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LABORATORY
TECHNICAL REPORT

NO. 12606

LASER HEAT TREATMENT OF TRACK
COMPONENTS IN COMBAT VEHICLES
(PHASE I)



Contract DAAK30-79-0136

JUNE 1981

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Rockwell Report SC5248.12FR

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2003/2/1014

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Laser Heat Treatment of Track Components in Combat Vehicles (Phase I)		5. TYPE OF REPORT & PERIOD COVERED Final Report 12606 09/26/79 through 09/25/80
7. AUTHOR(s) D.S. Gnanamuthu and R.J. Moores		6. PERFORMING ORG. REPORT NUMBER SC5248.12FR
9. PERFORMING ORGANIZATION NAME AND ADDRESS Rockwell International Science Center 1049 Camino dos Rios Thousand Oaks, California 91360		8. CONTRACT OR GRANT NUMBER(s) DAAK30-79-C-0136
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Tank-Automotive Research and Development Command Warren, Michigan 48090		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE June, 1981
		13. NUMBER OF PAGES 96
		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release: distribution unlimited		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) End connector, center guide, T-142 track, M-60 combat vehicle, low alloy steel, continuous wave CO ₂ laser, laser heat treating, energy absorbing coat- ing, self quenching, laser power, laser beam size, travel speed, case depth, case hardness, hardness profile, core hardness, abrasive wear, microstructure, martensite, tempered martensite, bainite, ferrite, optical tooling, mirrors.		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Abrasive wear locations in end connectors and center guides used in combat vehicles were precision heat treated with a continuous wave CO ₂ laser beam. Self quenched casings 3 to 4 mm deep, with predominantly martensitic micro- structure of hardness between Rc 50 to 54, were observed. Coverage rates up to 90 mm ² /s were obtained. Abrasive wear tests revealed that laser heat treated specimens had smaller wear scar dimensions than untreated specimens. In a 9 mm thick AISI 4140 steel plate, case depth of 6.5 mm was obtained.		

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Heat treatment was conducted with laser beam power of 4000 to 5000 W, with the beam shaped by a three-mirror optical tooling to provide a uniformly intense beam, of size 19 x 19 mm. With this optical tooling, a stand-off distance of 445 mm between beam directing mirror and work surface was available. Laser heat treating cost estimates for an end connector were found to be \$0.60 and for a center guide \$0.69. Specifications and cost estimates for a prototype laser heat treating facility were developed. Quality assurance specifications, to control consistency of laser heat treatment from part to part, were proposed. Implementation of laser heat treating technology for the manufacture of track components will not modify manufacturing steps currently practiced, but will substitute induction or flame hardening methods.

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FOREWORD

This report describes a methods and manufacturing technology program for the heat treating of combat vehicle track components by using a CO₂ laser beam. This program was awarded to the Rockwell International Science Center by the Army Tank-Automotive Research and Development Command (TARADCOM) under Contract DAAK 30-79-C-0136. Mr. C. Douglas Houston was the technical monitor for this program.

Designs for optical tooling were provided by Mr. E. W. Denny and Mr. R. L. Pierce of Spawr Optical Research, Inc. Metallographic analyses were performed by Mr. M. Calabrese of Rockwell International Science Center. Abrasive wear tests were conducted at the Southwest Research Institute. Authors of this report thank Mr. S. Goodman, Mr. G. Szakacs, and Mr. J. O. Fix all from TARADCOM, for providing data on tank tracks valuable for this program.

1.0 INTRODUCTION

Track components in a combat vehicle consist of end connectors, center guides, shoes, and connecting pins. These components require superior strength and therefore are fabricated from low alloy steel forgings. Figure 1 shows a M-60 combat vehicle and location of these track components. During service, an end connector's curved surfaces are subject to sliding contact with the drive sprockets in the presence of trapped abrasive ground soil between these sliding surfaces. End connectors currently are not surface hardened (to increase abrasive wear resistance) because of their geometry, but are instead used in service in the austenitized/quenched/tempered condition with a tempered martensitic core microstructure of hardness ranging between Rc 40 to 45. For center guides, the "bearing" type surfaces are subject to rubbing and riding against road wheels and entrapped abrasive ground soil between rubbing surfaces. The grouser areas in shoes come in direct contact with and rub against ground soil. Therefore, locations in center guides and shoes subject to abrasive wear are currently surface hardened by induction heating. Connecting pins are subject to a combination of cyclic loads and, therefore, to provide adequate fatigue life, are used in the austempered condition with a bainitic core microstructure of hardness of about Rc 45. Some of these track components are subject to severe abrasive wear under the increased load conditions experienced during frequent steering (turning) of vehicles. Service failure of any one of these components often requires the replacement of an entire set of track components.

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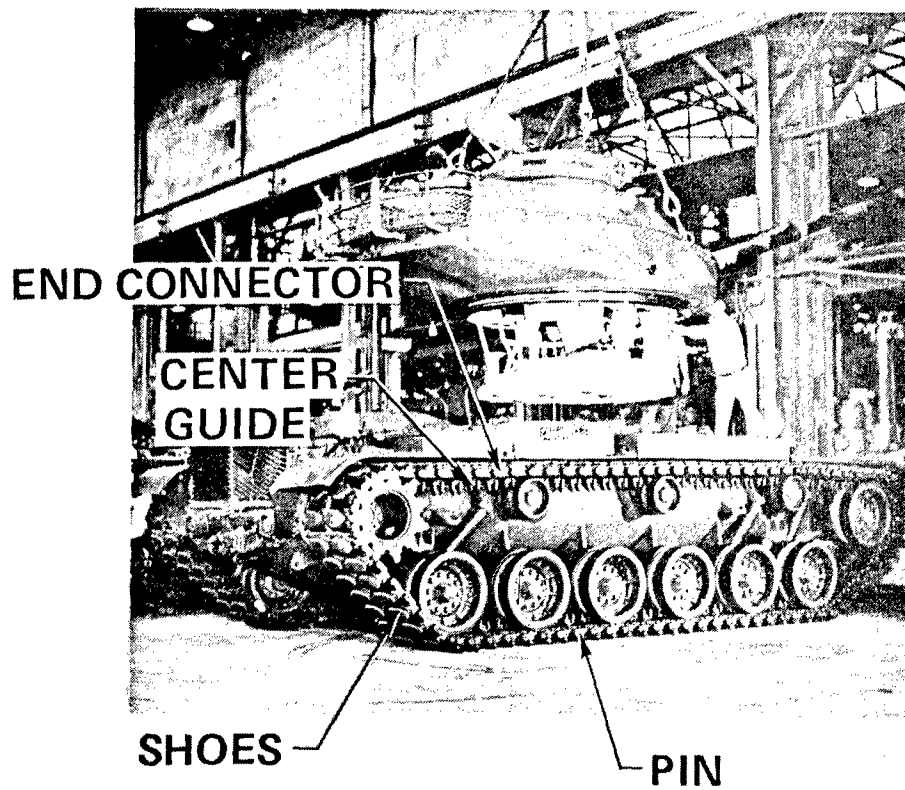


Fig. 1 Location of track components in a M-60 combat vehicle.

Figures 2 and 3 illustrate the required regions to be surface hardened in end connectors and center guides. Current methods of induction hardening are not well suited for surface hardening end connectors because these components are:

- Non axisymmetric around curved surfaces
- Complex shaped (complicated by the presence of a slotted hole)
- Slightly non-uniform in size around curved surfaces from part to part.

Therefore, induction heat treated depths can vary from part to part as well as within a part because of asymmetry along curved surfaces. In addition, surface hardening should be avoided near or at the slotted hole (to prevent crack initiation during service). Thus, end connectors in T-142 tracks used in M-60 combat vehicles currently are not surface hardened (problems may be similar for end connectors used in other combat vehicles).

Center guides in T-142 tracks now are induction heated then liquid quenched in a suitable medium. Formation of surface cracks during quenching must, however, be avoided. Also, the tips of the "fingers" in center guides must not be surface hardened in order to prevent spalling of the hardened case during impact against road wheels. Clearly, alternative methods of surface hardening would result in longer service life and/or lower surface hardening costs for these track components.

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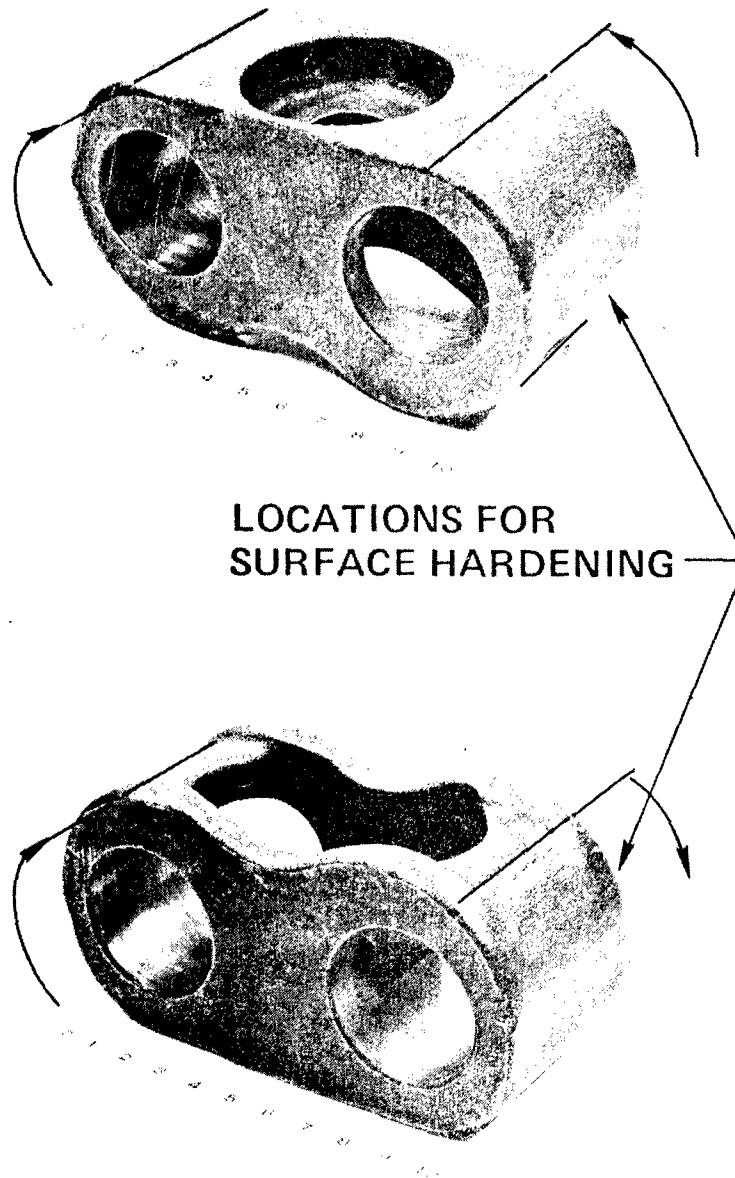


Fig. 2 Two views of an end connector showing locations for surface hardening.

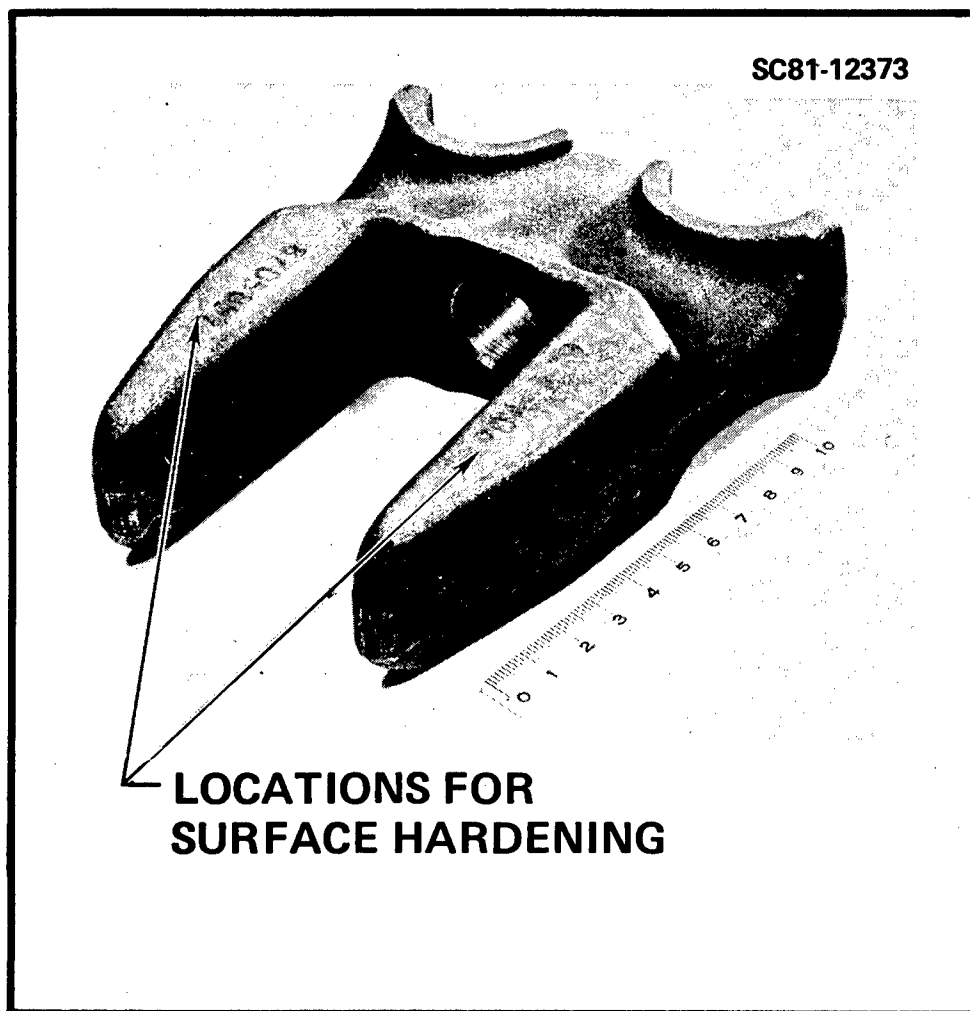


Fig. 3 Locations for surface hardening in center guides.

This MM&T (methods and manufacturing technology) study shows that surface hardening requirements for both end connectors and center guides from T-142 tracks can be met adequately by heat treatment with a CO₂ laser beam, and that these methods can be extended to track components in other combat vehicles as well. Basically, heat treating using a laser beam offers the following advantages:

- Efficiency in precision placement of hardened patterns
- Ability to heat treat parts of complex geometry
- Control of case depth and width from part to part
- Processing under normal atmospheric conditions
- Self quenching by workpieces
- Negligible workpiece distortion
- Large stand-off distance between optical tooling and work surfaces
- Adaptability to a manufacturing environment.

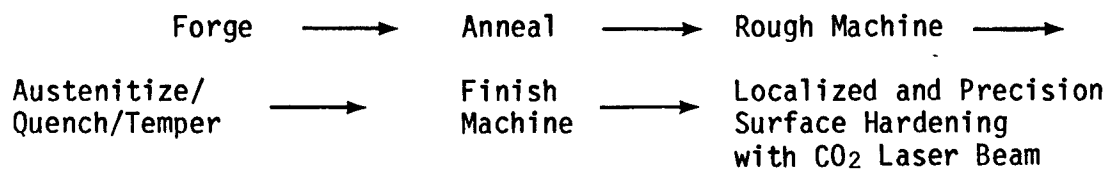
If the wearing and abrading surfaces of track components can be made resistant by means of precision heat treating, the service life of these components can be increased and therefore, increase the time between replacement of parts thus saving considerable maintenance costs. In general, for combat vehicle track components subject to wear, abrasion, and possibly impact, acceptable microstructural and hardness requirements are:

- Case microstructure of martensite with hardness near Rc 55, precisely localized to wear and abrasion zones

- A tough core structure of tempered martensite suitable to withstand impact and resist crack propagation
- A gradual hardness drop through the case depth.

These requirements can be met by using currently manufactured track components and adapting laser heat treatment for precision surface hardening only those locations subject to abrasive wear.

Implementation of laser heat treating of track components in a manufacturing environment will not alter the currently practiced manufacturing cycle illustrated here:



The above manufacturing cycle has adapted laser heat treatment for surface hardening instead of induction or flame hardening.

2.0 HEAT FLOW MODEL

A broad area CO₂ laser beam such as that used for heat treating (power density less than 10^4 W/cm²) is not fully absorbed by machined steel surfaces. However, when steel surfaces are coated with infrared absorbing paints, these surfaces become highly absorbing for CO₂ laser beams. Generally, laser heat treating is accomplished by sweeping a workpiece at controlled speeds under a laser beam, and each incremental area of work surface is therefore heated and cooled (by self quenching). Heat generated during the laser beam's interaction with the coating is localized at the surface. When heat is conducted into the substrate, a finite volume of the substrate is heated above austenitizing temperature and is subsequently cooled sufficiently rapidly to yield martensite. Figure 4 provides a schematic illustration of the process. Factors that govern hardness and depth of hardening are heat treating temperature and holding time. Range of heat treating temperature on work surface is controlled by absorbed laser power, beam size, beam configuration (e.g., scanning Gaussian beam, defocused Gaussian beam, uniformly intense beam), beam dwell time (processing speed), energy absorbing coating, and core microstructure of steel component (pearlite, bainite or tempered martensite).

