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TECHNICAL REPORT ARCCB-TR-93032

APPLICATIONS OF LASERS TO CANNON MANUFACTURE

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SEPTEMBER 1993

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE September 1993

3. REPORT TYPE AND DATES COVERED Final

4. TITLE AND SUBTITLE

APPLICATIONS OF LASERS TO CANNON MANUFACTURE

5. FUNDING NUMBERS

AMCMS No. 32970684260
PRON No. M78F0042M71A

6. AUTHOR(S)

John R. Senick, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army ARDEC
Benet Laboratories, SMCAR-CCB-TL
Watervliet, NY 12189-4050

8. PERFORMING ORGANIZATION REPORT NUMBER

ARCCB-TR-93032

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army ARDEC
Close Combat Armaments Center
Picatinny Arsenal, NJ 07806-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The process development, specification, procurement, and implementation of an industrial laser metalworking system was performed by Benet Laboratories under a Manufacturing Methods and Technology project at Watervliet Arsenal. The system was designed to include capabilities for welding, cutting, and heat treating a variety of cannon components that were historically difficult or impossible to process by conventional means.

Initially, several development contracts were established and executed to determine the parameters for laser processing various cannon components. These contracts involved welding and heat treating selected materials and prototype components using laser technology. Results generated from this work were used to design and specify a versatile laser metalworking system to complement Watervliet Arsenal's production facilities. The system was successfully implemented at the Arsenal, and is currently used in production for localized heat treatment of minor components.

14. SUBJECT TERMS

Light Amplification by Standard Emission of Radiation (Laser), Heat-Affected Zone (HAZ), Microhardness, Base Metal

15. NUMBER OF PAGES 34

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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INTRODUCTION

Industrial laser technology has advanced rapidly during the past few years as greater demands have been placed on lasers, particularly in the higher powered industrial applications. Through these advancements, high power lasers have effectively addressed the metalworking industry's needs by combining rugged, computer-controlled positioning systems with the unique thermal processing opportunities that lasers afford. The current systems can withstand the fast-paced production environment and maintain a high degree of accuracy and reliability, just like any other precision machine tool on the production floor. In addition, laser processing techniques have proven superior to conventional manufacturing methods in applications such as:

- Precision hardening, welding, and cutting with minimal heat-affected zones
- High quality surface finish for cutting
- Welding in atmospheric conditions
- Adaptability for computer numerical control (CNC)

This project was developed to apply lasers to traditional cannon manufacturing processes in order to supplement production capabilities and enhance processing efficiency, reliability, and component quality. Processing applications have included hardening of cam surfaces and cutting tool edges for enhanced wear resistance, component engraving (serialization), localized welding, and surface alloying.

STATEMENT OF THE PROBLEM

Conventional methods for metalworking cannon components, including cutting, marking, welding, heat treating, and alloying, have been effective for many years. However, the most recent generation of cannons has seen more stringent requirements imposed on the components. The need for high quality, cost effective processing techniques of these components has put laser technology in the spotlight.

PROPOSED SOLUTION

The proposed solution is to employ laser technology to these components. The laser provides a unique method for localized thermal processing of a component by delivering a concentrated, high power form of thermal energy to the surface of a part, while causing minimal distortion or metallurgical change to the surrounding material.

PROJECT OBJECTIVES

The main objective has been to develop process parameters and apply laser technology to thermal processing (welding, heat treating, cutting, etc.) a variety of cannon components with enhanced quality and/or less cost to the government. It has also been an objective to utilize this unique technology in areas where employing conventional manufacturing methods are not cost effective, or possible, because of component design requirements.

PROCEDURE

The project involved several major tasks. These tasks were performed accordingly:

1. Development of laser-processing techniques for weapon materials, followed by testing and evaluation of selected laser-treated weapon components.

2. Development of system specifications for a laser metalworking station. Specifications are based on results generated during part one of the procedure.

3. System acquisition, installation, and testing.

4. System implementation, including transfer of the system and technology into production at Watervliet Arsenal.

RESULTS

Process Development

A process development contract was established with Spectra Physics, Inc., San Jose, CA, a manufacturer of industrial lasers. Three components and their corresponding processing requirements were selected for potential laser application. The subject components and corresponding processes are:

1. 105-mm M68 Breechblock	- surface hardening of cam path
2. Step-Threading Tool	- cutting edge refinement via laser
3. End Mill	- cutting edge refinement via laser

The components are illustrated in Figures 1 through 3.

The goal of this effort was to establish the appropriate process conditions for increasing the surface hardness of selected areas of these components, which would also effectively increase the overall wear resistance of the components. These tasks were to be accomplished by laser processing of the designated areas. After the components were laser processed, a metallurgical evaluation was performed on them to characterize the material effects produced by the laser. The results of this analysis follow.

105-mm M68 Breechblock (4335 Steel)

A magnified view of the cam path is shown in Figure 4. The arrows in the figure designate the areas to be laser processed. Figure 5 shows a metallographic cross section of the cam path after laser processing. The light band at the surface is the hard, untempered martensitic microstructure produced by the laser. A microhardness profile of the 105-mm M68 breechblock laser-hardened region is shown in Table 1.

Table 1. Microhardness Profile of 105-mm M68 Breechblock Laser-Hardened Region

Depth (in.)	Hardness (HRC)
0.001	60
0.005	60
0.010	60
0.015	60
0.020	60
0.025	60
0.030	55
0.035 (base metal)	34

Parameters used to optimize the results are:

- Laser operating power - 5 Kw
- Laser beam spot size - 0.36 in.^{2}
- Laser power density - 1.26 Kw/in.^{2}
- Total processing time - 17 sec
- Linear traverse speed - 30 in./min
- Shielding gas - nitrogen

Step-Threading Tool Bit (M3 Tool Steel)

The cutting edges of the tool bit were exposed to the laser beam for a very short time (see parameters below). A cross-sectional view of one laser-processed edge is shown in Figure 6. As in the previous photomicrograph, the light region indicates the desired transformation to martensite was achieved during the process. Table 2 outlines a microhardness profile of the step-threading tool laser-hardened region.

Table 2. Microhardness Profile of Step-Threading Tool Laser-Hardened Region

Depth (in.)	Hardness (HRC)
0.001	60
0.010	60
0.020	60
0.030	60
0.040	60

Parameters used to optimize the results are:

Laser operating power	- 5.5 Kw
Laser beam spot size	- 0.64 in.^{2}
Laser power density	- 562 W/in.^{2}
Total processing time	- 1.6 sec
Shielding gas	- nitrogen

<u>End Mill (M3 Tool Steel)</u>

The spiraling cutting edges of the end mill were subjected to the laser, and a cross-sectional view of one of the edges is shown in Figure 7. Although the laser was effective for hardening the cutting edge, a softer region (see below) was generated deeper in the material, which was identified as a heat-affected zone consisting of tempered martensite. Table 3 shows a microhardness profile of the end mill laser-hardened region.

Table 3. Microhardness Profile of End Mill Laser-Hardened Region

Depth (in.)	Hardness (HRC)
0.001	60
0.005	55
0.010	55
0.015	55
0.020	55
0.030	55
0.040	45
0.080	60

Parameters used to optimize the results are:

• Laser operating power	- 2.5 Kw
• Laser beam spot size	- 0.0625 in.^{2}
• Laser power density	- 825 W/in.^{2}
• Total processing time	- 3 sec
• Shielding gas	- nitrogen

Summary of Process Development Results

Results of our analysis showed that the breechblock cam path and step-threading tool bit could be successfully surface-hardened with the laser. Although the end mill consisted of the same material as the step-threading tool, the end mill exhibited a region of decreased hardness beneath the laser-processed areas. We concluded that this was due to a tempering effect experienced during the lasing process, and that the overall processing time would have to be decreased even further to successfully harden the cutting edges of this component, while avoiding the generation of a heat-affected zone.

System Design and Specifications

Based on available literature for laser processing and the results generated from the process development contracts, a multi-functional laser station was designed. The proposed laser station needed to be a dynamic, extremely fast cutting, welding, and heat treating tool, placing particular demands on machine tool design. The unique geometries of military components, coupled with the difficulties of machining new exotic materials for the defense industry, generated the need for a versatile laser machine tool. In order for the laser to serve as a versatile tool, it should have the following general features:

1. A high degree of accuracy and repeatability.

2. Closed-loop process feedback systems coupled with a computer for integrated in-process quality control.

3. A modular design that lends itself from a simple three-axes design to a complex eight or more axes multiple machine. The axes motion is a combination of laser beams and workpiece manipulation.

4. Capability to attain very high energy density levels by beam manipulation. This capability would allow a variety of thermal processing techniques to be performed with a single laser system.

With this in mind, a set of detailed specifications was formulated highlighting the following laser system features and capabilities:

1. The contractor selected would provide and install a high power, carbon dioxide (CO_2), metalworking laser. The minimum output power range of the laser would span from 1000 to 5000 watts.

