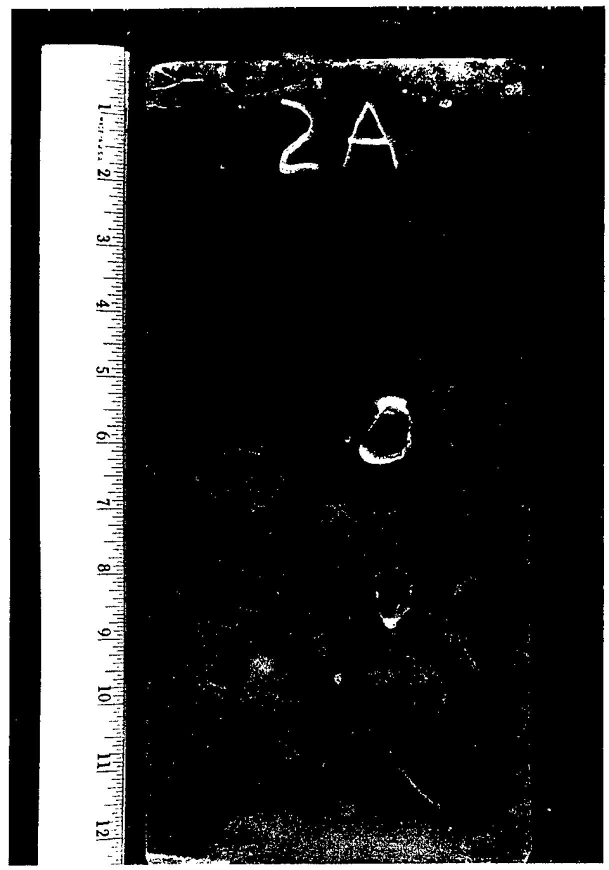


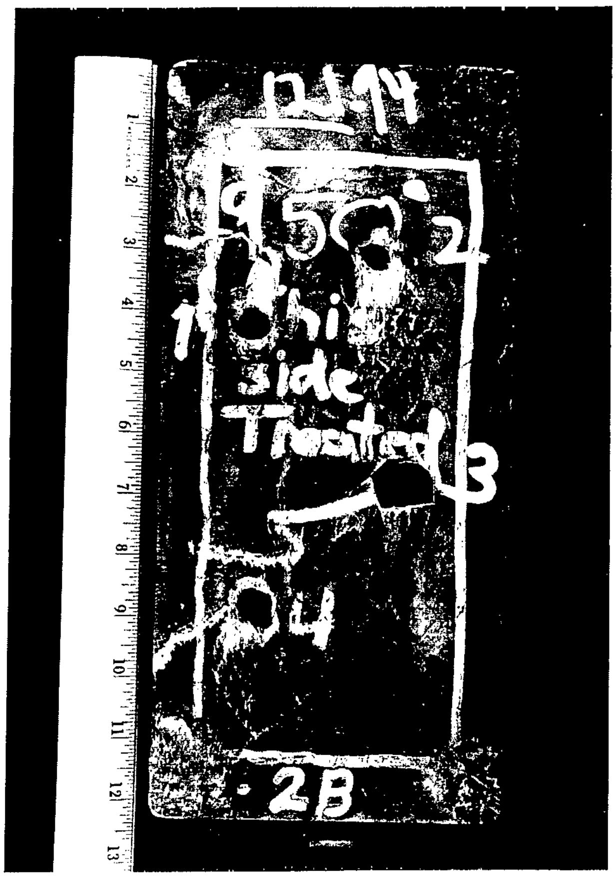
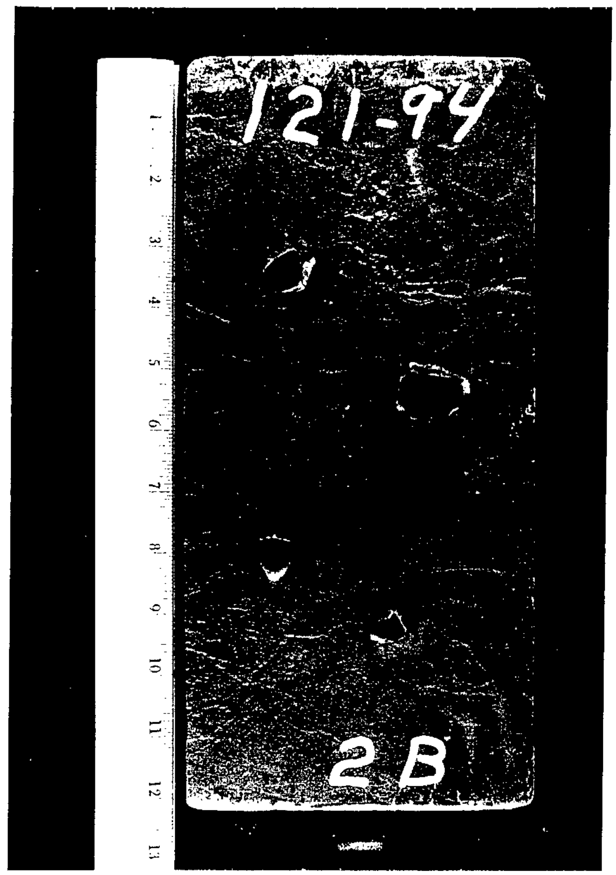