For a given track component, heat treating conditions to generate desired case depths under optimum processing conditions can be calculated by simple analytical models of laser heat treating. These models predict relationships between laser power and case depth for various processing speeds

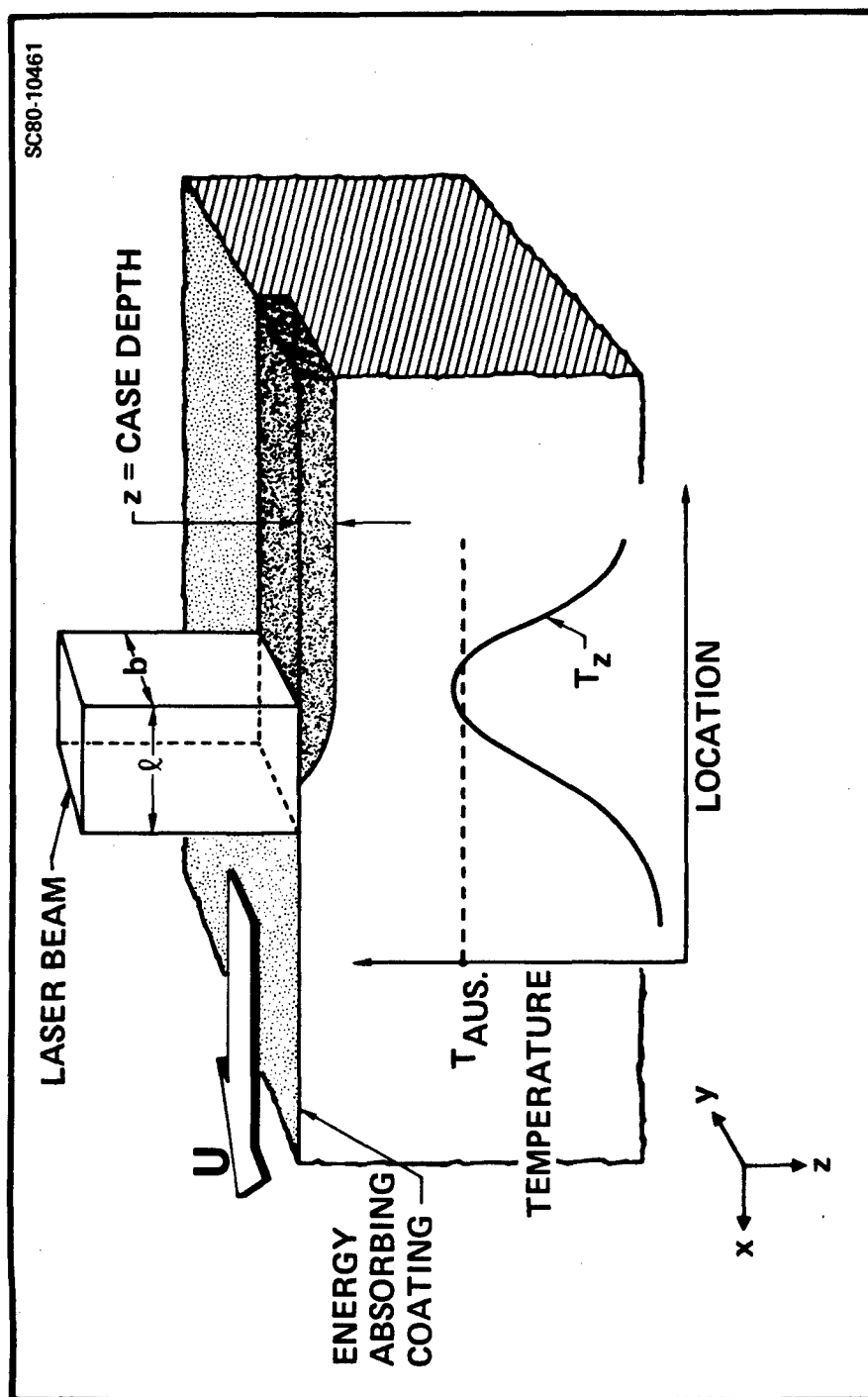


Fig. 4 Schematic illustration of laser heat treating process.

(that is, for a selected steel, energy absorber, beam configuration, and beam size).⁽¹⁾ Solutions for temperature elevation during heat treating using a rectangular shaped laser beam of uniform intensity (such as that obtained using a segmented mirror or beam integrator) irradiating a workpiece moving at constant speed is

$$T - T_0 = FPA/4b\ell\rho C_p U, \quad (1)$$

where

$$F = \frac{1}{\sqrt{\pi}} \int_0^{\infty} e^{-Z^2/4w} \left\{ \operatorname{erf} \frac{Y+L}{(4w)^{1/2}} - \operatorname{erf} \frac{Y-L}{(4w)^{1/2}} \right\} \\ \left\{ \operatorname{erf} \frac{X+B+2w}{(4w)^{1/2}} - \operatorname{erf} \frac{X-B+2w}{(4w)^{1/2}} \right\} \frac{dw}{(4w)^{1/2}}. \quad (2)$$

In Eq. (2),

Q = heat absorbed per unit time per unit area = $PA/4b\ell$

P = laser beam power

b = one-half laser beam length

ℓ = one-half laser beam width

A = absorption coefficient of the workpiece for laser radiation

$K = k/\rho C_p$ (K is the thermal diffusivity, k is the thermal conductivity, ρ is the density, and C_p is the specific heat)

w = dimensionless variable of integration

U = processing speed

$X, Y, Z = xU/2K, yU/2K, zU/2K$ (dimensionless coordinates)

$L, B = aU/2K, bU/2K$ (dimensionless quantities describing the heat source dimensions)

T_0 = base temperature prior to heat addition

T = temperature at a desired location in the workpiece.

Equation (1) is a numerical solution to the three-dimensional heat conduction equation.⁽²⁾ This solution does not consider the temperature variation of thermal and optical properties of steels. Equation (1) can be used to determine the absorbed laser power required to produce a desired depth of hardened case in steels. For a desired case depth (that is z), T can be set between Ac_3 (temperature above which austenite is stable in low alloy steels) and the melting temperature, and the required laser power for a range of processing speeds can be computed.

Computed heating rates for AISI 1045 steel during irradiation under CO_2 laser beams were reported to be $400^\circ C/s$ per 1000 W of absorbed laser power (with a uniformly intense beam of size 12×12 mm and travel speed of 4.2 mm/s, which translates to beam dwell time of 2.86 s).⁽¹⁾ At these high heating rates, transformation temperatures such as Ac_1 (pearlite transformation temperature) and Ac_3 for steels are substantially raised, as shown in

Fig. 5 (eventhough Fig. 5 pertains to a medium carbon steel, this trend may apply to other steels as well).⁽³⁾ In addition, beam dwell time during laser heat treatment typically ranges between 0.5 to 10 s. Therefore, adequately high surface temperature should be generated during laser heat treatment for the surface to be austenitized, yet the surface temperatures should be lower than the melting range.

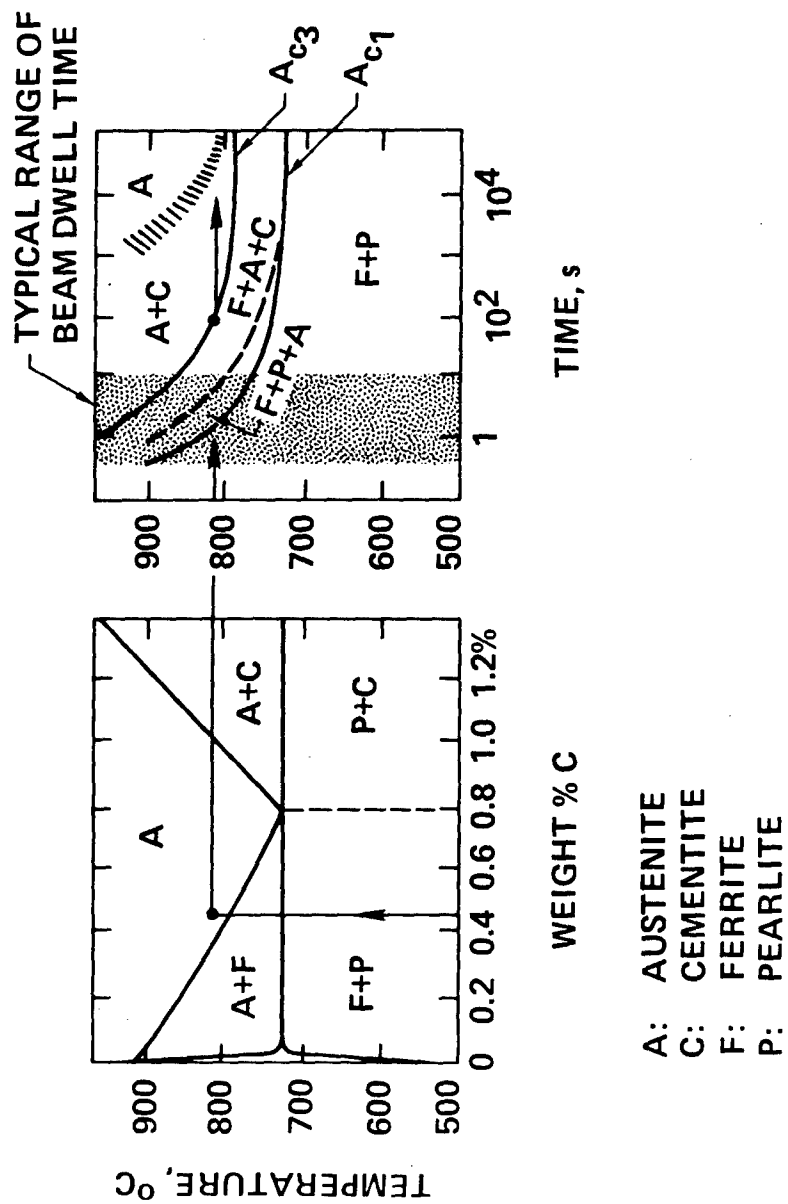


Fig. 5 Structural transformation on heating a 0.45% carbon steel (after Rose and Strassburg³).

3.0 PARAMETRIC EVALUATION OF LASER HEAT TREATMENT

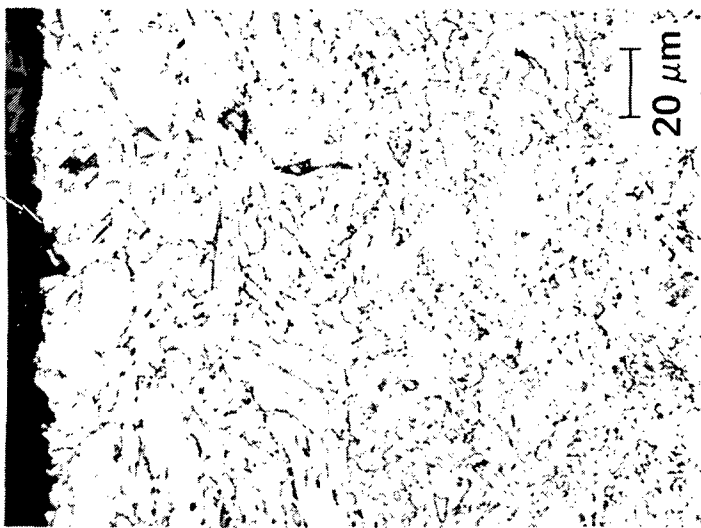
A detailed parametric study was conducted to provide guidelines for laser heat treating end connectors and center guides. Experiments were conducted using AISI 4140 steel plates, as this steel composition nearly represented those of end connectors and center guides from T-142 tracks.

3.1 Preparation of AISI 4140 Steel Plates

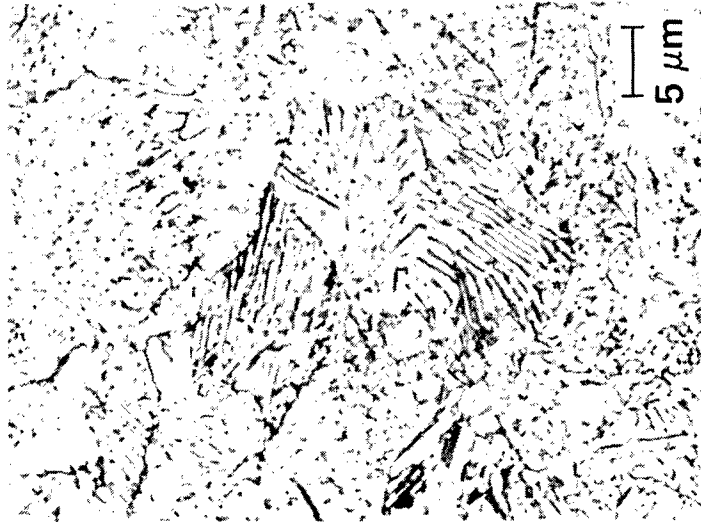
AISI 4140 steel plates were machined to a convenient size for ease of handling. The approximate size of these plates was 100 mm long, 25 mm wide, and 9 mm thick. The thickness of these plates was nearly similar to the wall thickness of end connector's curved surfaces, thereby attempting to develop similar cooling rates during laser heat treatment in order to develop similar hardness profiles. In the as-received condition, the core microstructure of these plates was pearlitic, and the surface had a decarburized layer to a depth of nearly 0.16 mm as a result of prior thermo-mechanical processing. To represent the core hardness and core microstructure of end connectors and center guides, these plates were furnace heat treated at the austenitizing temperature of about 840°C for nearly 1 hour, oil quenched, and tempered at about 480°C for nearly 2 hours. Figure 6 shows microstructures of the plates in the as-received and furnace heat treated conditions. After furnace heat treating, the core microstructure of the plates was tempered martensitic with hardness ranging between Rc 36 to 42. These plates were surface ground to remove the decarburized surface layer and to expose the tempered martensitic

SURFACE

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(a)



(b)



(c)

Fig. 6 Microstructures of AISI 4140 steel plates showing (a) decarburized surface layer in the as-received condition, (b) pearlitic structure of as-received plates, and (c) tempered martensitic structure of furnace heat treated plates.

structure of the core. The finish of the ground surface was typically 3 μm . Prior to laser heat treating experiments, the surfaces of these plates were spray coated with Krylon 1602 paint (manufactured by Borden, Inc.), to enhance absorption of CO₂ laser beam. This commercially available paint contains carbon black, silicate compounds, and nonvolatile and volatile organic compounds. After the paint dried the plates were ready for laser heat treatment.

3.2 Laser Heat Treatment of AISI 4140 Steel Plates

Heat treating experiments were conducted using a Spectra-Physics Model 975 continuous wave (cw) CO₂ laser rated at 5000 W of laser output power at a wavelength of 10.6 μm . Optical tooling utilizing three mirrors (two spherical and a flat), as illustrated in Fig. 7, provided a broad area laser beam with fairly uniform intensity distribution suitable for heat treatment. Figure 8 illustrates intensity distribution of such a laser beam from "burn patterns" in Lucite. Detailed specifications on this laser and optical tooling are provided in Chapter 6. Experiments were conducted at selected laser power levels of 4000 and 5000 W (power on work surface) using a laser beam of size 19 x 19 mm. Coated steel plates were translated under the laser beam at selected speeds ranging from 1 mm/s to 12 mm/s, to generate a heat treated stripe. Translating table speeds were numerically controlled (NC) by a Summit/Bandit NC controller (manufactured by Dana Corp.) to be within $\pm 4\%$. During heat treatment, a stream of air was blown across the work surface to prevent smoke (from burning paint) from interacting with the laser beam.