2. Laser beam divergence should not exceed three milliradians.

3. Output power stability should be within five percent of any selected power level.

4. A power monitor would be supplied with the laser.

5. A helium-neon alignment laser would also be supplied and installed coaxial to the main CO_2 output beam.

6. The contractor would provide and install a part-positioning unit. The positioner would be capable of CNC.

7. The positioner must be capable of supporting an external load of up to 1000 pounds, in addition to rotary, tilt, and T-slot tables. The rotary/tilt table must be capable of supporting a minimum workpiece load of 100 pounds.

8. The positioner would be capable of 5-axis motion. The axes of travel would be X, Y, Z, rotary, and tilt. Movement along these axes must be a minimum of:

- X - 24 inches
- Y - 12 inches
- Z - 12 inches
- Rotary - 360 degrees
- Tilt - 90 degrees

Rates of movement along these axes must be a minimum of:

- X,Y,Z - 300 ipm
- Rotary - 10 rpm

Repeatability and accuracy of movement in all axes specified must be within 0.005 inch.

9. The positioner would include the following features:

- Programmable home position.
- Programmable stop limits for table speed and working volume, c.
- Capability for positioning cylindrical components by means of a tailstock mounted on a T-slot table.

10. The contractor would provide and install a CNC unit capable of controlling elements of both the laser and positioner. This CNC unit would be capable of maintaining/varying X,Y,Z and rotational movement and corresponding rates of movement for the positioner selected. The unit would be equipped with an open and closed-loop digitizing (teach mode) capability to create part programs for positioning of a workpiece. It would utilize a bubble memory system and floppy disk storage system and be adaptable to a paper tape reader. The CNC unit must be capable of maintaining/varying CO_2 laser output power, rate of power increase and decrease, and assist gases. Shutter movement and helium-neon alignment laser would also be controlled by the unit.

11. The contractor would provide optics for both welding and heat treating applications.

12. A gas-to-liquid heat exchanger would be provided for the laser.

13. A portable enclosure must be provided which surrounds the beam focusing assembly and attachments, positioner, and workpiece.

Description of Equipment

The system, a combustion engineering industrial laser (CEIL) laser processing center (LPC), is a heavy-duty industrial machine designed for demanding production needs. The LPC series includes laser machine tools that employ the design principles of a vertical bed-type milling machine center. The column and base are heavy-duty stress-relieved Meehanite castings. The square machine ways are precision-machined, induction-hardened, and ground; the mating surfaces are Turcite-coated for wear resistance and minimization of stick and slip. The ways are protected by telescoping steel way covers that resist any high temperature deposits. Under the steel covers are the precision-ground, class A, preloaded ball screws.

The CEIL LPC series is designed to be virtually maintenance free. All three linear machine ways, the precision-ground nut and screw assembly, and all support bearings for the precision ball screws are automatically lubricated through a central lubrication system. The standard A/B-axes (rotary and tilting) tables are permanently lubricated by a built-in oil bath. All axes are driven by high performance, rare earth magnet DC motors controlled by a closed-loop CNC system. The linear axes are programmable in 0.0001-inch increments and the rotary and tilting axes in 0.001-degree increments. This high precision programmability, coupled with the high gain, quick responding motors, results in high speed positioning capability, which is important for fast and precise laser machining.

In line with CEILs philosophy to build heavy-duty, highly reliable laser machining centers, CEIL has chosen the design principles of a stationary-focused laser beam. The absence of moving beam bender mirrors virtually eliminates beam path alignment problems found on moving optics systems. Cost efficiency is improved as optical components and maintenance are reduced, which increases the overall "up-time" of the machine. The laser beam is only manipulated in the Z-axis, which travels in line with the vertical laser beam and therefore does not pose an alignment problem.

A schematic of the laser station is shown in Figure 8, and an overall photograph of the laser metalworking center is shown in Figure 9. Descriptions and selected statistics of the major components are given below.

Figure 10 shows the Spectra Physics 975 Laser. Its significant features include:

- 1-5 kilowatt power range
- Continuous wave
- Carbon dioxide lasing medium
- 10.6 micron wavelength (invisible)
- 3.0 milliradian divergence
- Power output stability of ±5 percent
- Beam diameter = 44 mm
- Beam pointing stability = 0.15 milliradians
- Shutter time = 0.1 second
- Helium-neon spotting laser (visible)

The laser power supply is shown in Figure 11, with significant features as follows:

- Output current = 0-40 amps
- Output voltage = 0-3000 volts
- Current ripple = < 5 percent peak-to-peak
- Current regulation = +1 percent for 24 hours

The laser control console is shown in Figure 12 featuring controls for:

- Supplied current
- Assist gas selection
- Laser power
- Helium-neon laser activation
- Shutter activation

Figure 13 shows the Allen Bradley 8200 CNC Pendant Controller. Its significant features include:

- 5-axis control
- CNC minifile floppy disk storage capability
- Paper tape reader capability

Figure 14 shows the X-Y workpiece positioner with the following features:

- X-axis travel of 36 inches
- Y-axis travel of 18 inches
- Precision of 0.0008 in./ft
- Repeatability of 0.0004 in./ft
- 1500 pound capacity

The rotary/tilt table (A-B) is not shown in this figure. However, it is mounted to the positioner to provide two additional axes of motion and maintains the following qualities:

- A-axis travel of 360 degrees (continuous)
- B-axis travel of 0-90 degrees
- Precision of 25 arc seconds
- 150 pound capacity

Figure 15 is a photograph depicting the variable Z-axis for focusing optics up to 18 inches. Its features include:

- Speeds of motion for X, Y, and Z axes of 400 ipm max
- Speeds of motion for A and B axes of 11 rpm max
- Fine focus assembly (welding head)
- Beam integrators (1/4, 3/8, and 1/2 in.^{2})

Figure 16 shows the remote operation digitizer and Figure 17 shows the roll-away enclosure. The Application Engineering heat exchanger/chiller is shown in Figure 18, with a magnified view of its diagnostic control panel in Figure 19. Significant features of the heat exchanger include:

- Closed-loop one degree accuracy water-to-air
- Flow:

  Minimum (gpm) - 20

  With accessories (gpm) - 24
- Pressure:

  Recommended supply pressure (psig) - 60

  Maximum supply pressure (psig) - 100

  Maximum back pressure (psig) - 10
- Temperature:

  Minimum temperature (°F) - dew point

  Recommended temperature (°F) - 72°

  Temperature control (°F) - 2°
- Resistivity:

  Low (k/cm) - 8

  High (k/cm) - 200
- Filtration at supply line (microns) - 250

The facility requirements for system operation include:

- Primary power of 60 Hz operation
- 460 volts attenuating current (VAC)
- 200 amps/line
- Three-phase
- Cooling water of 24 gpm flow
- Pressure of 40 psig with minimum differential of 100 psig
- Maximum supply temperature of 95°F
- Minimum supply temperature above dew point temperature
- Temperature control of ±2°F
- Resistivity of 20-50 k/cm
- Compressed air clean, dry, 20 standard cubic feet per hour (SCFH)
- Flow pressure of 0.5 cfm at 60 psig
- Gas consumption:

Helium:	4.0 SCFH - industrial grade 99.99 percent pure
N_20_2:	1.8 SCFH - industrial grade 99.99 percent pure
CO_2:	0.3 SCFH - welding grade 99.50 percent pure

- Average cost per hour of laser consumables:

CO_2	$ .10
Helium	.68
N_20_2	.14
Argon (welding)	.30
Water	1.87
Electricity	5.04
Total cost of consumables per hour	$7.74

System Implementation

Initial applications for the laser involved surface transformation hardening (heat treatment) of selected areas on several cannon components. It was decided that heat treatment would be the main processing technique initially evaluated using a laser. This decision was based on the fact that cutting, welding, and engraving are much more established techniques that employ lasers and have already been proven as viable alternatives to conventional processes. Heat treatment, on the other hand, is a less developed area with virtually unlimited potential.

The selected components had very stringent mechanical property requirements imposed on them that were difficult or impossible to fulfill utilizing conventional thermal processing methods, such as bulk furnace, induction, or flame-hardening techniques. The laser offered numerous advantages over these techniques in the heat treatment process. These advantages include:

- Minimal distortion
- Minimal heat-affected zone
- Automation of process
- Superior control of case depth and location
- No need for quenchant

These components were subjected to laser heat treatment processes and then destructively analyzed by our laboratory to determine the optimum lasing parameters to be used for production. Once reliable parameters were established, the process was scaled up and utilized to selectively harden the cam paths on the M119 breechblock. A material analysis was performed on three of these breechblocks, two of which had been laser-hardened and one of which had been induction-hardened. The objective of this analysis was to determine and compare the microhardness profiles of each cam path produced by the two thermal processes.

Each breechblock was examined according to the following procedure with results described below:

- Visual examination
- Metallographic examination
- Microhardness measurement
- Case depth measurement and calculation

Figures 20(a) and (b) show the visual examination findings. These figures illustrate the laser-hardened portion of the M119 breechblock cam path.