This side
1A

This
1B

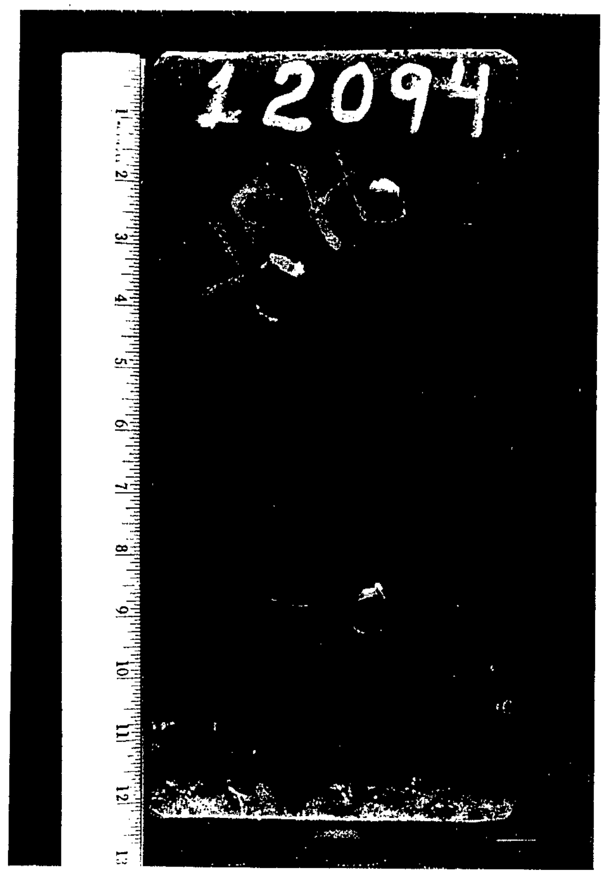

1A


1B


2A


hi
side
Treated
3
4
2B

121-94
2B


12094


12094

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APPENDIX E:

PHOTOGRAPHS OF HEAT NO. Z-62A 1ST POUR 2ND SERIES

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PLATE - 5
WESTCOTT RULER


WESTCOTT RULER


PLATE - 7
0165.9
165.9
WESTCOTT RULER


WESTCOTT RULER

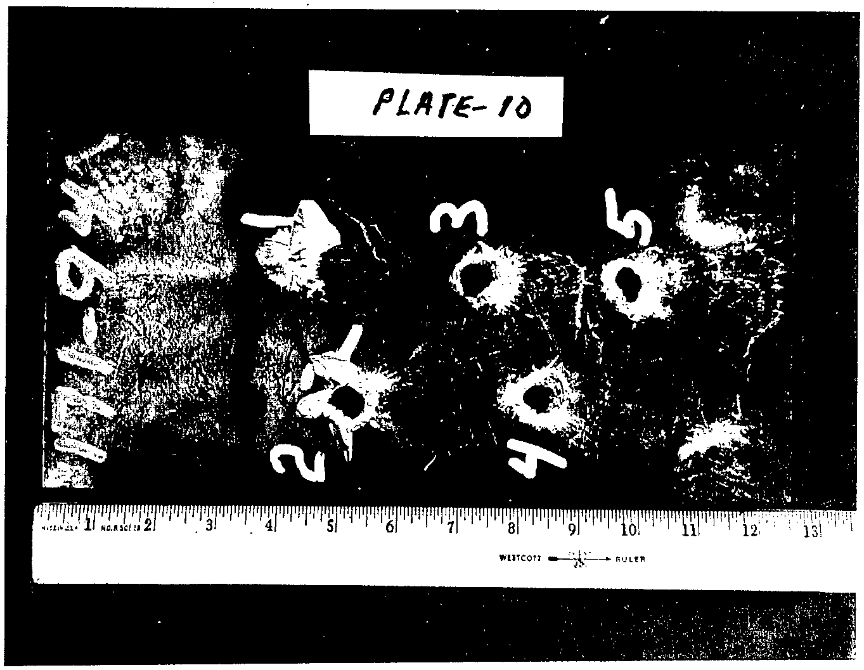
PLATE-10


PLATE-11


PLATE- 13
WESTCOTT RULER


PLATE - 13
WESTCOTT

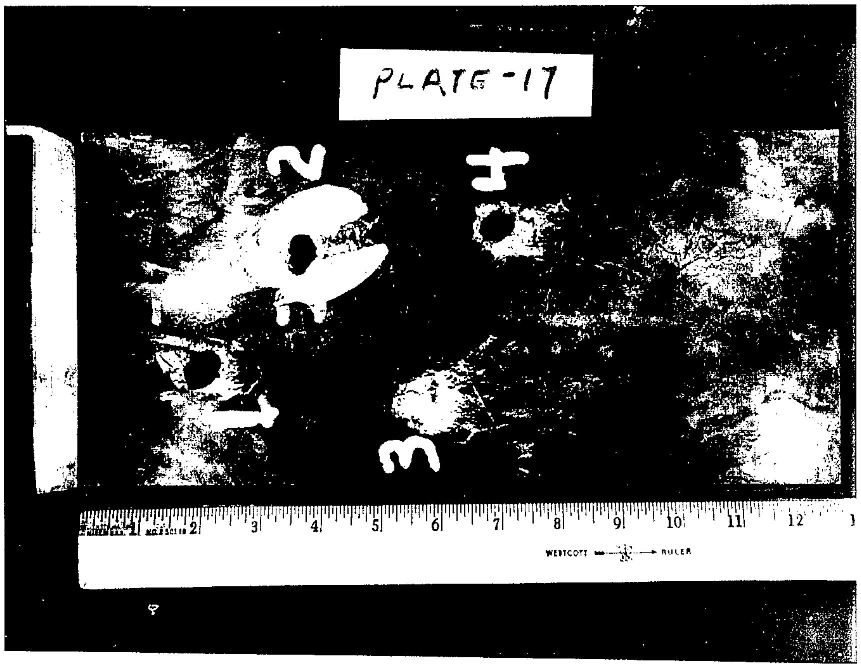