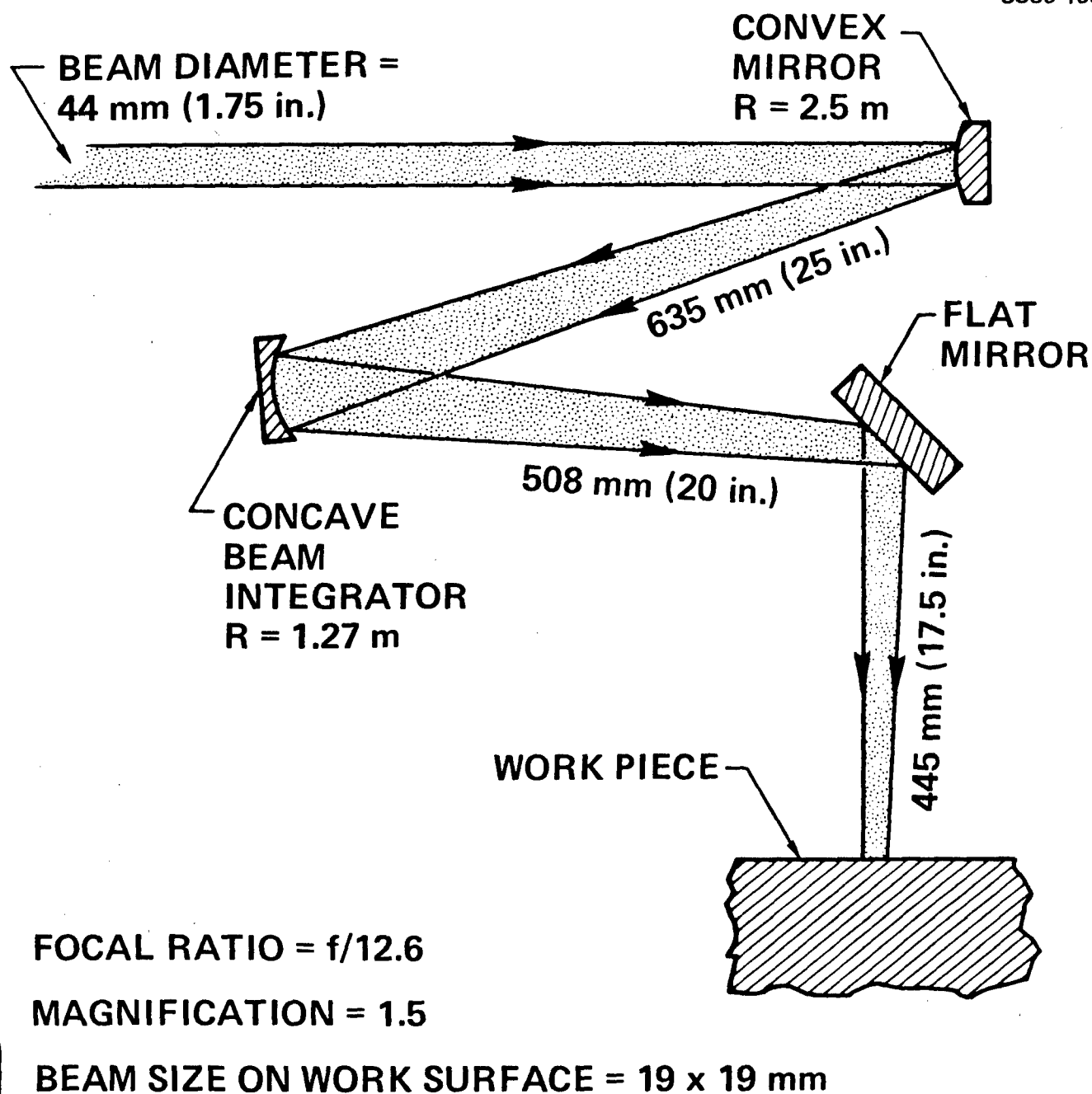


Fig. 7 Optical tooling to provide uniformly intense laser beam.

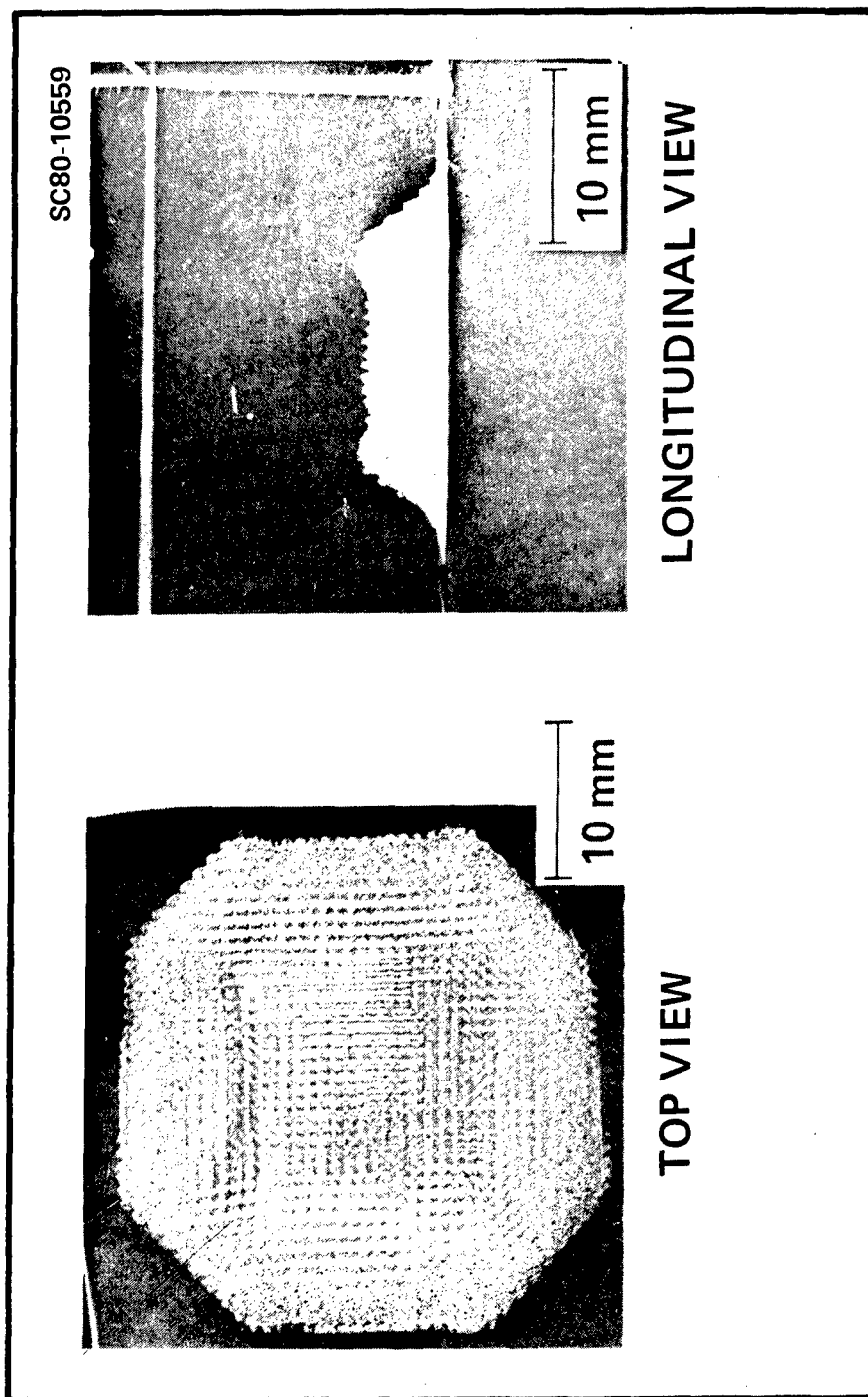


Fig. 8 Intensity distribution of CO_2 laser beam for heat treatment.

3.3 Results

Laser processed plates were sectioned into two equal halves, perpendicular to the heat treated stripe. Figures 9 and 10 show cross-sectional views of plates laser heat treated at 4000 and 5000 W of power, respectively, and at various travel speeds. Hardness profiles along the heat treated casings were measured with a Wilson Tukon microhardness tester adapted with a Knoop indenter and an applied load of 500 g. Microhardness measurements were made at regular intervals along a line passing through the center of the specimen cross-section, where heat treated casing is the deepest. Maximum hardness readings along these measured hardness profiles were noted. Surface hardness of all laser heat treated coupons was measured with a Rockwell hardness tester. Hardness values observed on separate specimens processed at selected conditions are illustrated in Fig. 11. The range of parameters suitable for heat treating end connectors and center guides is indicated in these figures by the dotted region.

From Fig. 11, 3 mm deep casings can be obtained with 4000 W of laser power at a travel speed of 5 mm/s. Casings illustrated in Figs. 9 and 10 were obtained without using an external quenching medium and exhibited:

- No surface melting
- No surface cracking
- Hardness in excess of Rc 50.

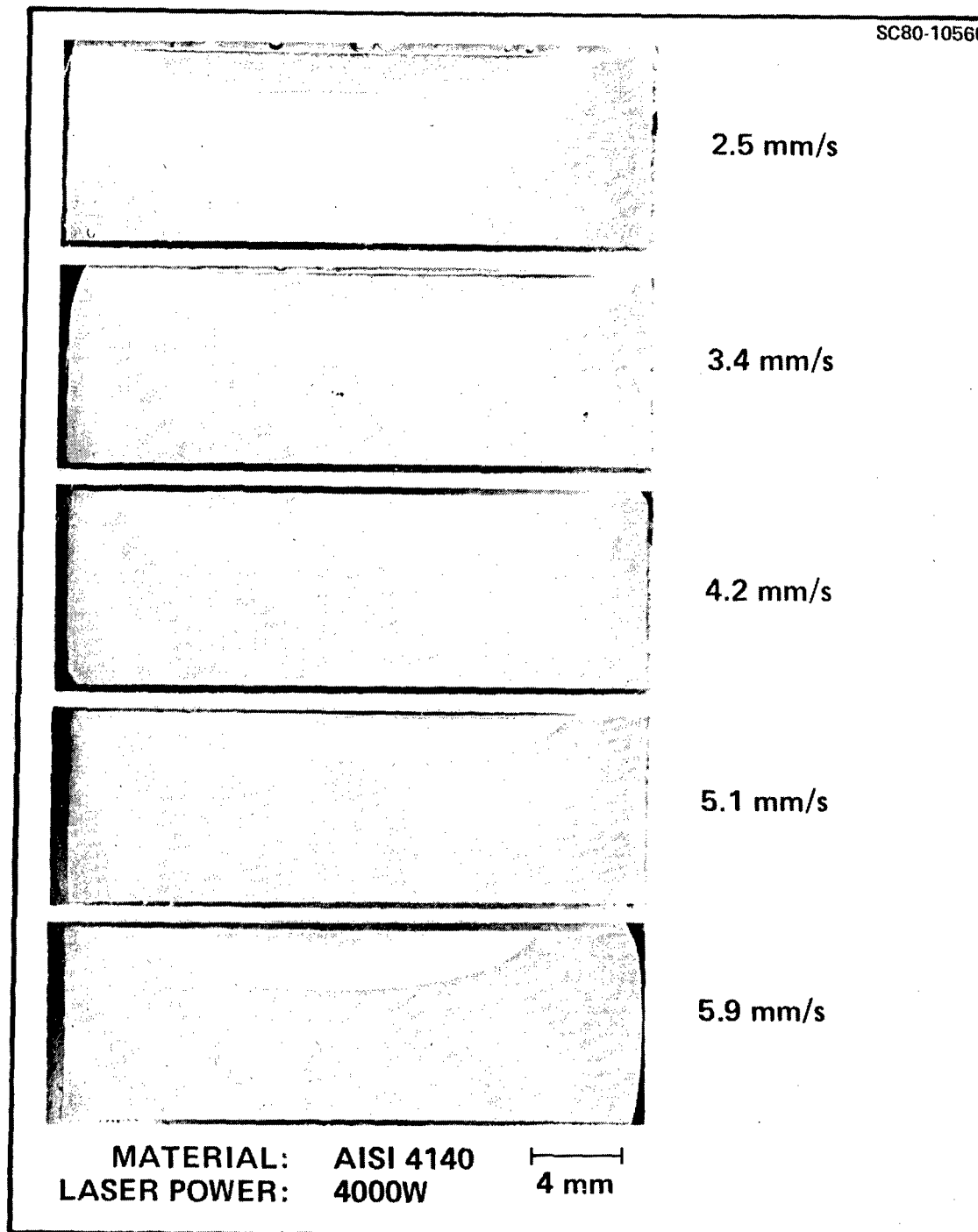


Fig. 9 Cross-sectional views of steel plates heat treated with 4000 W of laser beam power. (Note: Knoop hardness impressions across heat treated casings).

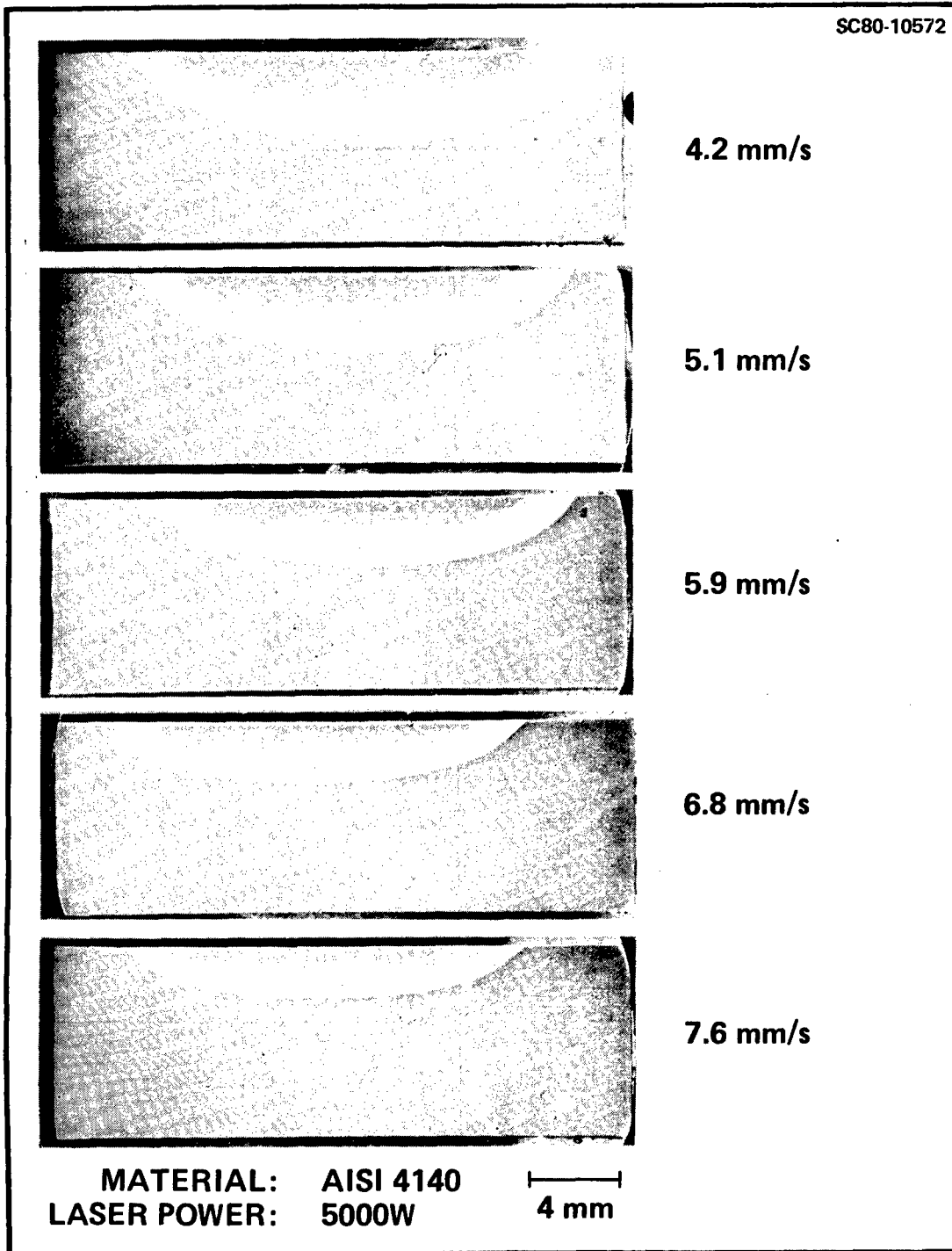


Fig. 10 Cross-sectional views of steel plates heat treated with 5000 W of laser beam power. (Note: Knoop hardness impressions across heat treated casings.)

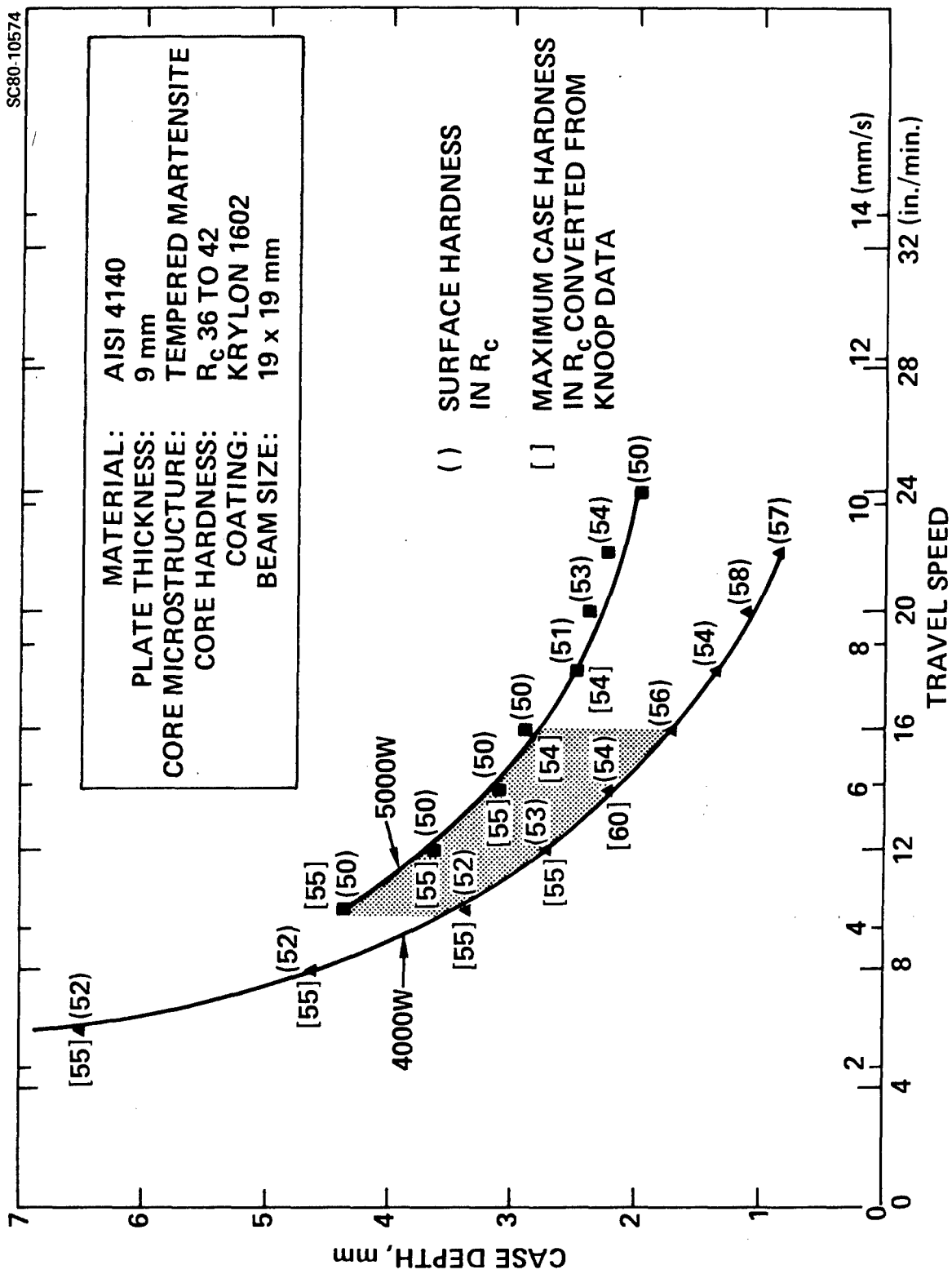


Fig. 11 Case depth as a function of travel speed and laser beam power.