Results of our metallographic evaluation are displayed in Figures 21 and 22. Figures 21(a) and (b) depict three distinct zones, 1 through 3, created by the laser and induction-hardening processes. For both processes, zone 1 is the hardened zone closest to the surface, zone 2 is the heat-affected zone underneath, and zone 3 is the base metal. Higher magnification photomicrographs of these zones are exhibited in Figures 22(a) through (c). In addition, it was also discovered optically that zones 1 and 2 in the laser-hardened sample were much thinner than the corresponding zones in the induction-hardened specimen. Therefore, the overall hardened region of the induction-processed material extended much deeper than that of the laser-processed material.

The converted results of microhardness testing are contained in Table 4. The values presented in this table are the Rockwell hardness numbers (HRC), which correspond to and have been converted from the original Knoop microhardness numbers. Placement of the Knoop indentations within the three zones is illustrated in Figure 23. The overall trend that occurred in both the laser and induction-hardened specimens was a decrease in hardness from zones 1 to 3. In the hardened zone, results of 47 to 55 HRC were recorded for the laser samples versus 44 to 49 HRC for the induction specimen. For zone 2, the heat-affected zone, hardness readings were 38 to 46 HRC for laser-hardened material and 41 to 48 HRC for induction-hardened material, respectively. Lastly, the base metal from the laser process was 37 to 42 HRC and from the induction-hardened process, it was 28 to 44 HRC.

Table 4. Microhardness Measurements
(Converted to HRC values)

	Laser-Hardened				Induction-Hardened		
Sample ID*	1T	1L	2T	2L	3T	3L1	3L2
Hardened Zone HRC	51	52	55	49	47	47	47
Heat-Affected Zone HRC	42	40	46	39	46	48	41
Base Metal HRC	41	41	42	38	35	44	28

* "T" samples are transverse; "L" samples are longitudinal.

Table 5 contains the case depth measurements (depth of the hardened zone) for both the laser and induction-hardened material. Photomicrographs similar to Figures 21(a) and (b) were utilized to physically measure the depth of the hardened zones, and subsequently, case depth was calculated according to the following equation:

$$\text{case depth} = \frac{\text{measured length of hardened zone}}{\text{magnification of photograph}}$$

Results indicate that the case depth of the induction-hardened material ranged from 0.031 inch to 0.219 inch, and was approximately three to twenty times greater than the case depth of the laser-hardened material which was determined to range from 0.010 inch to 0.012 inch. This corroborates the earlier optical observation that the case depth of the hardened zone of the induction-processed material was visibly much larger than the corresponding zone of the laser-processed material. One of the most publicized benefits of laser-hardening is case depth uniformity, which was verified in our experiments. However, deep cases are difficult to attain with lasers, and induction-hardening is the method of choice.

Table 5. Case Depth Measurements

	Laser-Hardened				Induction-Hardened		
Sample ID*	1T	1L	2T	2L	3T	3L1	3L2
Magnification	100X	100X	100X	100X	40X	40X	19.2X
Measured Hardened Zone (in.)	1.12	1.06	1.25	1.06	1.31	1.25	2.4-4.2
Case Depth (in.)	0.011	0.010	0.012	0.010	0.033	0.031	0.125-0.219

* "T" samples are transverse; "L" samples are longitudinal.

In summary, this analysis comprised a metallographic and microhardness comparison between laser and induction-hardened M119 breechblock cam paths. Metallographic evaluation revealed three distinct zones: hardened, heat-affected, and base metal. Knoop microhardness measurements located in the corresponding zones indicated that hardness decreased from zones 1 to 3. In addition, case depth measurements were found to be approximately three to twenty times greater in the induction-hardened material than in the laser-hardened material.

CONCLUSION

The laser metalworking station has proven to be a unique, versatile tool for thermal processing of cannon components. The station's successful implementation at Watervliet Arsenal has not only served to supplement and expand their existing production facilities/capabilities, but in many instances has outperformed all other available processing techniques. In particular, the laser has been utilized for localized heat treatment of selected production components (i.e., 105-mm M20 followers and pivot bearings), and has consistently exhibited a number of advantages over conventional heat treatment methods. These advantages include complete process automation, very small heat-affected zones, and minimal part distortion during heat treatment. Experimentation has also shown that the system is capable of producing laser beam power densities high enough for component melting (welding applications) or vaporization (cutting applications) to occur. These capabilities have opened new horizons for cannon manufacture at Watervliet.

FUTURE APPLICATIONS AND EQUIPMENT

During the course of this project, Watervliet Arsenal and Benet Laboratories personnel have become increasingly more knowledgeable of and experienced with the laser station and its capabilities. As a result of this increased understanding of laser systems and technologies, a number of additional production applications have been proposed. In order to take full advantage of the station's versatility, these potential applications for the station have included laser welding and cutting of selected cannon components/materials, as well as specialized heat treatment tasks. The applications include:

1. Heat treatment

- XM284 minor breech components
- 40-mm cover roller path
- 105 M68 driver tab
- Various case hardened pins (155-mm M185 spring rack)
- 120-mm bearing shaft
- Tank bolts (elevating mechanism for M1)
- 155-mm XM284 hammer (case hardened)

All of the above components have proven to be difficult to process using conventional heat treatment methods.

- Research related - hardening beneath chromium plating on gun tubes for increased adherence
- Hardening of critical radii for increased fatigue life (155-mm M185 housing - blockway radii)

2. Welding

- 120-mm bore evacuator (automate process)
- Tube stiffeners (105 enhanced)
- 120-mm muzzle reference system
- Localized repair jobs (gouges)

3. Plating/cladding/surface alloying

- Mandrel coatings (rotary forge)
- Forge hammer coating
- Tool surface modification by rapid solidification processes (rifling broaches, sector cutters, end mills, etc.)

4. Cutting/vaporizing

- 120-mm bore evacuator sheet metal cutting (stainless)
- Deburring origin-of-rifling
- Specialized sample cutting

In order to accomplish many of the proposed tasks, additional accessory equipment is required. These accessories are currently being procured and include the following capabilities:

1. Laser beam scanner - The laser beam scanner is an industrial lightweight product that has been designed to be rugged and easy to use. The beam is transmitted and focused through this water-cooled unit via two standard off-axis molybdenum-coated copper mirrors. The mirrors are identical to those used in the standard and rotary mirror focus units. The focusing mirror can be oscillated about its center line to 1.2 degrees, which translates to about a 0.50 inch scan of a focused beam. By varying the spot size and scan width, virtually any desired energy distribution can be attained. The weight of the scanner is approximately 75 pounds in a compact design. The laser beam scanner is capable of handling up to 6000 watts of CO_2 laser power, and is commonly used for heat treatment applications requiring in-process spot size control.

Specifications of the beam scanner include:

- Power - 0-6000 watts
- Beam diameter - 2.0 in.
- Maximum scan width - 0-1.0 in.
- Spot size - controlled by the Z-axis on CNC
- Power supply requirements - 110 VAC

2. Powder feed delivery system - The powder delivery system includes a powder metering hopper and nozzle assembly. It is capable of metering metal powder (mesh size 125 to 325) at a rate of 12 to 30 gpm. The powder nozzle is water-cooled, and is used for welding operations when filler metal is required.

3. Fume removal system - The selected vacuum unit will be used to draw-off the fumes from laser processing and collect the fumes and debris in an easily accessible receptacle.

The addition of these accessories, coupled with their utilization on the applications listed above, will complete implementation of the laser station at Watervliet Arsenal.

Figure 1. 105-mm M68 breechblock with arrows showing cam path region.

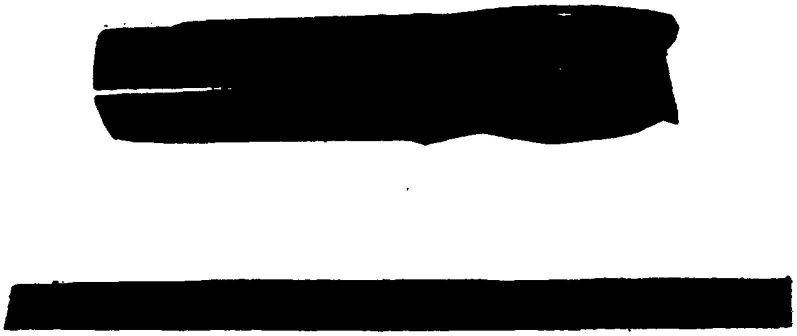


Figure 2. Dual point, step-thread cutting tool with cutting edges exposed to laser processing.

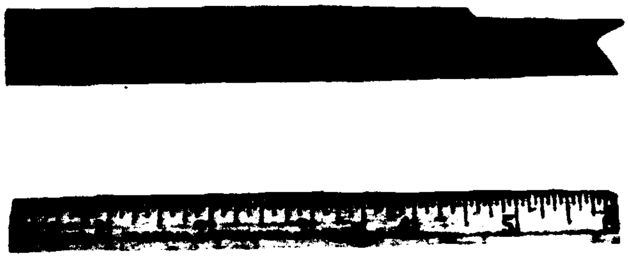


Figure 3. Common tool steel end mill cutter with cutting edges exposed to laser processing.