PLATE-17
WESTCOTT RULER


PLATE-23
1-13-94
WESTCOTT

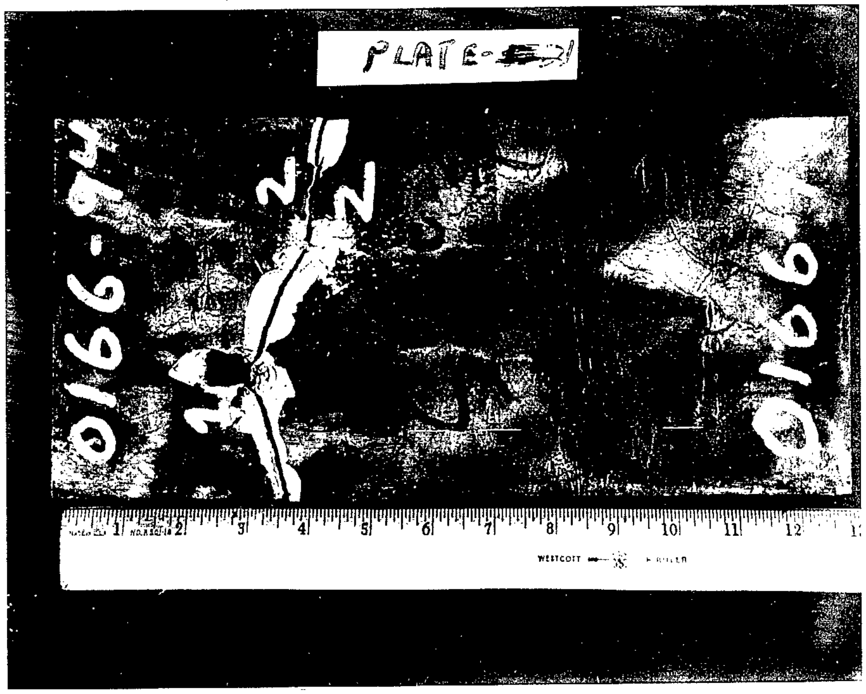
PLATE-21
0166-94
0166

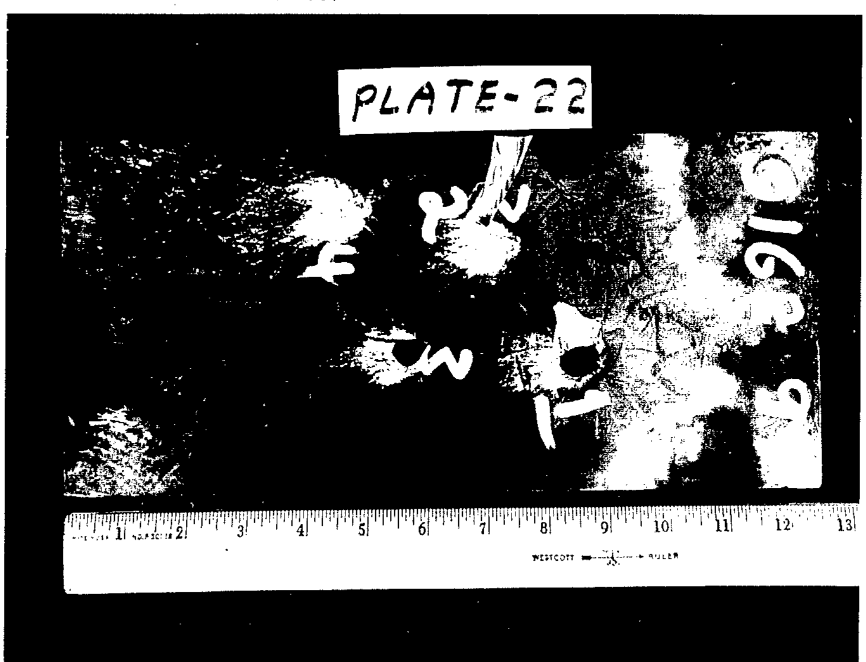
PLATE-22


WESTCOTT RULER

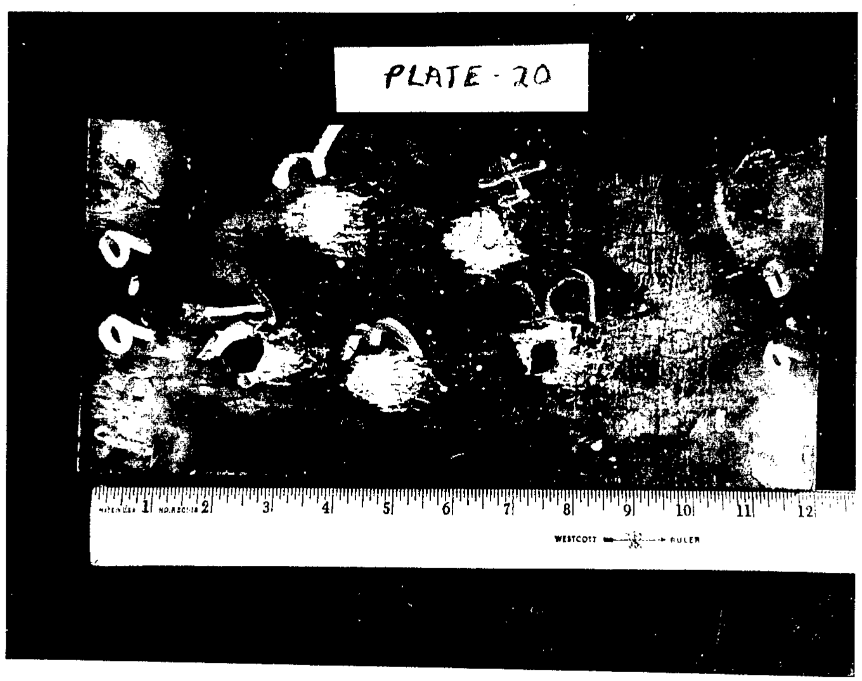
PLATE - 20
WESTCOTT RULER


PLATE - 19
0160-94

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