Figure 12 shows a hardness profile for a 6.5 mm deep heat treated casing. Hardness between Rc 50 and 55 was observed in the casing (scatter in micro-hardness data may be due to local variation in chemical composition of elements). Below the hardened casing, a tempered zone with hardness of Rc 31 was observed; in comparison, the core hardness was Rc 38.

Similar experiments were also conducted with an AVCO HPL* cw CO₂ laser at 3000 to 6000 W of laser power (on work surface). These results are illustrated in Appendix A.

*HPL is a trademark of AVCO Everett Research Laboratory, Inc.

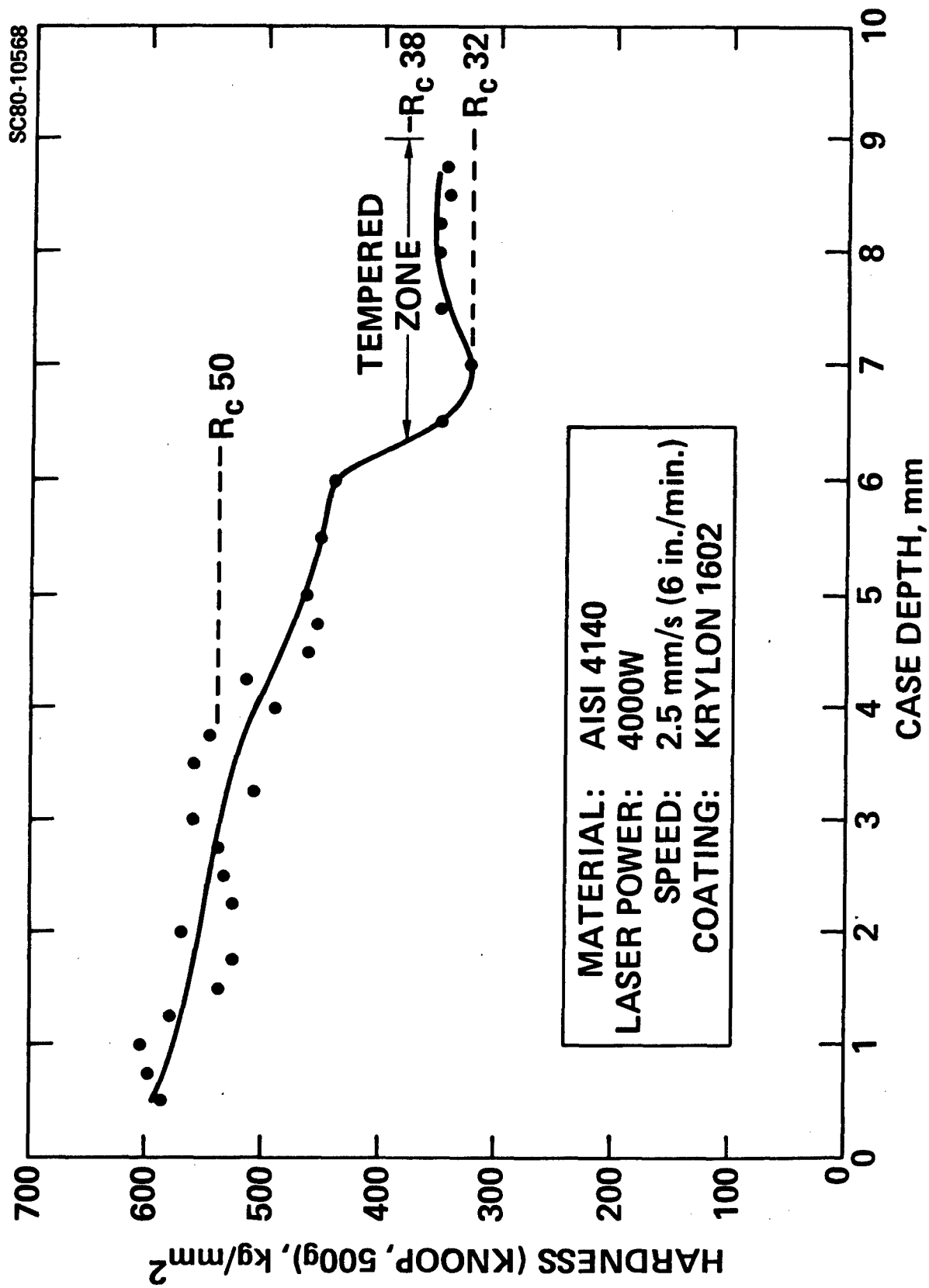


Fig. 12 Hardness profile along the surface of a laser heat treated steel plate.

4.0 LASER HEAT TREATMENT OF TRACK COMPONENTS

End connectors and center guides from T-142 tracks used for laser heat treating experiments were in the finish machined condition and were not previously induction hardened. Wearing surfaces of these components were in the shot blasted condition and the surface roughness was between 3.5 and 6.5 μm . Microstructure of these components was tempered martensitic. Total area of critical wearing and abrading surfaces in end connectors is approximately 6000 mm^2 (50 mm wide and 60 mm long on each curved end); in center guides, the area is 2840 mm^2 (1420 mm^2 for both sides of a "finger"). Heat treating experiments were conducted with a laser beam size of 19 x 19 mm (this beam size was obtained with a three mirror optical tooling, using spherical and flat mirrors as mentioned in Chapter 3). For end connectors, three heat treat stripes placed side by side were designed for each curved end (total of six stripes per connector). These stripes were perpendicular to the riding direction of end connectors. A gap of about 2 mm between two heat treated stripes prevented back tempering of an adjacent stripe. For center guides, a total of four separate heat treat stripes were designed to cover the wearing surfaces on both "fingers." Track components with a tempered martensitic or bainitic core microstructure in other combat vehicles can also be heat treated by using similar methods developed in this program.

4.1 Laser Heat Treatment Procedure

Track components in the as-received condition were degreased in acetone to remove machine oil from wearing surfaces. These surfaces were subsequently spray coated manually with Krylon 1602 paint and allowed to dry. End connectors and center guides were mounted on separate fixtures, as shown in Figs. 13 and 14. These fixtures enabled wearing areas to be located easily for placement of heat treat stripes. The components were separately heat treated with 4000 to 5000 W of laser power (on workpiece), at travel speeds between 4 and 6 mm/s, and without using an external quenching medium. A stream of air was blown across work surface location undergoing heat treatment, as mentioned in Chapter 3 in order to remove smoke (from burning paint) from interacting with the beam.

4.2 Metallurgical Tests

Response of track components for laser heat treatment was evaluated to specifically measure case depth, increase in hardness, microstructural changes, and improvements in abrasive wear.

Laser heat treated end connectors and center guides were sectioned perpendicular to heat treated stripes to note case depths. Those specimens showing case depths in excess of 1.5 mm were metallographically mounted to characterize gradients in microhardness and microstructure along heat treated casings. Cross-sectional views in Figs. 15 and 16 illustrate placement of heat treat patterns localized to abrasive wear regions. By adapting a broad

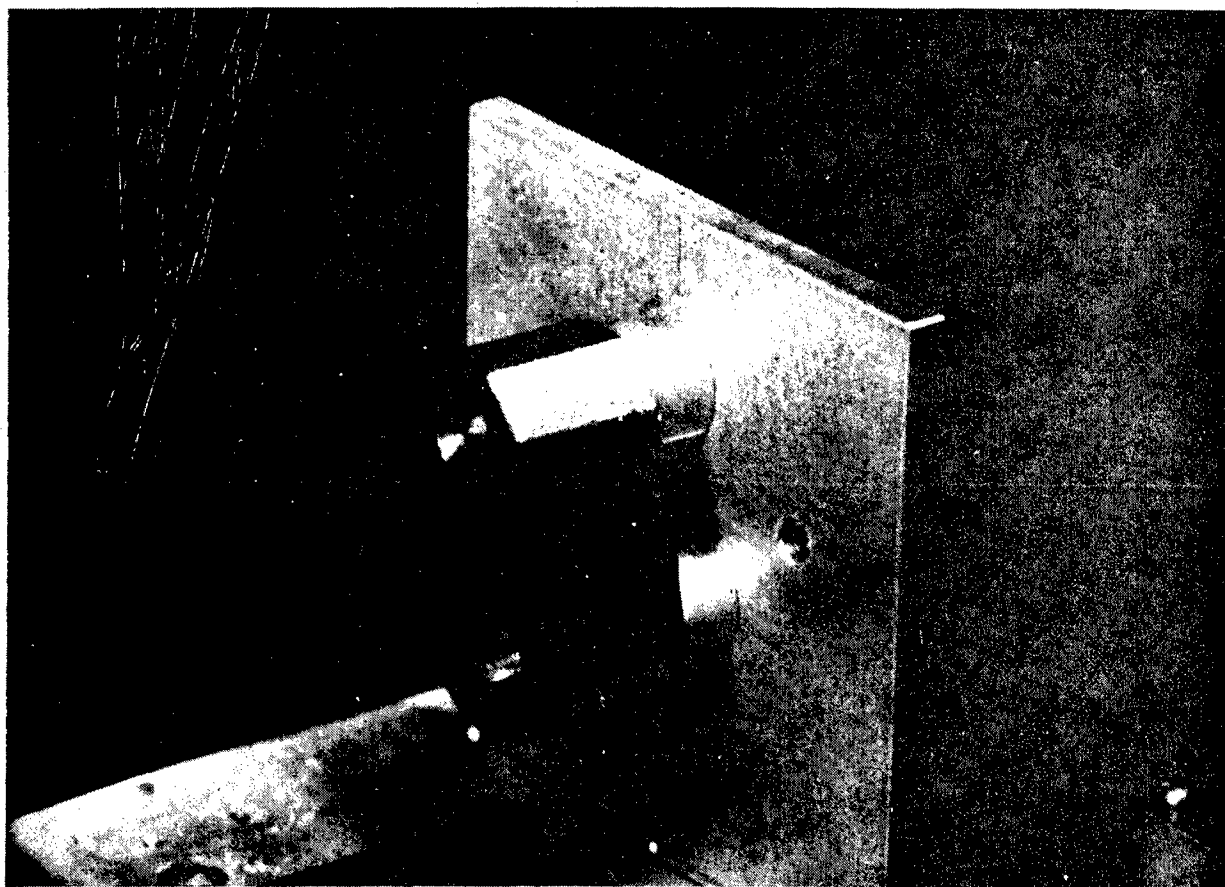


Fig. 13 Laboratory fixture for end connectors to enable placement of three successive heat treat stripes on each curved surface, with a gap of about 2 mm between the stripes.

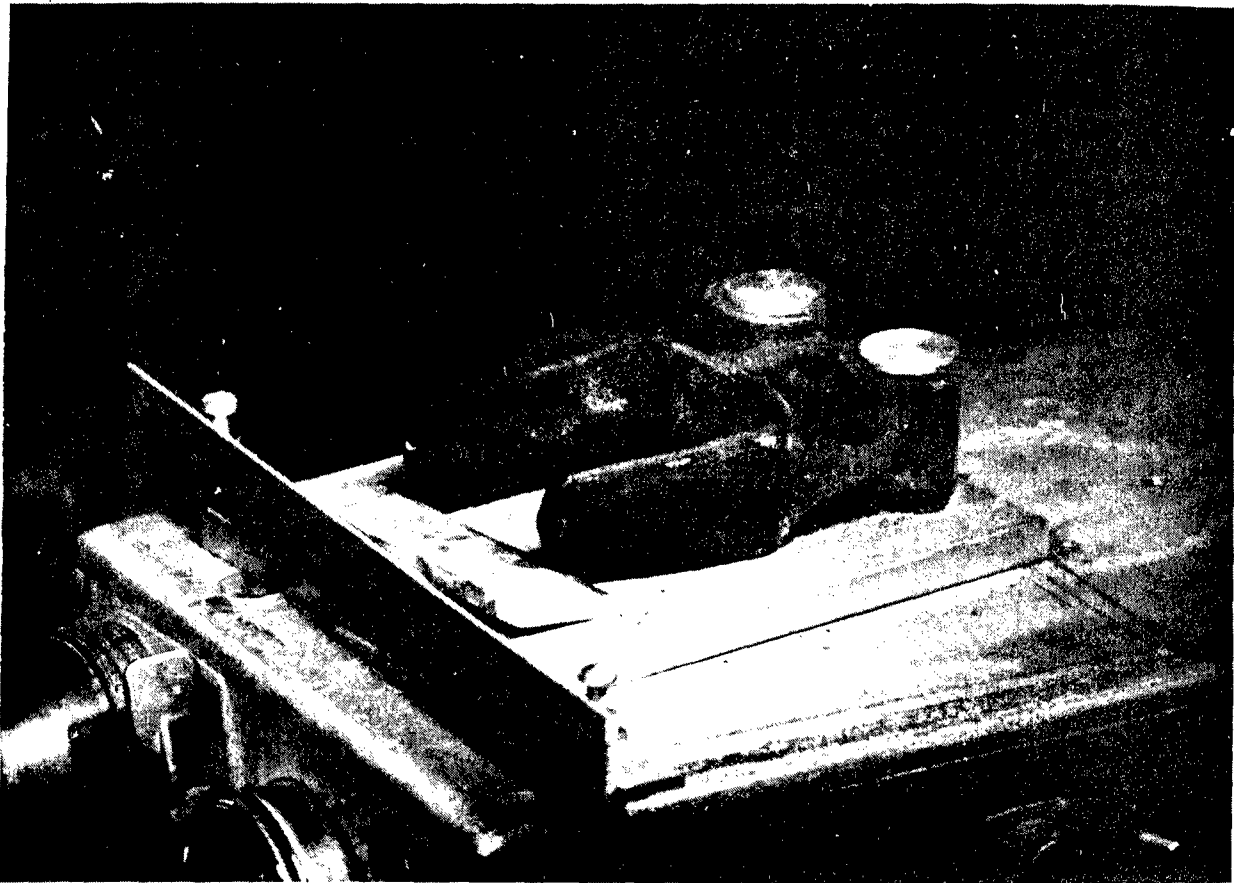
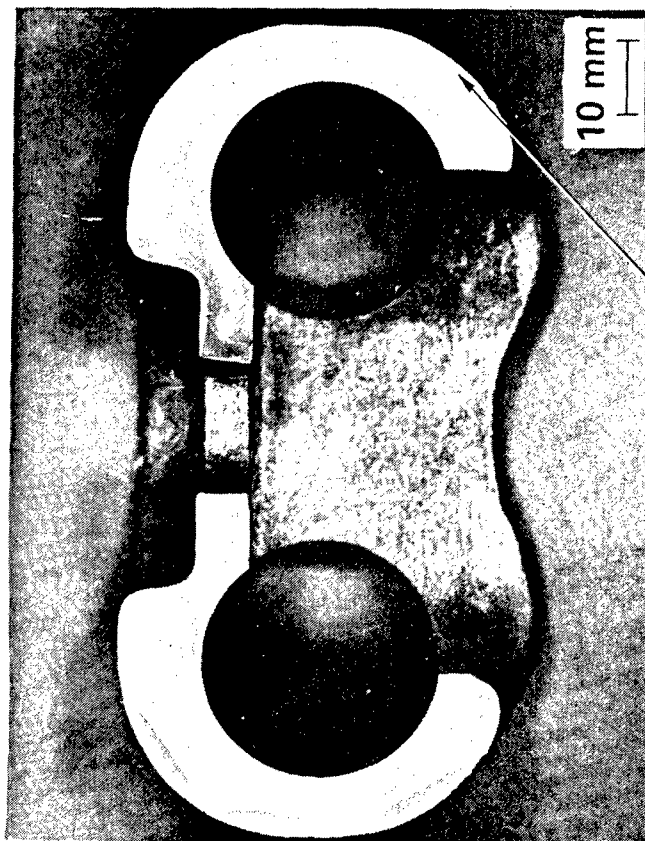


Fig. 14 Laboratory fixture for center guides to enable placement of separate heat treat stripes on both sides of each "finger."