Figure 4. Magnified view of 105-mm M68 breechblock cam path with arrows pointing to areas to be laser treated (hardened).

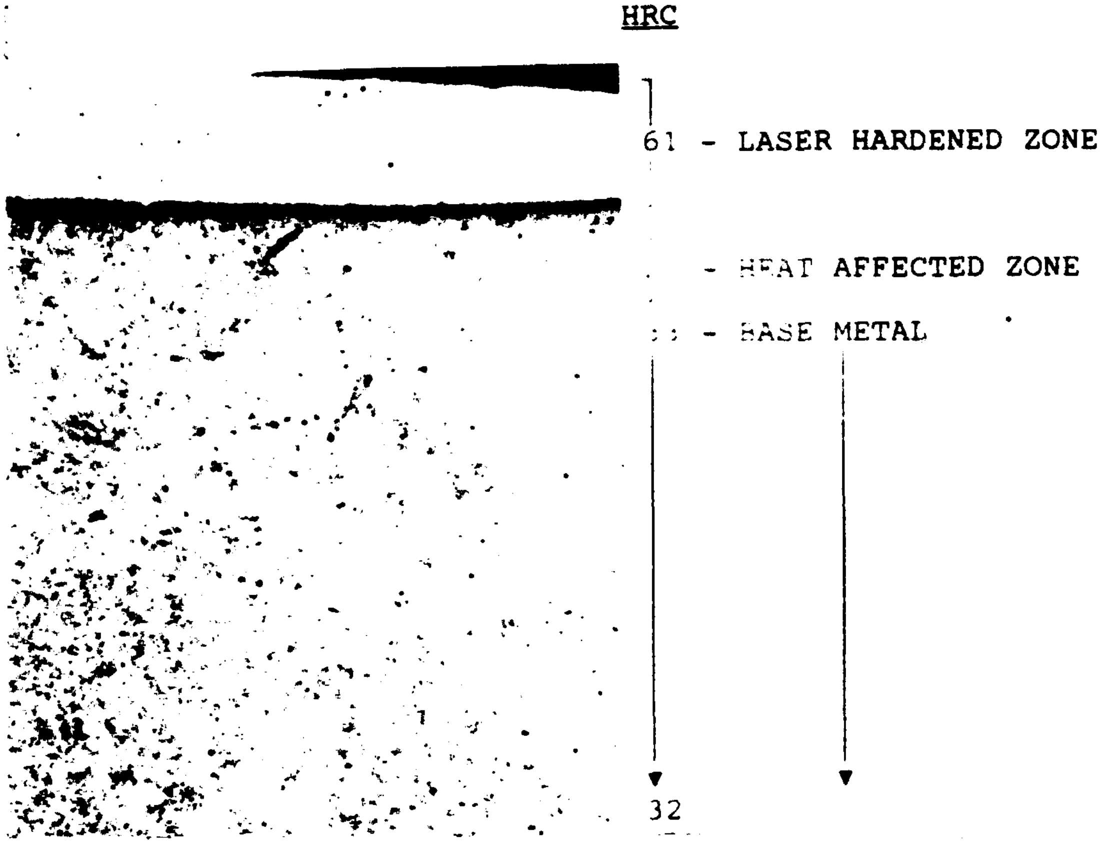


Figure 5. Cross-sectional view of breechblock microstructure after laser treatment. The light band at the top is hard, untempered martensite produced during exposure to the laser beam (25X).

Figure 6. Cross-sectional view of the cutting edge of the dual point cutter.
The top, lighter band indicates the area exposed to the laser beam (32X).

Figure 7. Cross-sectional view of the cutting edge of the end mill cutter.
The top, lighter band indicates the area exposed to the laser beam (32X).

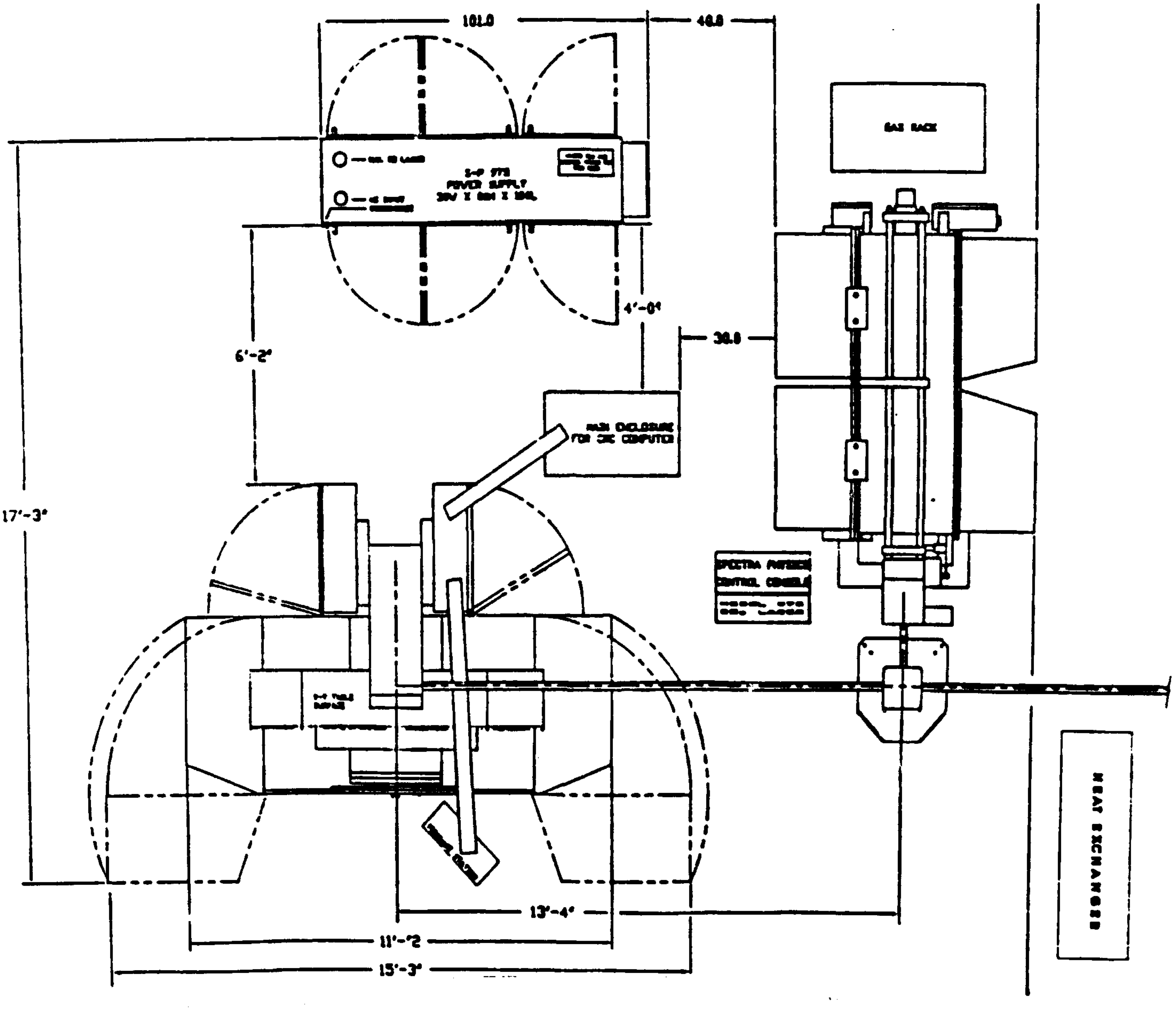


Figure 3. Schematic drawing of laser metalworking station.