T-142 END CONNECTOR

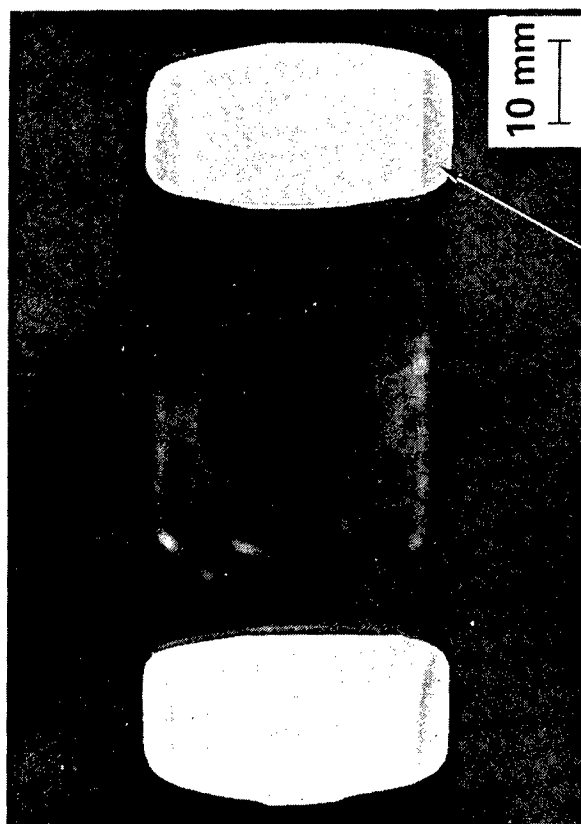


MATERIAL:	AISI 4140
LASER POWER:	4000W
SPEED:	5.1 mm/s (12 in./min.)

HARDENED
CASE (R_c54)

Fig. 15 Cross-sectional view of laser heat treated T-142 end connector, showing placement of hardened casings away from the slotted hole by about 12 mm and only to those locations subject to abrasive wear.

T-142 CENTER GUIDE



HARDENED
CASE ($R_c 52$)

MATERIAL:	AISI 4150
LASER POWER:	5000W
SPEED:	5.1 mm/s (12 in./min.)

Fig. 16 Cross-sectional view of laser heat treated T-142 center guide, showing placement of hardened casings on both abrading sides of each "finger."

area laser beam, shaped to cover entire width of an end connector, it is possible to produce a continuous heat treat pattern along the curved ends during one continuous sweep of a connector under the beam. Such an optical tooling will utilize appropriate spherical and cylindrical mirrors. The offset in heat treat pattern along one side of the center guide in Fig. 16 is due to the simple fixtures used in these experiments. Refinements in optical tooling and fixtures will enable superior control in precision placement of heat treat patterns. These are important factors for further technology development.

4.2.1 Hardness Tests

Hardness profiles for end connectors and center guides are illustrated in Figs. 17 and 18. As the core hardness of track components is sufficiently high, hardness profiles along heat treated casings show the following regions:

- A broad region with uniform hardness higher than core
- A narrow region with hardness lower than core (tempered zone).

Heat treating conditions (such as laser power on workpiece and travel speed) used for these experiments resulted in well defined tempered zones among end connectors, but these zones were not so well defined among center guides; this is due to the higher core hardness (average of nearly Rc 43) of end connectors when compared to the core hardness (average of nearly Rc 37) of center guides. Formation of tempered zones is related to the response of core

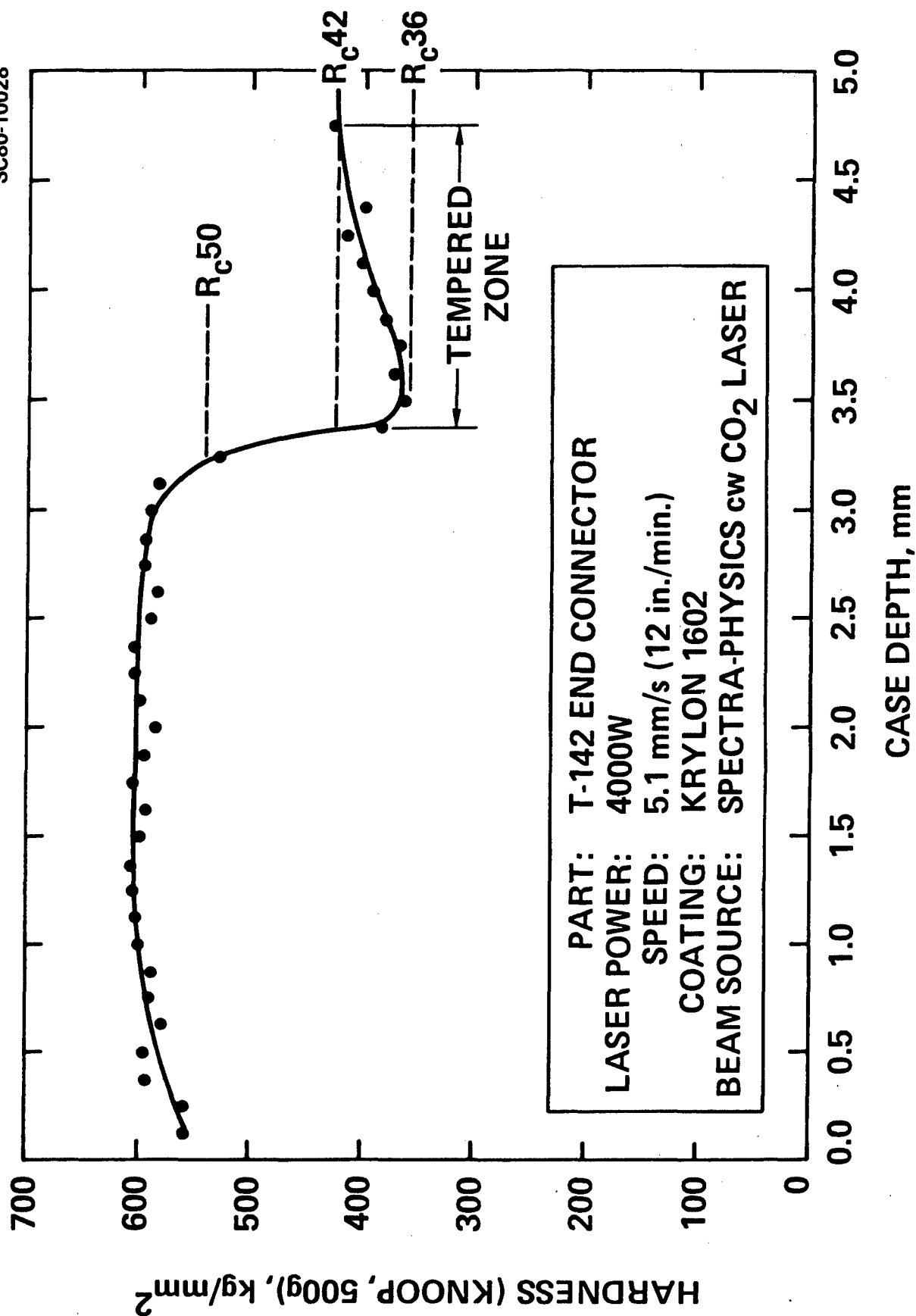


Fig. 17 Hardness profile along hardened casing in a laser heat treated end connector.

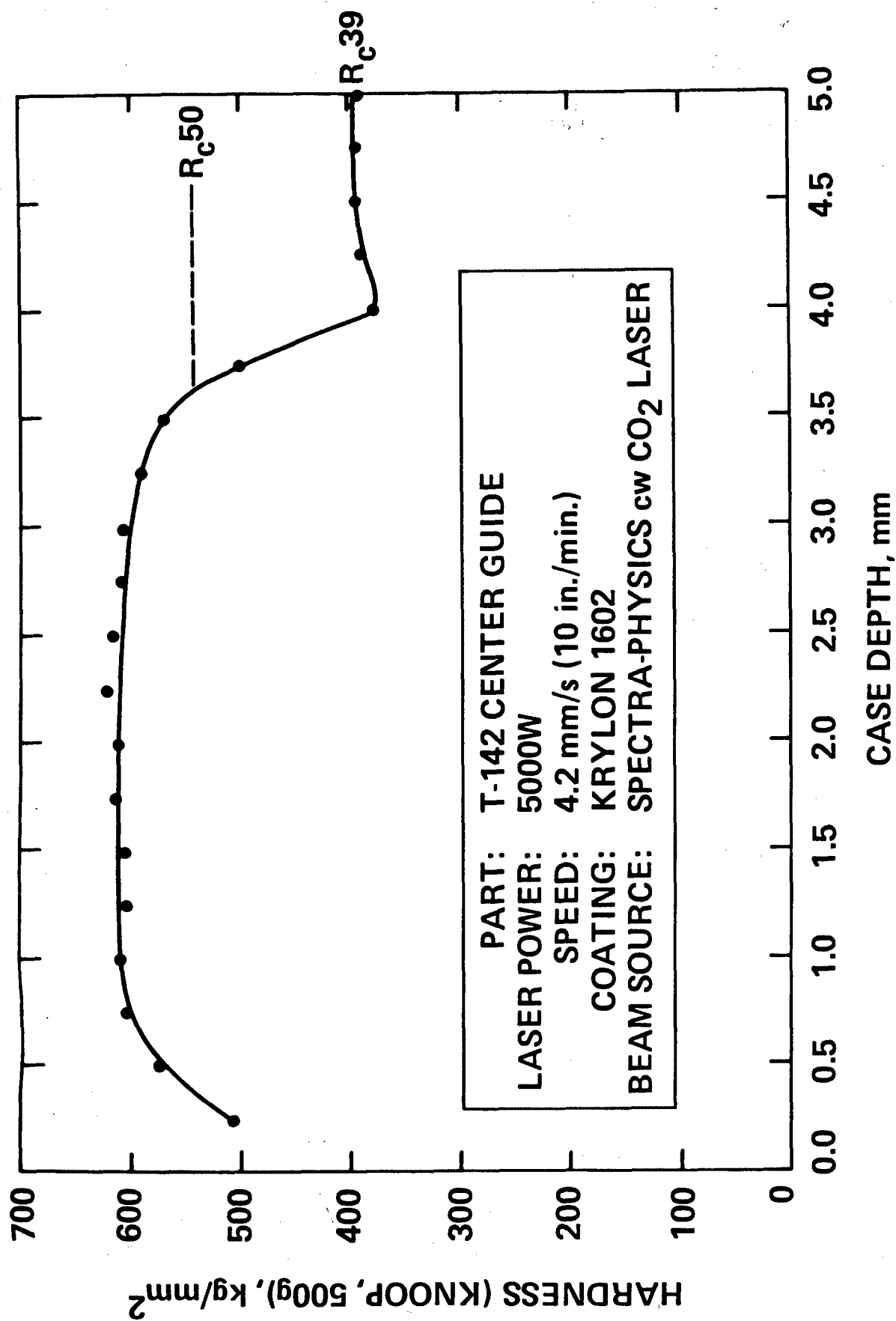


Fig. 18 Hardness profile along hardened casing in a laser heat treated center guide.

microstructure to the imposed temperature-time history (heat conduction by self quenching) during laser heat treatment.

Table 1 provides a summary of laser operating parameters and results obtained for end connectors and center guides. Along the hardened zone, hardness (from microhardness profiles) observed for these components was between Rc 52 and 55 and remained fairly constant over most of the casing. Along the tempered zone, a decrease of 6 points below core hardness for end connectors and a decrease of 3 points below core hardness for center guides was observed. For purposes of comparison, hardness and case depth data for an induction hardened T-142 center guide (in production) are included in Table 1, and hardness profile is illustrated in Fig. 19. The following comparisons are drawn from separately laser heat treated and induction hardened center guides:

- Percent of casing above Rc 50 for a laser heat treated guide is more than that for an induction hardened guide
- Percent of casing that is tempered for a laser heat treated guide is considerably less than that for an induction hardened guide.

4.2.2 Microstructure

A series of representative microstructures along the laser heat treated casing in an end connector is illustrated in Fig. 20. Included in this figure are hardness values observed at each location pertaining to these microstructures. A predominantly martensitic structure is observed at the surface and at 0.3 mm, 0.5 mm, and 1 mm below the surface. Martensite and

**TABLE 1. HARDNESS DATA FOR T-142 END CONNECTORS
AND CENTER GUIDES**

POWER ON WORK (W)	TRAVEL SPEED (mm/s)	CORE HARDNESS (R _c)	MAXIMUM CASE HARDNESS (R _c)	CASE DEPTH (mm)	CASE DEPTH FOR R _c 50 (mm)	TEMPERED ZONE		% CASING ABOVE R _c 50	% CASING TEMPERED
						DEPTH (mm)	HARDNESS DECREASE (ΔR _c)		
LASER HEAT TREATED END CONNECTORS									
4000	5.1	42	54	4.75	3.10	1.55	6	65	33
4000	5.9	42	54	4.25	2.70	1.43	6	64	34
LASER HEAT TREATED CENTER GUIDES									
5000	4.2	39	54	4.50	3.65	0.55	2	81	12
5000	5.1	39	52	4.00	2.55	0.50	3	64	13
INDUCTION HARDENED CENTER GUIDE									
—	—	38	55	11.75	5.25	4.60	4	45	39

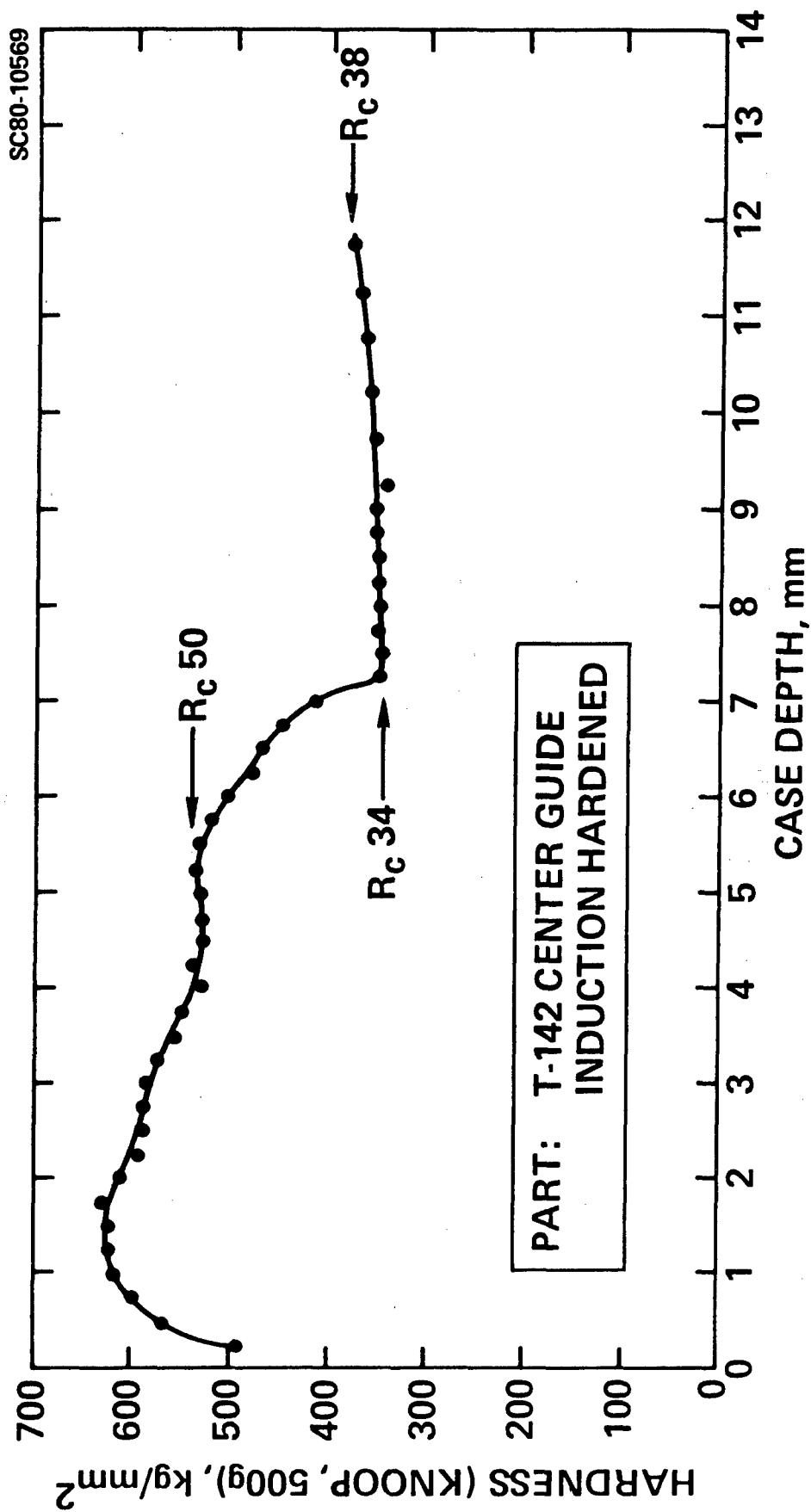


Fig. 19 Hardness profile along hardened casing in an induction hardened center guide (in production).