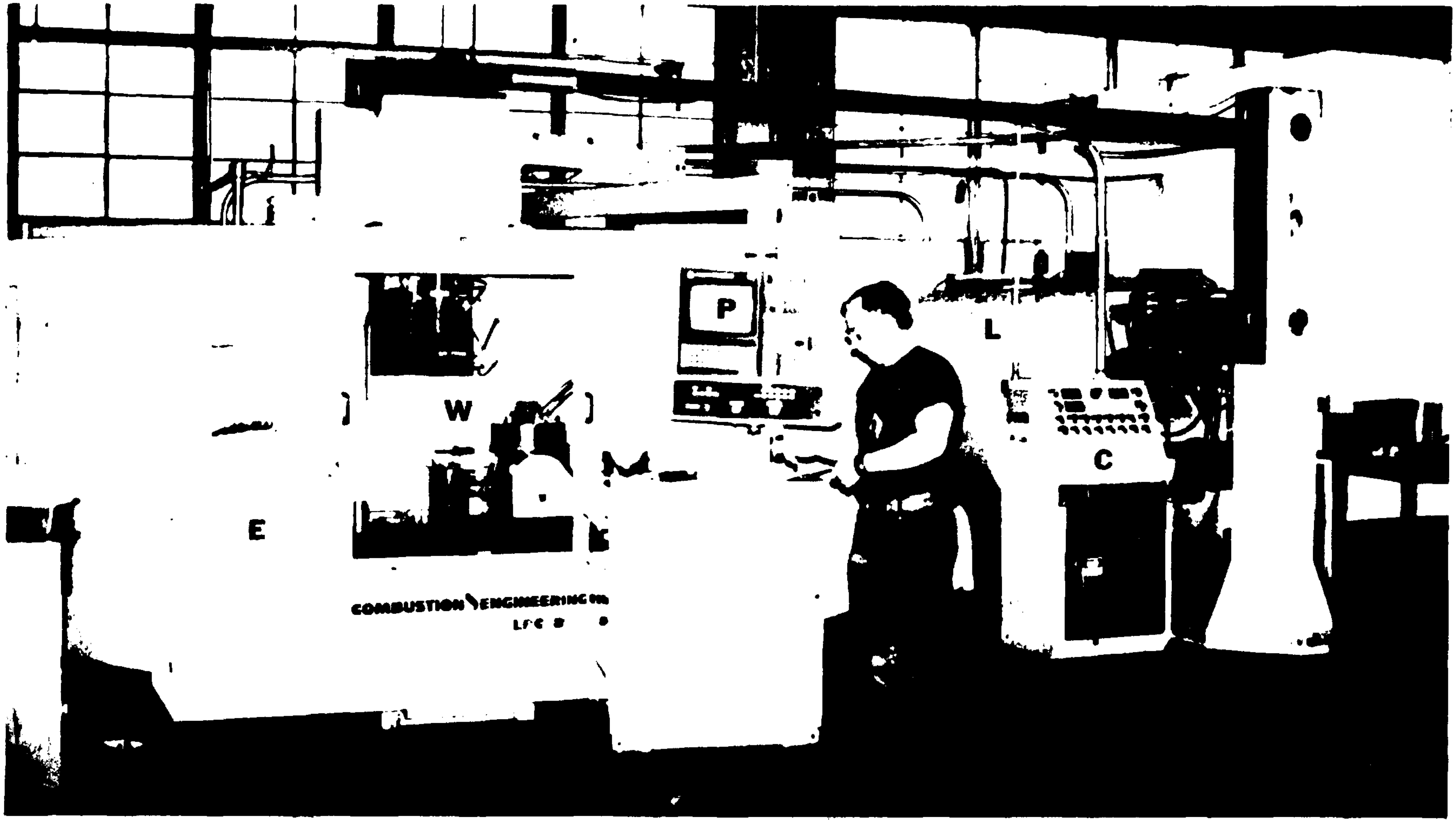


Figure 9. Photograph of laser metalworking station implemented at Watervliet Arsenal. This photo shows most of the station's major components: (L) laser resonation chamber, (P) CNC pendant controller, (E) portable enclosure, (C) laser control console, and (W) enclosed work cell.

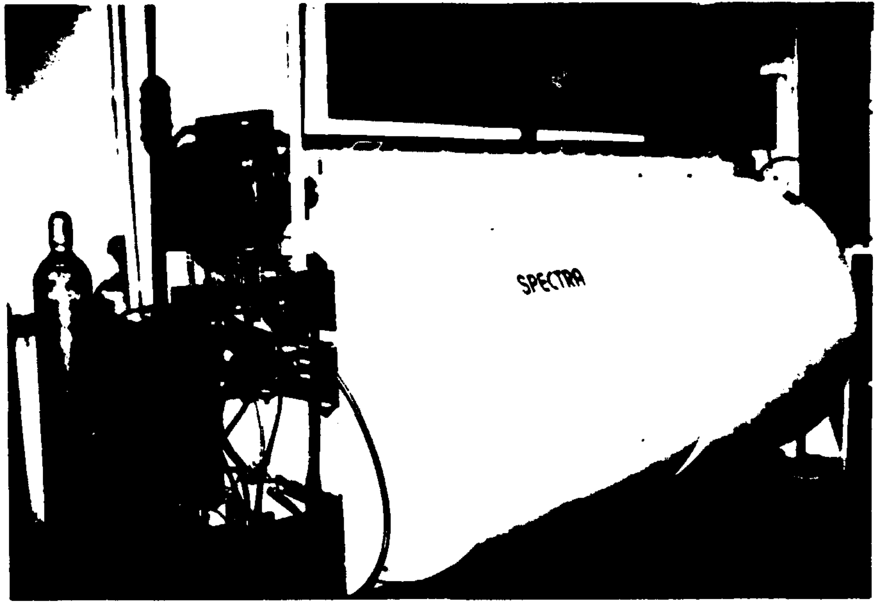


Figure 10. Spectra Physics 975 Carbón Dioxide Laser.

Figure 11. Power supply cabinet for laser.

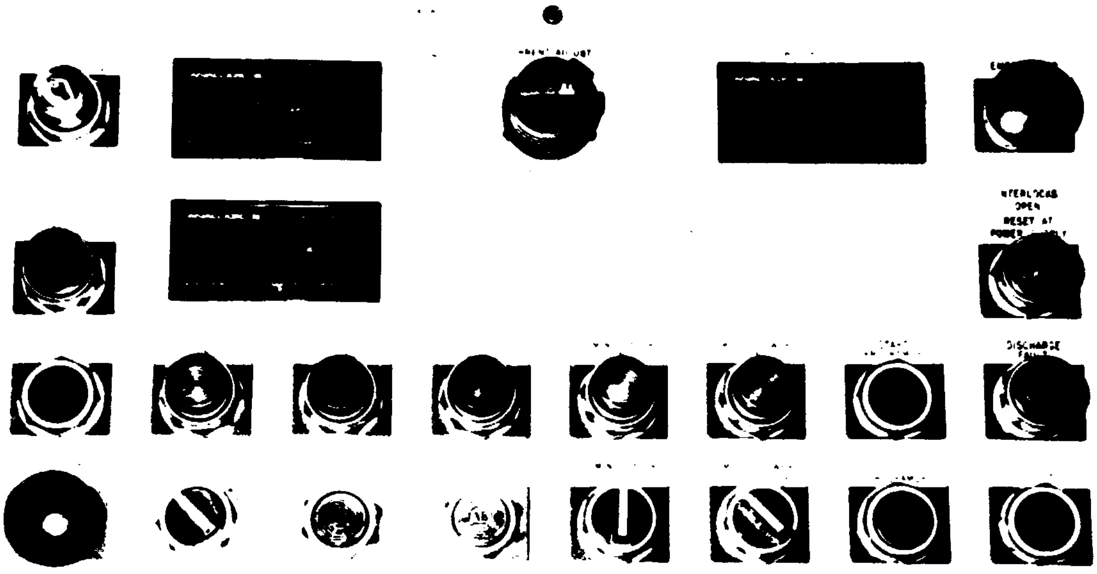


Figure 12. Laser control console.

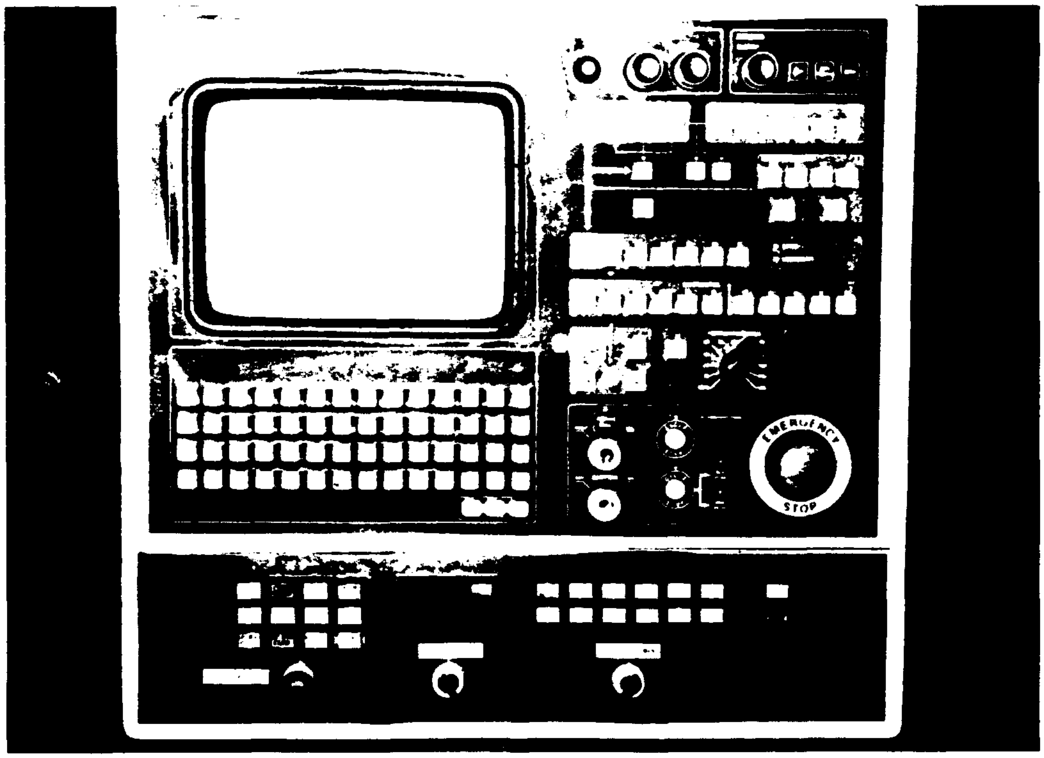


Figure 13. Allen Bradley 8200 CNC Pendant.

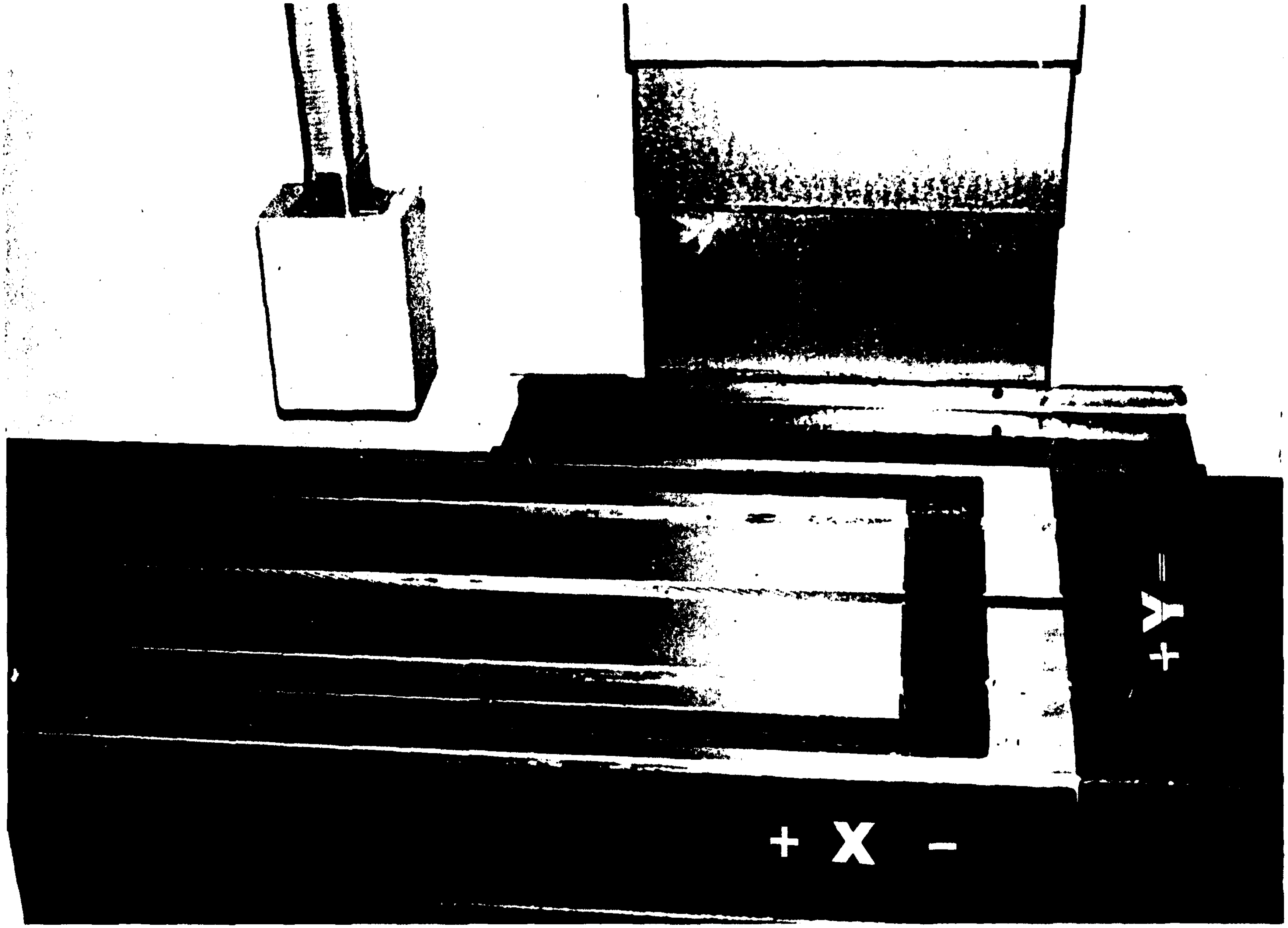


Figure 14. X-Y workpiece positioner. The rotary tilt table (not shown) is mounted to this positioner to provide two additional axes of motion.

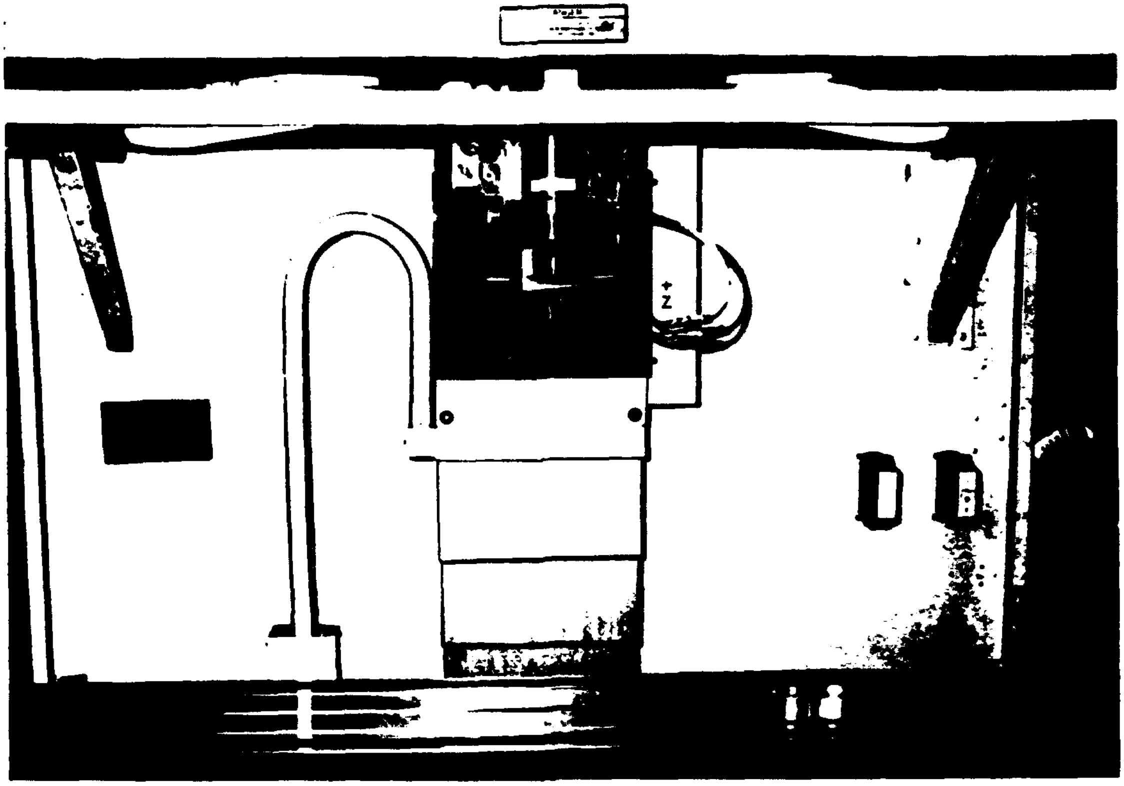


Figure 15. Photograph showing beam focusing assembly mounted to the Z-axis of the laser station. This axis is used to accommodate varying workpiece heights.

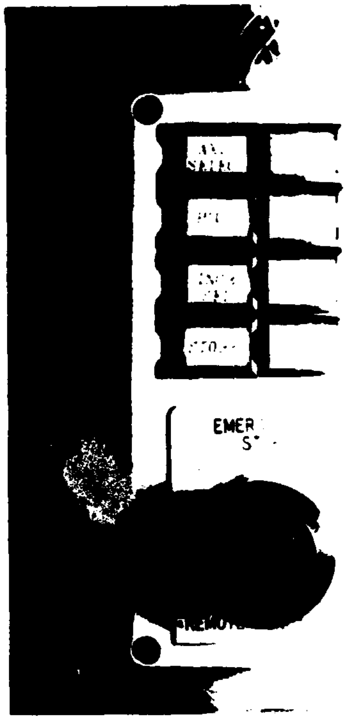


Figure 16. Program digitizer used for remote cable control and programming of component motion.