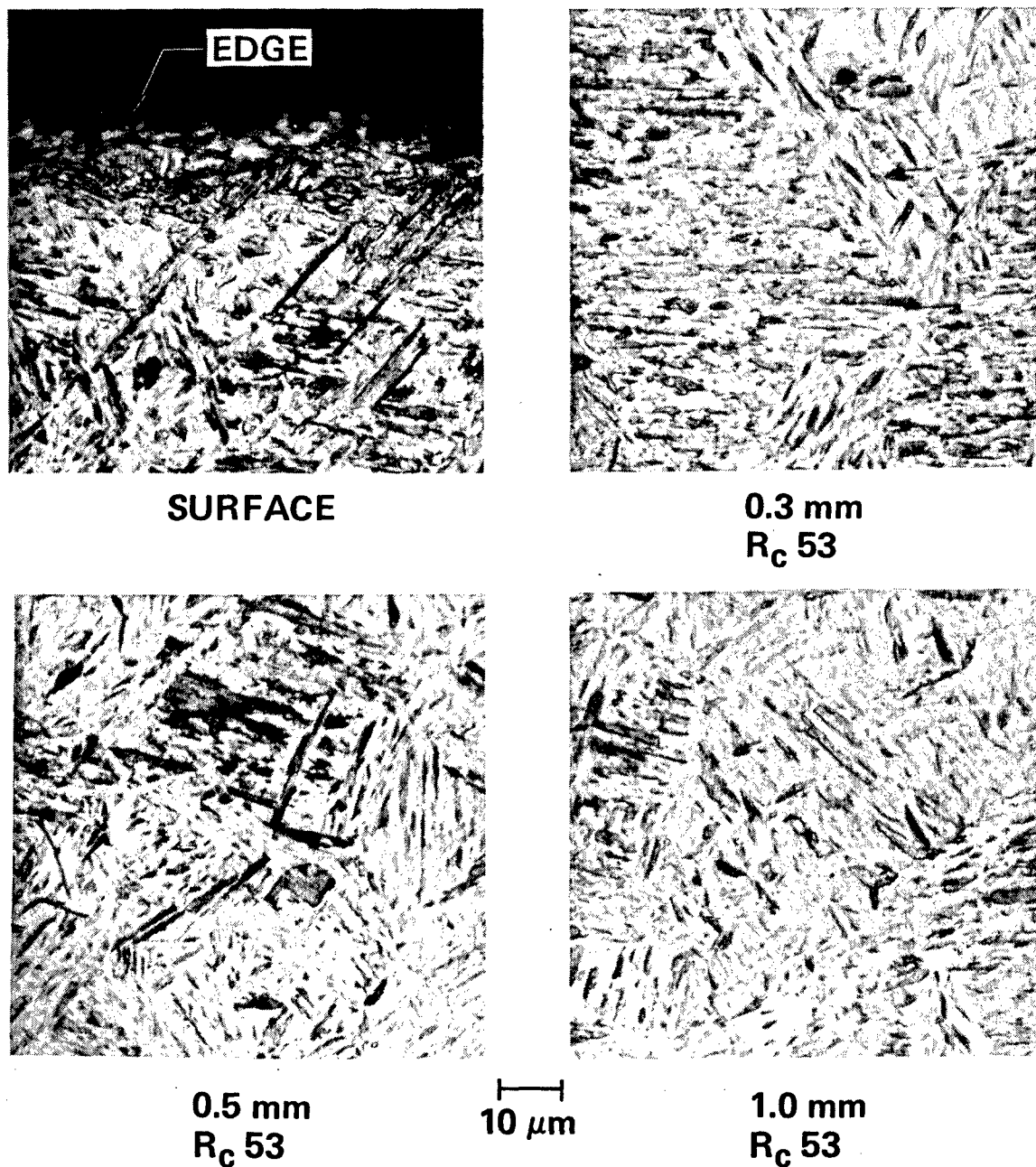
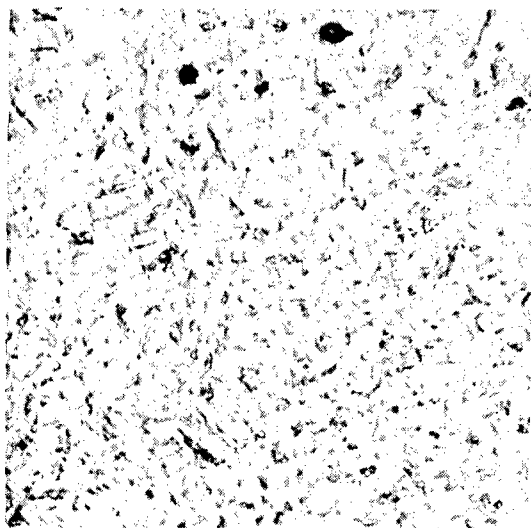
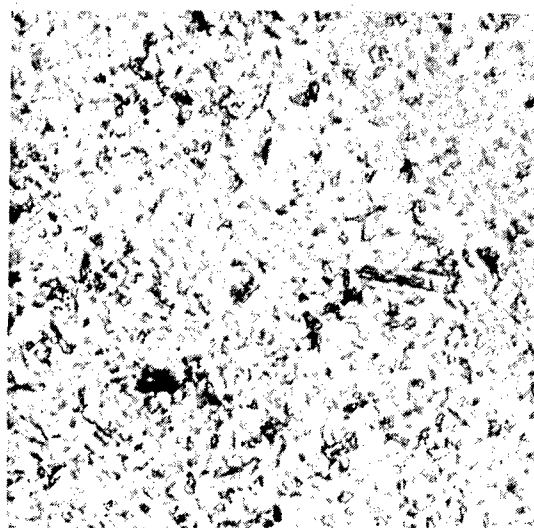


Fig. 20 Microstructures along hardened casing in a laser heat treated end connector. Depths below surface and appropriate hardness values are indicated. Heat treating conditions are illustrated in Fig. 17.

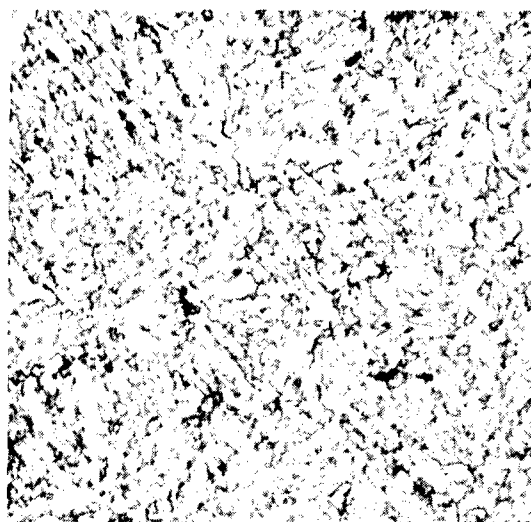
SC80-10555



2.0 mm
 R_c 54

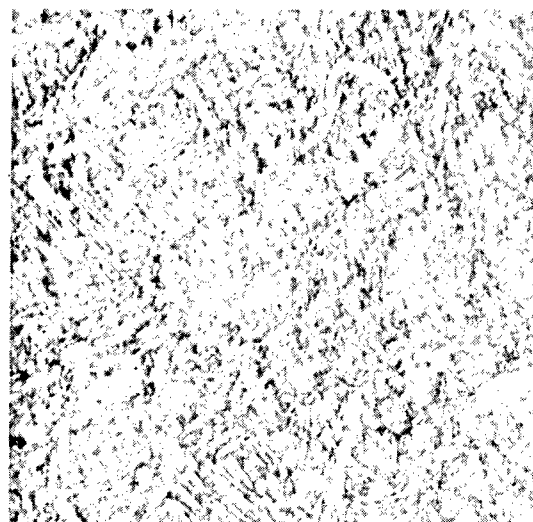


3.0 mm
 R_c 52



3.25 mm
 R_c 38

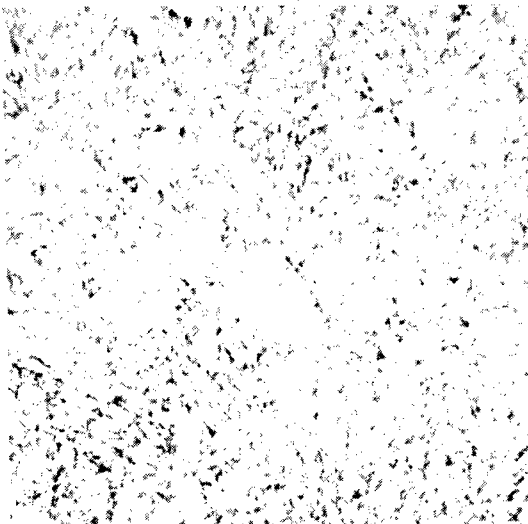
10 μ m



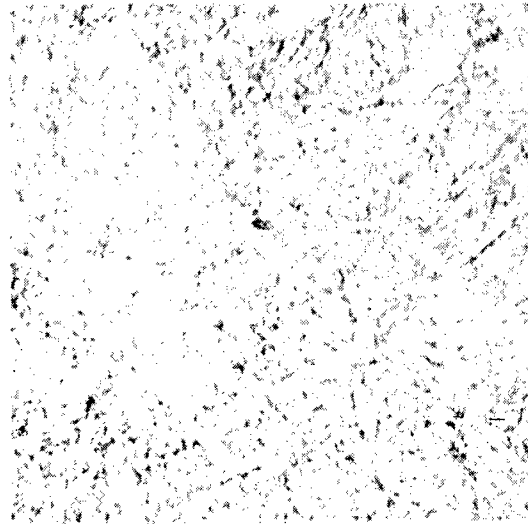
3.5 mm
 R_c 36

Fig. 20 Cont.

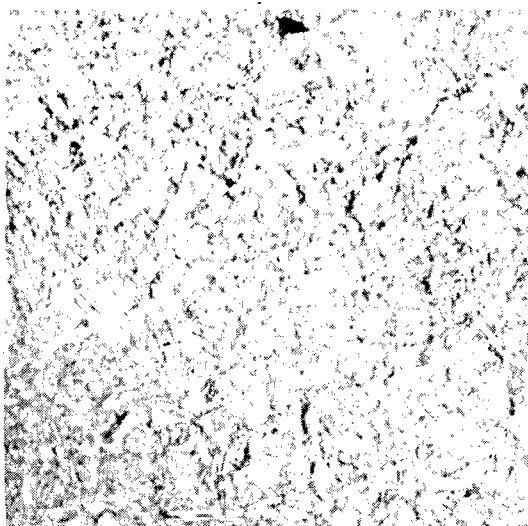
SC80-10556



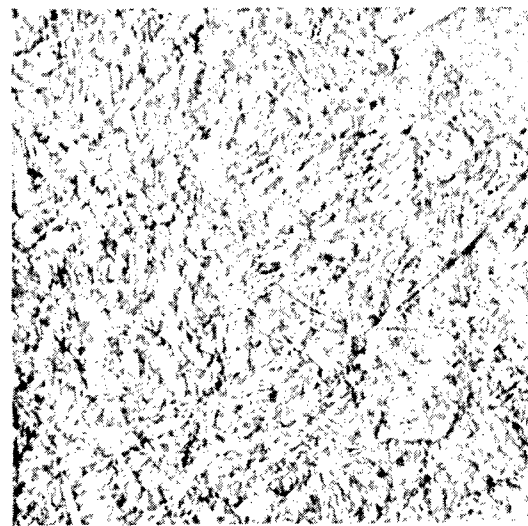
4.0 mm
 R_c 40



4.5 mm
 R_c 42



5.0 mm
 R_c 42



CORE
 R_c 42

10 μ m

Fig. 20 Cont.

small amounts of possibly ferrite and bainite are observed at 2 mm and 3 mm. Tempered martensitic structures are observed at 3.25 mm, 3.5 mm, 4 mm, 4.5 mm and 5 mm. Selected laser heat treated specimens were nickel plated and metallographically prepared to make detailed observations of specimen edges. Photomicrograph of an end connector specimen edge is shown in Fig. 21. Specimen edges were examined for (1) quench cracks, (2) degradation of surface (due to impregnation of energy absorbing coating into substrate steel surface), and (3) localized surface melting. Figure 21 shows martensitic microstructure extending to specimen edge with no surface damage.

Representative microstructures along the laser heat treated casing in a center guide are illustrated in Fig. 22. Microstructure at the surface appears to resemble that of low carbon martensite and ferrite (possibly due to surface decarburization during prior thermomechanical processing). At 1 mm, 2 mm and 3 mm below the surface, a predominantly martensitic structure is observed. At 3.5 mm, a "dark etching" phase which may be bainite appears in the microstructure. At 4 mm and 4.5 mm, the structure is predominantly tempered martensitic.

Figure 23 illustrates cooling transformation diagram for AISI 4140 steel, and schematic projections of heating and cooling curves at several depths below the surface during laser heat treating. These cooling curves are illustrated to relate microstructures (shown in Fig. 20) at the surface, 1 mm and 3 mm below the surface in a laser heat treated end connector.

SC81-12404

SPECIMEN
EDGE

NICKEL PLATE
FOR EDGE
PROTECTION

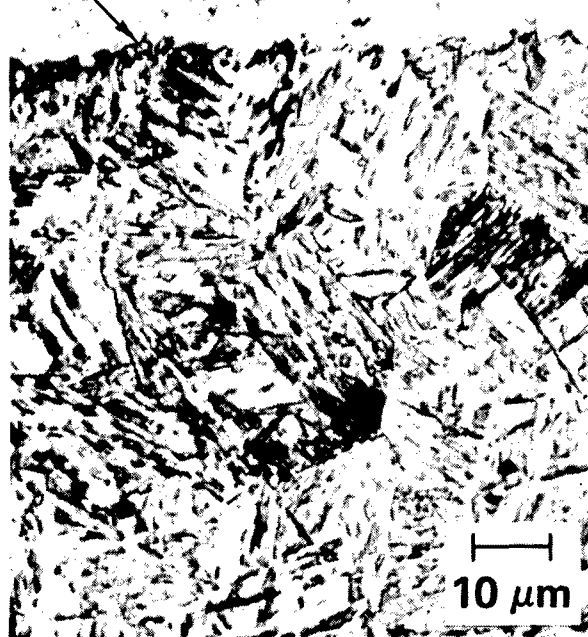


Fig. 21 Microstructure of laser heat treated end connector, showing martensite along specimen edge.

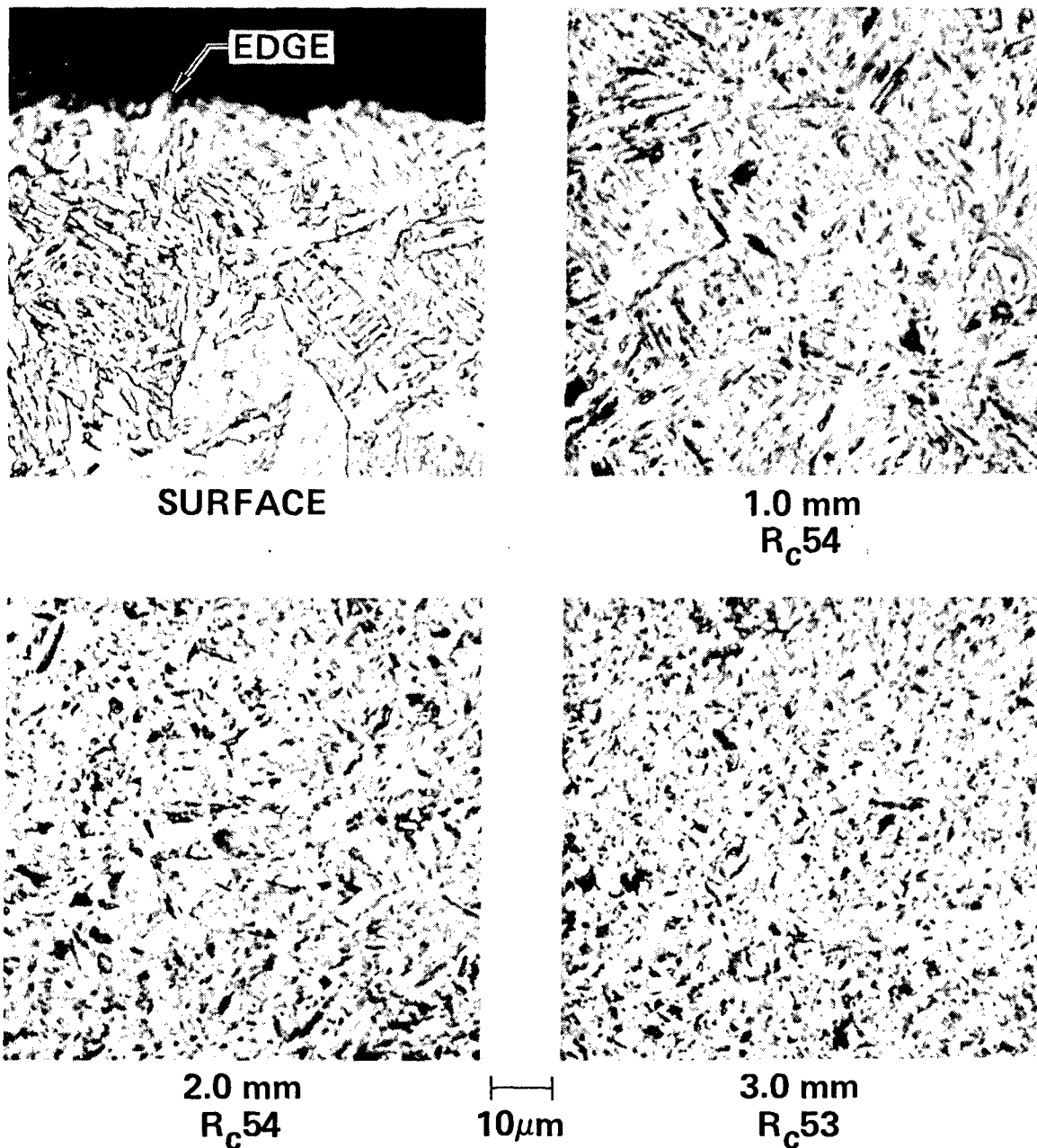
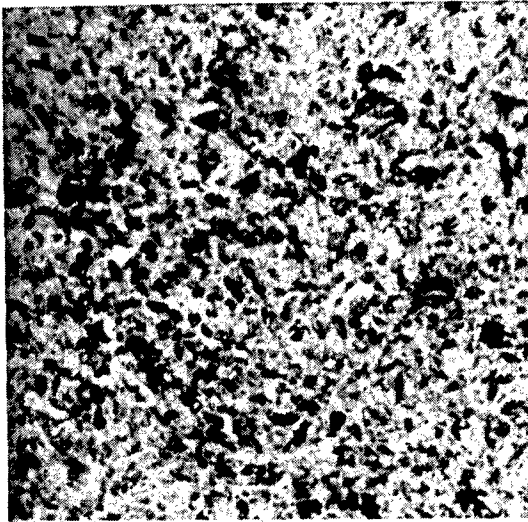
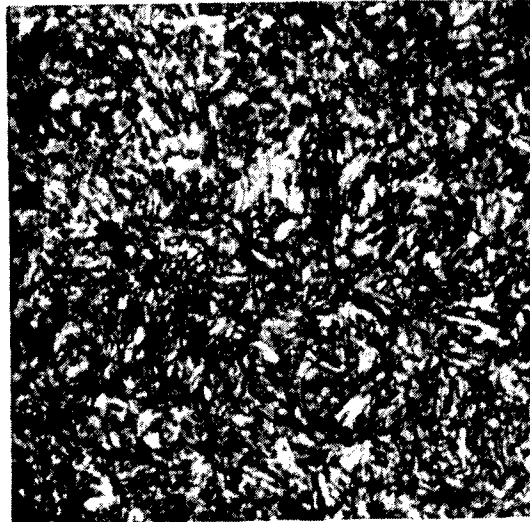