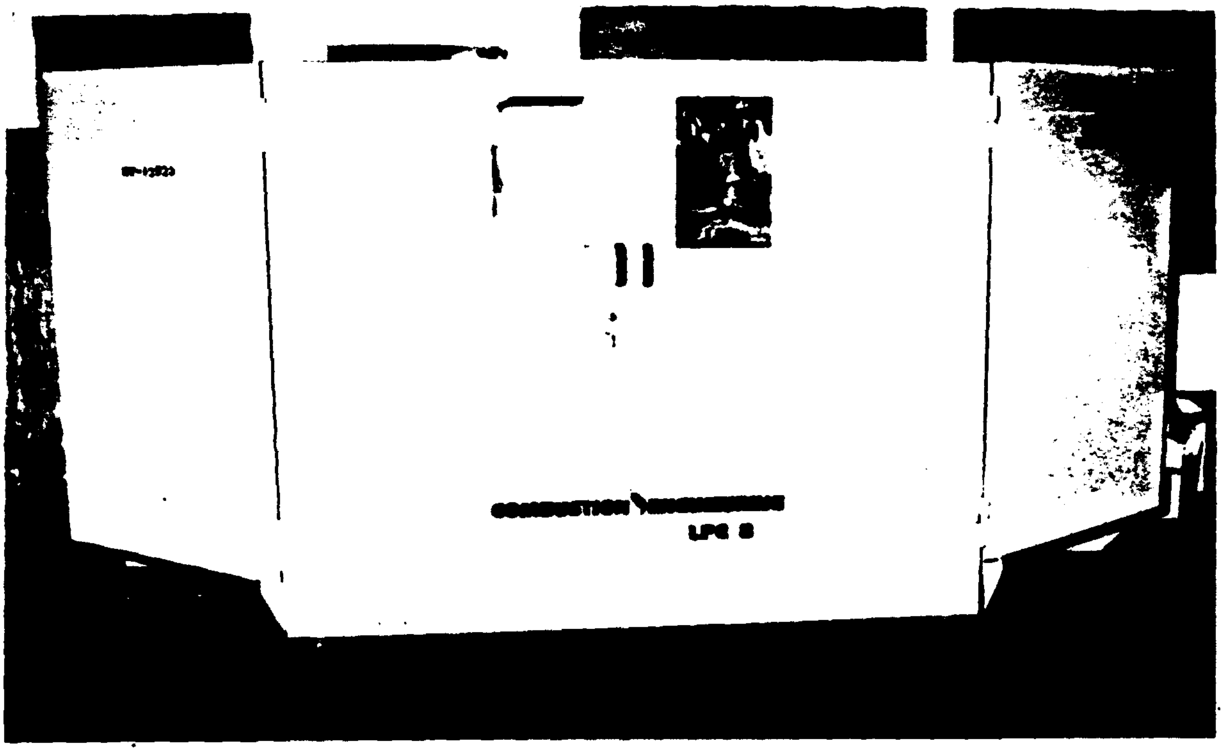


Figure 17. Portable safety enclosure for work area.

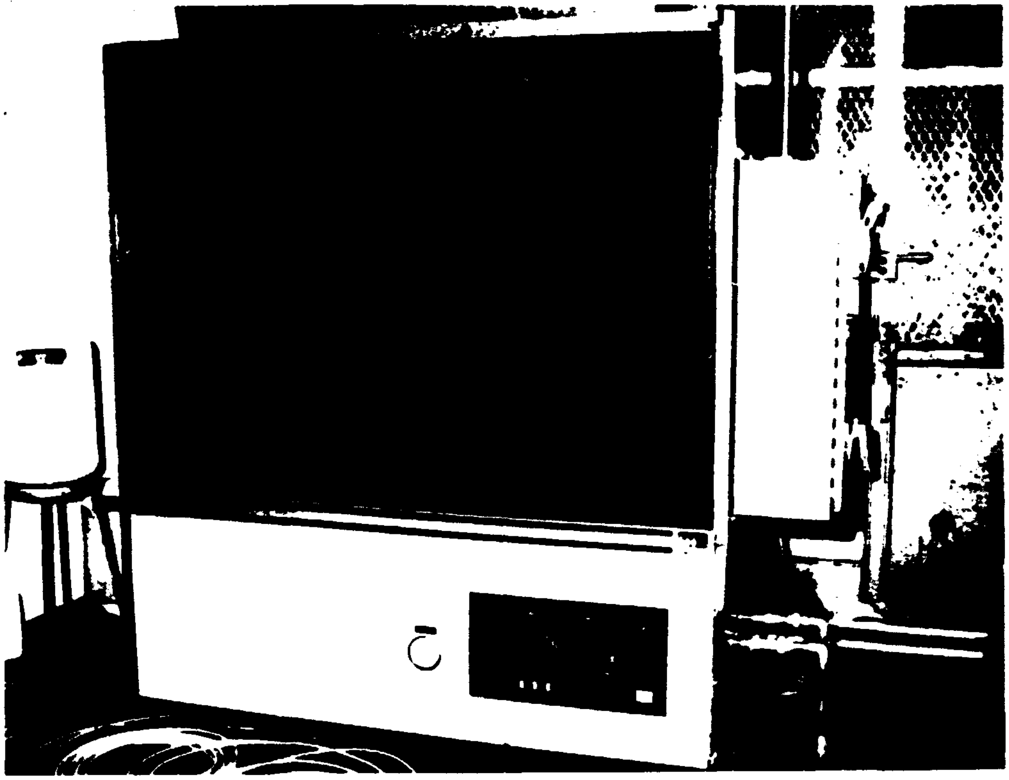


Figure 18. Application Engineering Model HE-33 heat exchanger.

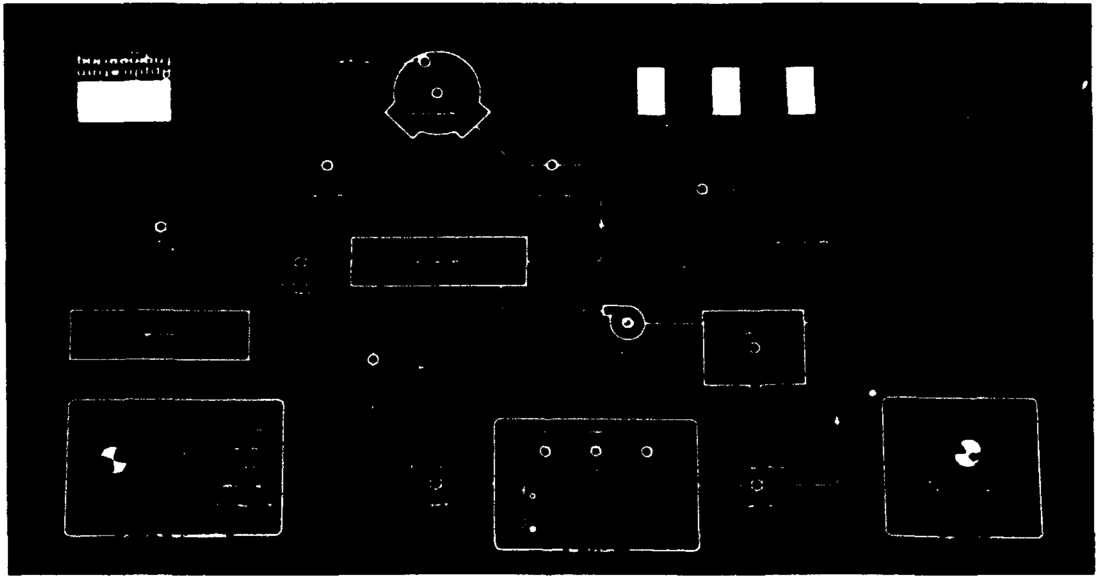
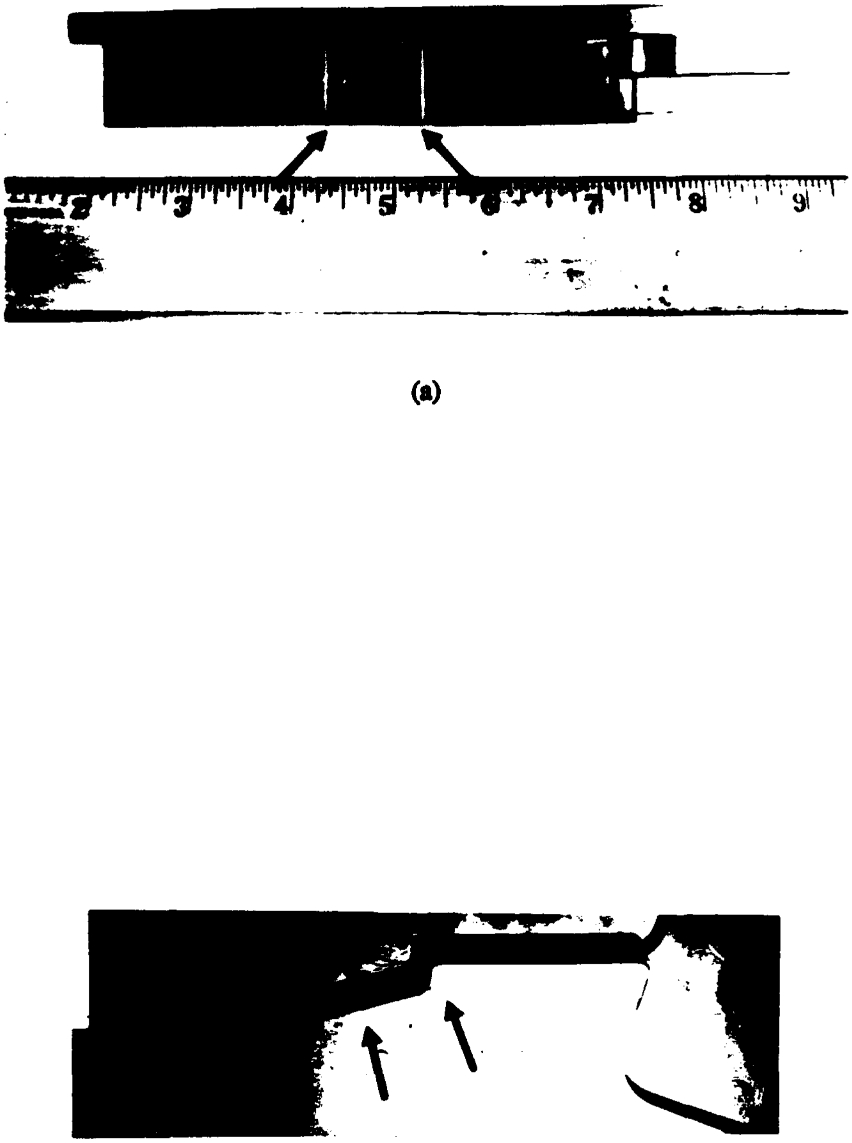


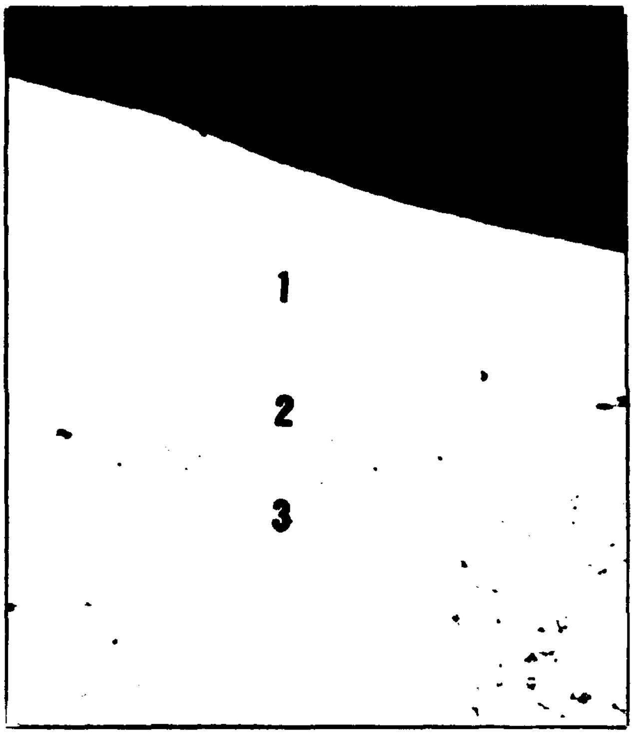
Figure 19. Magnified view of heat exchanger's diagnostic control panel.



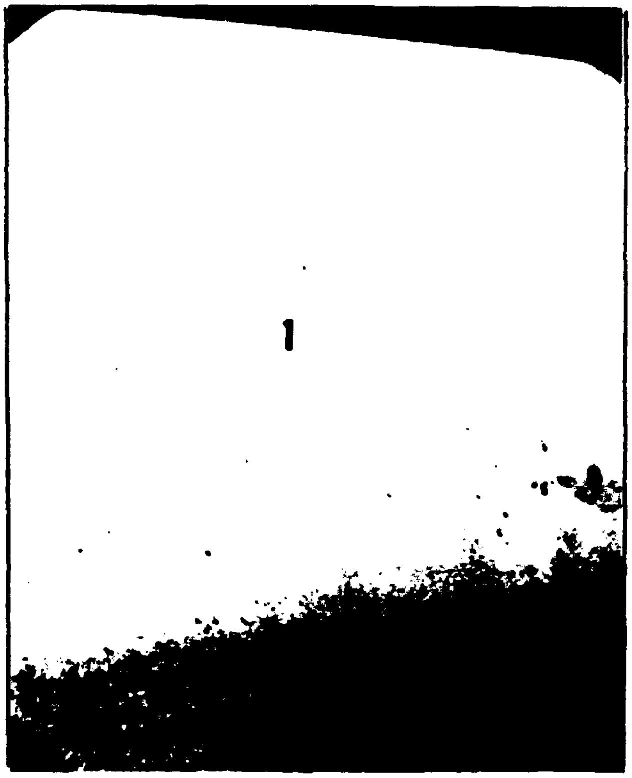
(a)

(b)

Figure 20. Photographs detailing laser-hardened portion of M119 breechblock cam path, as-received.

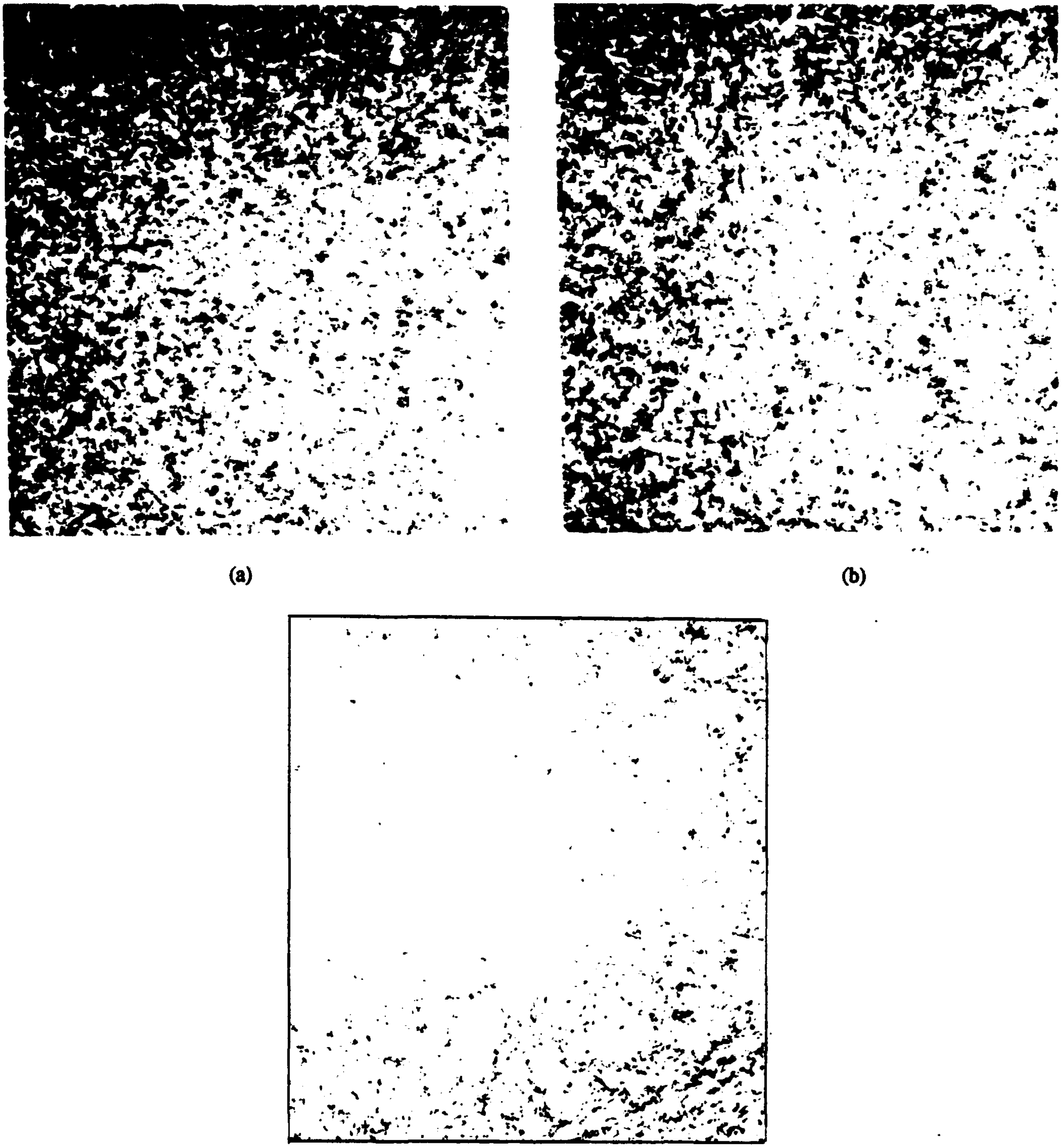


(a) 100X



(b) 19.2X

Figure 21. Photographs showing (1) hardened, (2) heat-affected, and (3) base metal zones of laser and induction-hardened breechblock cam paths, respectively. 2% Nital.



(a) (b)

(c)

Figure 22. High magnification photomicrographs illustrating hardened, heat-affected, and base metal zones, respectively, of laser-hardened breechblock. 2% Nital (1000X).

Figure 23. Photomicrograph illustrating location of Knoop indentations from microhardness testing on laser-processed sample. 2% Nital (100X).

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