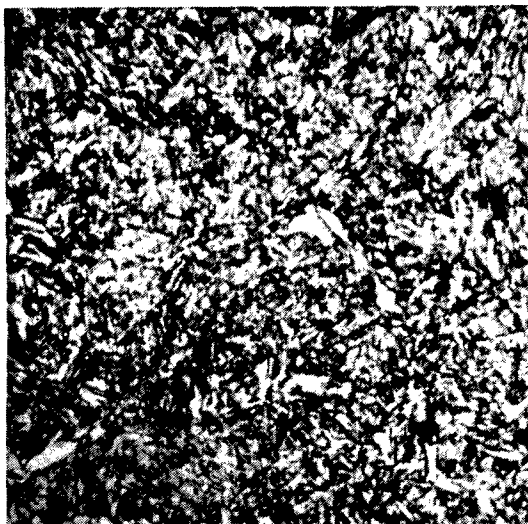
Fig. 22 Microstructures along hardened casing in a laser heat treated center guide. Depths below surface and appropriate hardness values are indicated. Heat treating conditions are illustrated in Fig. 18.



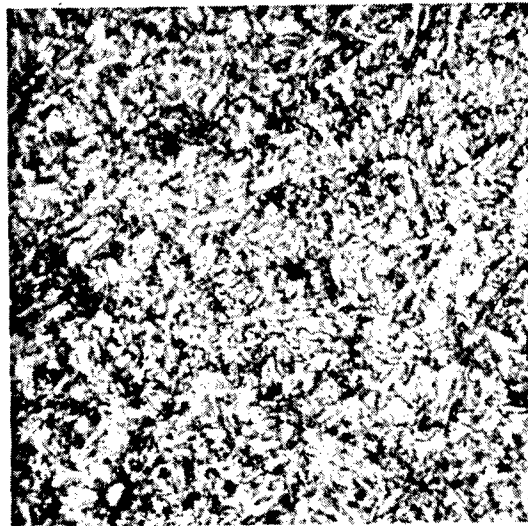
3.5 mm
 R_c51



4.0 mm
 R_c37



4.5 mm
 R_c39



CORE
 R_c39

10 μ m

Fig. 22 Cont.

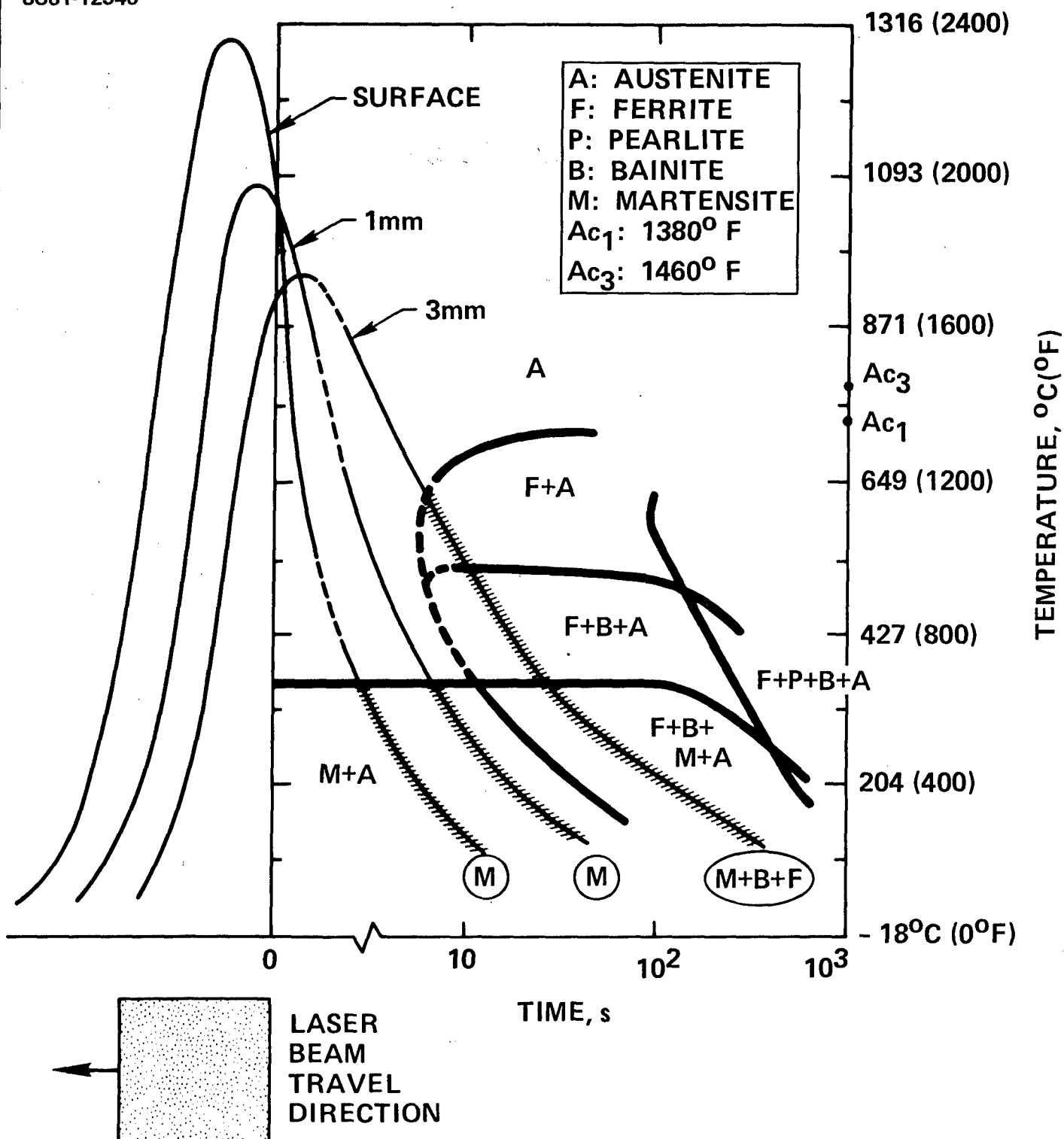


Fig. 23 Cooling transformation diagram for AISI 4140 steel (Reference 4). Heating and cooling curves possible during laser heat treatment are schematically projected.

4.2.3 Abrasive Wear Tests

In order to evaluate abrasive wear characteristics of laser heat treated components, a limited number of wear tests were conducted with a LFW-1 friction and wear tester (manufactured by Faville-Levally Corporation). Test conditions used were as follows:

Load: 0.91 kg

Sliding Speed: 550 mm/s

Test Duration: 2h

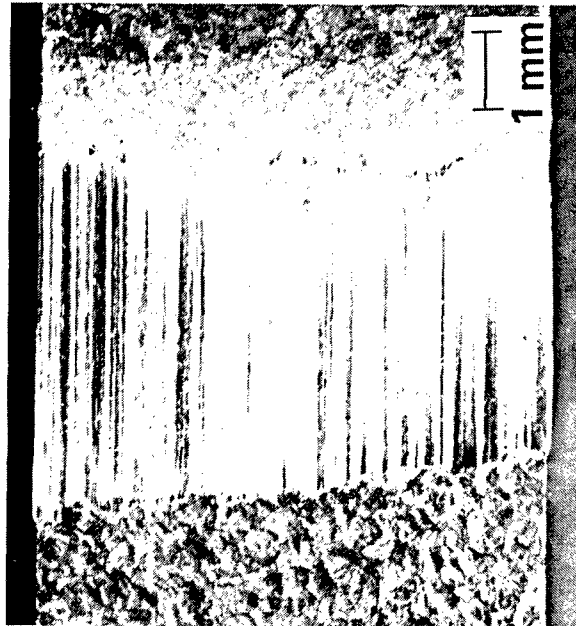
Abrasive: Silica Sand, 60/80 mesh (177 to 250 μm)

Slurry: 40 weight percent sand in white mineral oil

In these tests, a stationary test specimen was loaded against a rotating ring partially immersed in an abrasive-oil slurry, so that abrasive particles were continuously contacted between the test specimen and ring. Test specimens were machined from non surface hardened (untreated), laser heat treated end connectors and center guides (using AVCO HPL laser) and induction hardened center guides. Wear surfaces of these specimens had a ground finish (obtained by grinding on a 600 grit (24 μm) silicon carbide impregnated paper). Test rings were fabricated from AISI 4620 steel and carburized to R_c 58 to 63, then subsequently surface ground to obtain a finish of 0.5 to 1 μm RMS.

Figures 24 and 25 illustrate wear scars observed in laser heat treated, induction hardened, and untreated specimens. Macrophotographs in these figures are oriented so that entry of abrasive slurry is from right side (rough area). Among end connectors (Fig. 24), a laser heat treated specimen

T-142 END CONNECTOR



UNTREATED

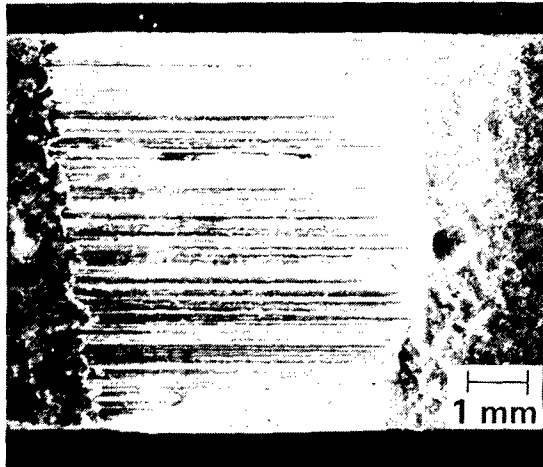


LASER TREATED

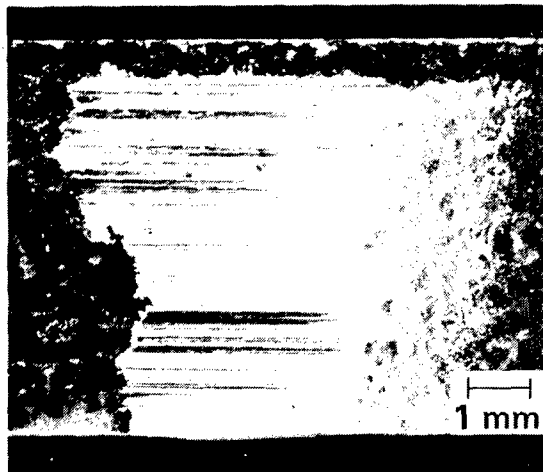
Fig. 24 Abrasive wear scars in untreated (non surface hardened) and laser heat treated T-142 end connector specimens after LFW-1 wear test.

SC80-10587

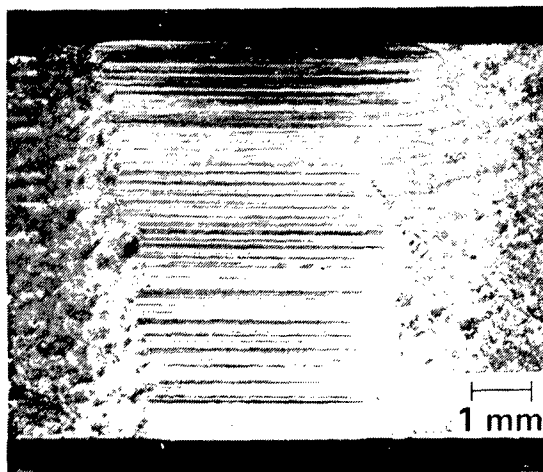
T-142 CENTER GUIDE



UNTREATED



**INDUCTION
TREATED**



**LASER
TREATED**

Fig. 25 Abrasive wear scars in untreated (non surface hardened), induction hardened, and laser heat treated T-142 center guide specimens after LFW-1 wear test.

shows reduction in width of wear scar when compared to an untreated specimen. Among center guides (Fig. 25), wear scars observed in a laser heat treated specimen appear comparable to an induction hardened specimen, while an untreated specimen shows a much wider scar. Further laboratory wear tests need to be conducted on specimens heat treated with a Spectra-Physics laser. These wear tests need to be complemented by actual field tests.

4.3 Preliminary Quality Assurance Specifications

These specifications provide the conditions necessary for laser heat treating procedures adapted to track components to be both reliable and reproducible. Among other factors, service life of heat treated components is influenced by case hardness and case depth. To control hardness profiles, microstructures, and case depths over an acceptable range during laser heat treatment, the following factors must be taken into consideration.

- **Energy Absorbing Coating**

Laser power absorbed by a workpiece is influenced by the surface finish of the workpiece, energy absorbing coating material, and coating thickness. Mixed coatings containing organic compounds, carbon black and silicate compounds (e.g., Nextel Black manufactured by 3-M Company) adequately diluted in a liquid carrier are well suited for dip coating components such that consistent coating thickness are provided from part to part.

- Laser Power

Laser power irradiating the workpiece is constantly monitored with pre-calibrated power meters to maintain power variation within $\pm 5\%$.

- Travel Speed

This must be maintained within $\pm 5\%$ by work handling equipment.

- Part Examination

Visual examination of burnt surface coating can provide indications of effectiveness of heat treatment. This visual check must be supplemented by selecting a part at regular time intervals to measure case depth and hardness.

- Beam Quality

Fresh air needs to be is circulated at regulated flow rates through ducts transporting laser beams to prevent possible loss in beam quality.

- Mirror Surfaces

Good optical quality and clean mirror surfaces are needed to prevent absorption of laser beam. Mirror surfaces require periodic cleaning to remove oxidized surface layers and dust.

- Microstructure

Core microstructure of track components needs to be consistent from part to part in order to develop hardness levels and case depths to be within a specified range after laser heat treatment.

5.0 PRELIMINARY COST ESTIMATES FOR LASER HEAT TREATING TRACK COMPONENTS

As pointed out in Chapter 4, end connectors and center guides from T-142 tracks can be heat treated with 4000 to 5000 W of laser power (on work-pieces). This range of power requirement indicates that an industrially rated 5000 W CO₂ laser (e.g., currently available Spectra-Physics Model 975 laser) will be suitable for heat treating these track components. With a 5000 W CO₂ laser system, the time for heat treatment of end connectors is 60 s, and for center guides is 70 s. Set-up time in a manufacturing environment is estimated to be less than 5 s for these components. Total processing time, which includes both heat treatment and set-up, is expected to be less than 65 s for end connectors and 75 s for center guides. Further development work aimed at refining laser heat treating procedures may lower heat treating times and costs for these track components.

Estimates obtained from a tank track manufacturer's subcontractor (Horst Manufacturing Company, Belleville, Michigan) indicate that current annual production rate of T-142 end connectors and center guides is 640,000 and 320,000 respectively. Based on these estimates, the number of lasers needed to heat treat this quantity of end connectors and center guides in one year is indicated:

Number of hours per year (on the basis of one shift, eight hours per shift, and five day work week)	: 2080 h
Processing time per end connector including set-up	: 65 s
Processing time for 640,000 end connectors	: 11556 h
Processing time per center guide including set-up	: 75 s
Processing time for 320,000 center guides	: 6667 h
Number of hours per year, assuming 90% uptime for a prototype laser heat treating system	: <u>1872 h</u>
Estimated number of lasers needed (at 90% uptime) to heat treat 640,000 end connectors and 320,000 center guides	: 10

5.1 Non-Recurring Investment Cost

This cost element provides estimates for implementation of a prototype laser heat treating facility utilizing ten laser systems to achieve initially the total production capability for T-142 end connectors and center guides. Cost estimates provided are expressed in FY 1979 dollar figures.

Ten (10) Laser Systems Spectra-Physics Model 975 CO ₂ Laser @ \$220,480/system	\$2,204,800
Ten (10) Gas Supply Panels Spectra-Physics Model 481 @ \$2,760/unit	\$ 27,600
Ten (10) Beam Delivery Systems and Heat Treating Stations estimated @ \$200,000/system (includes optical tooling, work handling tooling, computer numerical control, and installation)	\$2,000,000
Estimated Total	\$4,232,400

This estimated cost does not include site preparation at the manufacturing floor. Site preparation would include layout, design, construction, plumbing, and electrical work.

5.2 Production Cost

This cost element includes estimated costs directly associated with heat treatment of T-142 end connectors and center guides, using a prototype laser heat treating facility. To operate such a facility, the following are some of the estimated costs based on a Spectra-Physics Model 975 CO₂ laser.

Cost of gas mixture (He, N ₂ , O ₂ , CO ₂)	:\$ 1.50/h
Cost of electricity @\$ 0.06 per hour for 70 kW	:\$ 4.20/h
Estimated cost of an operator	:\$20.00/h
Maintenance cost (based on two labor hours per week at a labor cost of \$20.00 per hour)	:\$ 1.00/h
Tool replacement cost	:\$ 5.70/h
Estimated operating cost	:\$32.40/h

Tool replacement cost would include the periodic replacement of optical cavity, mirrors, electrodes, blower motors, vacuum pump, filters, and printed circuit cards. The estimated total cost does not include additional costs for implementing quality control and engineering effort in support of processing.

Based on \$32.40/h for the operation of a laser heat treating facility, heat treatment costs for end connectors and center guides are provided below.

	T-142 End Connectors	T-142 Center Guides
Heat Treatment Time	65 s	75 s
Heat Treatment Cost (Estimate)	\$ 0.59	\$ 0.68
Cost to Apply Energy		
Absorbing Coating (Estimate)	\$ 0.01	\$ 0.01
Estimated Production		
Cost	\$ 0.60	\$ 0.69

6.0 DESCRIPTION OF PROTOTYPE LASER HEAT TREATING SYSTEM

Heat treating parameters (such as laser power, beam size, beam configuration and processing or travel speed) to obtain hardened casings 3 to 4 mm deep on end connectors and center guides are used to propose preliminary specifications for a prototype laser heat treating system. Figure 26 shows a preliminary conceptual drawing of a prototype laser heat treating facility showing a work station, a beam delivery system, and a Spectra-Physics Model 975 laser system which includes the laser head, power supply, and control console. In Fig. 26, the prototype system is illustrated on one floor level in a manufacturing plant. Since manufacturing floor space is premium, it is appropriate to place the entire laser system on a balcony located above the floor. In this case, only the heat treating station with beam handling system and operator console are located on the manufacturing floor.

6.1 Heat Treating Station

A heat treating station contains proper work handling equipment to traverse track components at required speeds under a stationary laser beam. Normally for these components, either a linear traverse along an axis or rotation about an axis is appropriate. Control of work handling equipment and the laser system is manual, semiautomatic, or automatic. Semiautomation or full automation of this equipment is achieved when a CNC (computer numerical control) system is adapted. In fully automated systems, track components are loaded through transfer lines into work station and are positioned for the

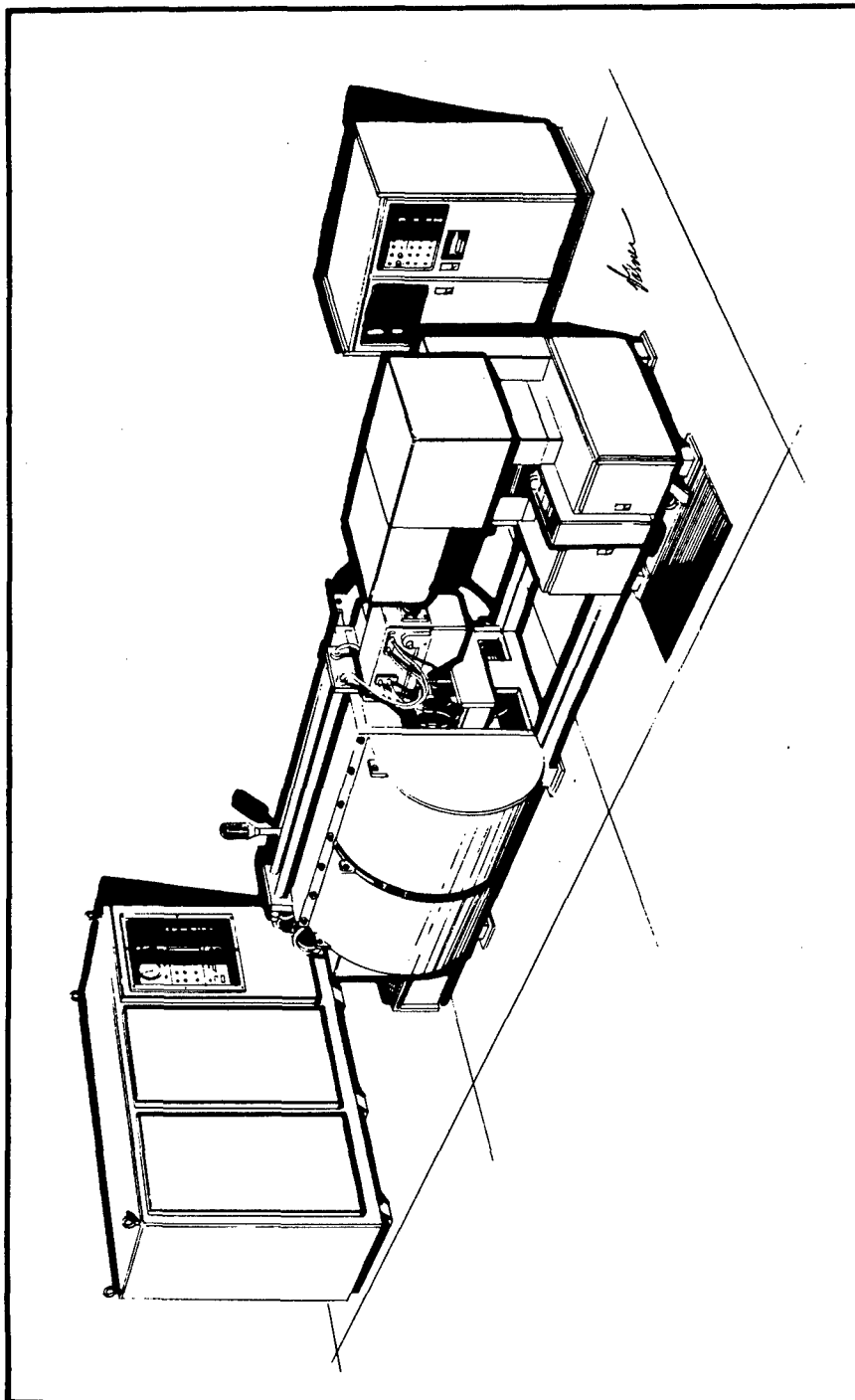


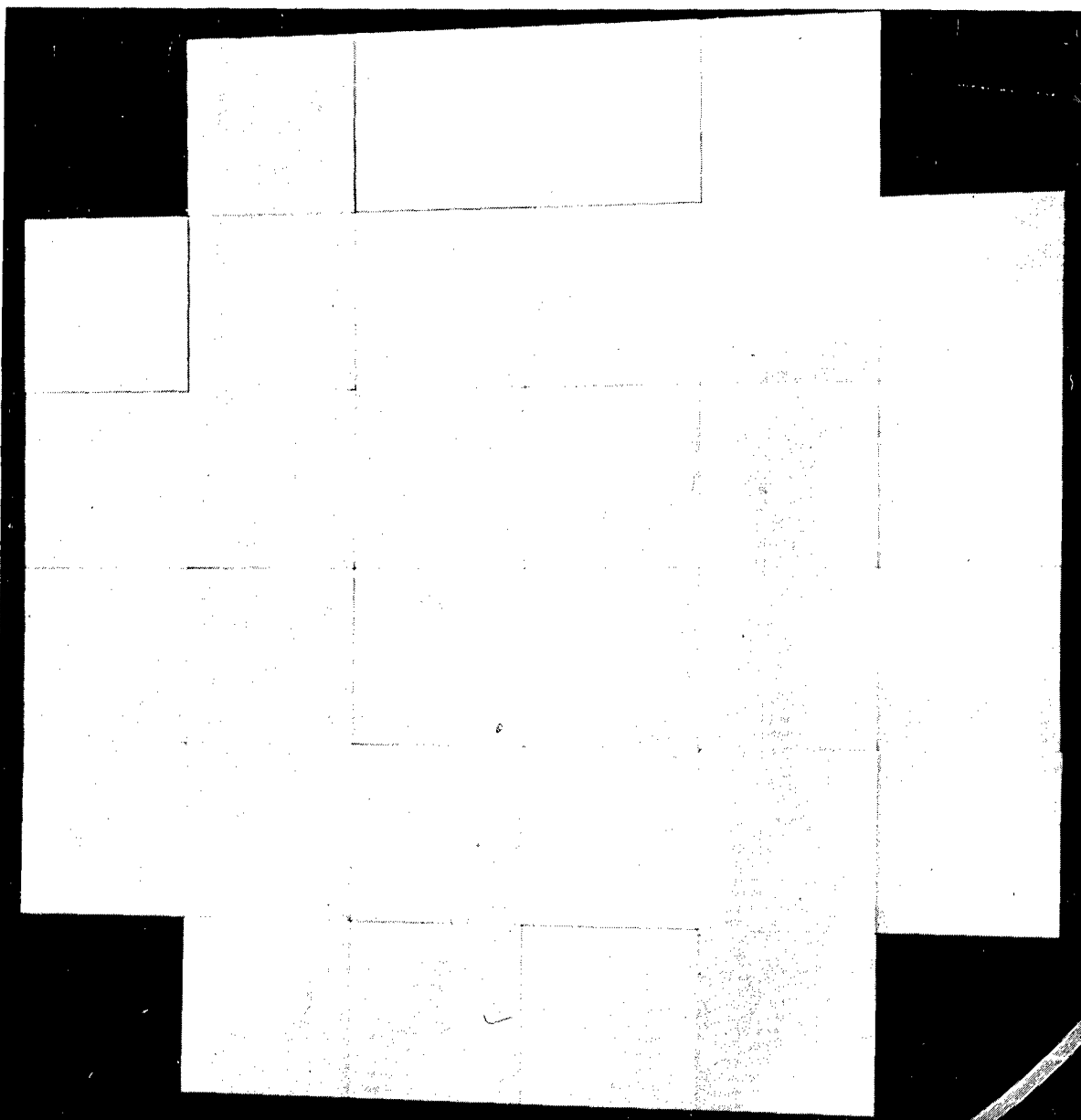
Fig. 26 Conceptual drawing of a prototype laser heat treating facility.

start of heat treatment and traversed at a programmed speed; a laser beam of appropriate power is then turned on to irradiate a track component for a required time and then turned off, and the workpiece is halted and transferred out of the station. For an automated system, one operator is usually needed to oversee the entire prototype laser heat treating system.

6.2 Beam Delivery System

Optical tooling to shape and deliver laser beam for heat treatment of track components is illustrated in Fig. 27. This tooling utilizes a spherical convex mirror (radius of curvature = 2.5 m), a Spawr spherical concave beam integrator (radius of curvature = 1.27 m), and a flat mirror. These mirrors shape and modify a 44 mm diameter output laser beam (from the laser system) having a nonuniform intensity distribution, into a 19 x 19 mm square beam with uniform intensity distribution suitable for the heat treatment of track components. By utilizing few mirrors, as in this system, total power loss due to beam absorption by mirrors is lowered; in addition, serviceability of these mirrors is easier. Based on this optical tooling design, other designs to suit various track components are possible.

In the beam delivery system, a convex mirror enables 44 mm diameter output laser beam to be expanded to 67 mm diameter on the face of a Spawr integrator, so that efficient beam integration can result. Spawr integrator shown in Fig. 28, transforms an asymmetrical beam into a uniformly intense beam. This is accomplished when the beam is optically dissected by mirror segments into 12.7 x 12.7 mm squares, and superimposed at the integrator's



MIRROR SEGMENT SIZE = 12.7 x 12.7mm

Fig. 28 Spawr beam integrator or segmented mirror showing 32 mirror segments.

focal point. Convex mirror used in conjunction with integrator enables size of the beam to be 19 x 19 mm square at the focal point, located 908 mm from the integrator, where the work surface is positioned.

Spawr integrator has a reflectivity of better than 96% for 10.6 μm CO₂ laser radiation and is constructed of molybdenum for durability. Convex and flat mirrors are made of high purity (oxygen free high conductivity) copper and have the following characteristics:

Reflectivity: 99% for 10.6 μm laser radiation

Surface Accuracy: $\lambda/20$

Surface Smoothness: 30 Å RMS

Scratch/Dig per
MIL-O-13830A: 20/10

6.3 Laser System

Spectra-Physics Model 975 laser system produces a cw CO₂ laser radiation at 10.6 μm wavelength. The system is built to comply with JIC Electrical Standards for Mass Production Equipment Tools (EMP-1-1967) and NEMA Standards (IS 1.1-1975). Major assemblies in power supply and laser head are made in the form of replaceable modules to facilitate maintenance. Operation, specification, and facility requirements for this laser are provided in Tables 2 and 3.

Table 2
Specifications of Spectra-Physics Model 975 Laser

Characteristic	Specification
A. <u>LASER</u>	
Wavelength	10.6 micrometers
Rated Output Power	5000 watts
Power Output Stability	±5% variation (plus change in cooling water inlet temperature).
Beam Divergence	3.0 milliradians
Beam Diameter	44 millimeters
Beam Pointing Stability	<0.15 milliradians
Shutter Open or Close Time	0.1 second
Time to Reach Steady State from Cold Start	Allow 15 minutes warm up at normal operating current
Vacuum Pump	Pump down from atmospheric pressure to 1 torr in 30 minutes
B. <u>POWER SUPPLY</u>	
Output Current	0-40 amperes
Output Voltage	0-3000 volts
Arc Detection	Detects $\Delta V/\Delta T$ and turns off high voltage when arc constriction occurs
Leakage current	5 milliamperes line to ground through 1500 ohm
Current Ripple	Less than 5% peak-to-peak
Current Regulation	±1% for 24 hours at 25°C

Table 3

Facility Requirements for Spectra-Physics Model 975 Laser

REQUIREMENTS	VALUE
A. <u>ELECTRICAL</u>	
Primary Power (60 Hz operation)	460 Vac., 200 amperes/line, 3-phase, Delta winding
Primary Power (50 Hz operation)	380 Vac., 200 amperes/line, 3-phase, Delta winding
Phase Unbalance	<2.5%
Ground Connection	2/0 AWG copper wire to house ground
B. <u>COOLING WATER</u>	
Flow (without accessory optics)	24 GPM
Pressure	40 PSIG Minimum Differential; 100 PSIG Maximum Supply
Temperature:	
Maximum Input Temperature	95°F
Temperature Control	±2°F Recommended*
Resistivity	20 to 50 kΩ/cm, Typical
C. <u>COMPRESSED AIR</u>	
Flow-Pressure	0.5 CFM at 60 PSIG
D. <u>LASER GASES</u>	
Helium	Industrial Grade (99.99% pure or equivalent at 4.4 SCFH.
Oxygen-Nitrogen Mixture	Industrial Grade (99.99% pure or equivalent) NOTE: mixed oxygen-nitrogen should consist of 10% O ₂ and 90% N ₂ at 1.98 SCFH.
Carbon Dioxide	"Welding Grade" (99.5% or higher purity) at 0.33 SCFH.
*Power varies approximately 0.5% per °F change in water temperature.	

6.3.1

Laser Head

Main structure of the laser head is a vacuum shell consisting of the following primary components which are illustrated in Fig. 29.

1. Two center sections containing discharge electrodes and active laser volume.
2. Two blower housings, each containing a vaneaxial blower to transport gas mixture.
3. Two upstream end bells, each of which contains gas-flow directing vanes.
4. Two downstream end bells, each of which contains a gas-to-liquid heat exchanger and gas-flow directing vanes.
5. An optical mount structure.

Basically, the laser head is an optical oscillator consisting of a resonant optical cavity and a lasing medium of He, O₂, N₂, and CO₂ gases. Within the optical cavity are two electrodes (cathode and segmented anode) between which an electrical glow discharge is developed to excite N₂ in the gas mixture to an upper vibrational energy level. Vibrational energy from N₂ is subsequently transferred to CO₂ during collisions between gas molecules, exciting CO₂ molecules to an upper vibrational energy level. Excited CO₂ molecules then fall spontaneously to a lower energy level, emitting photons at 10.6 μ m wavelength. These molecules then relax from lower energy levels to ground state. He gas is added in the gas mixture to facilitate cooling of gas

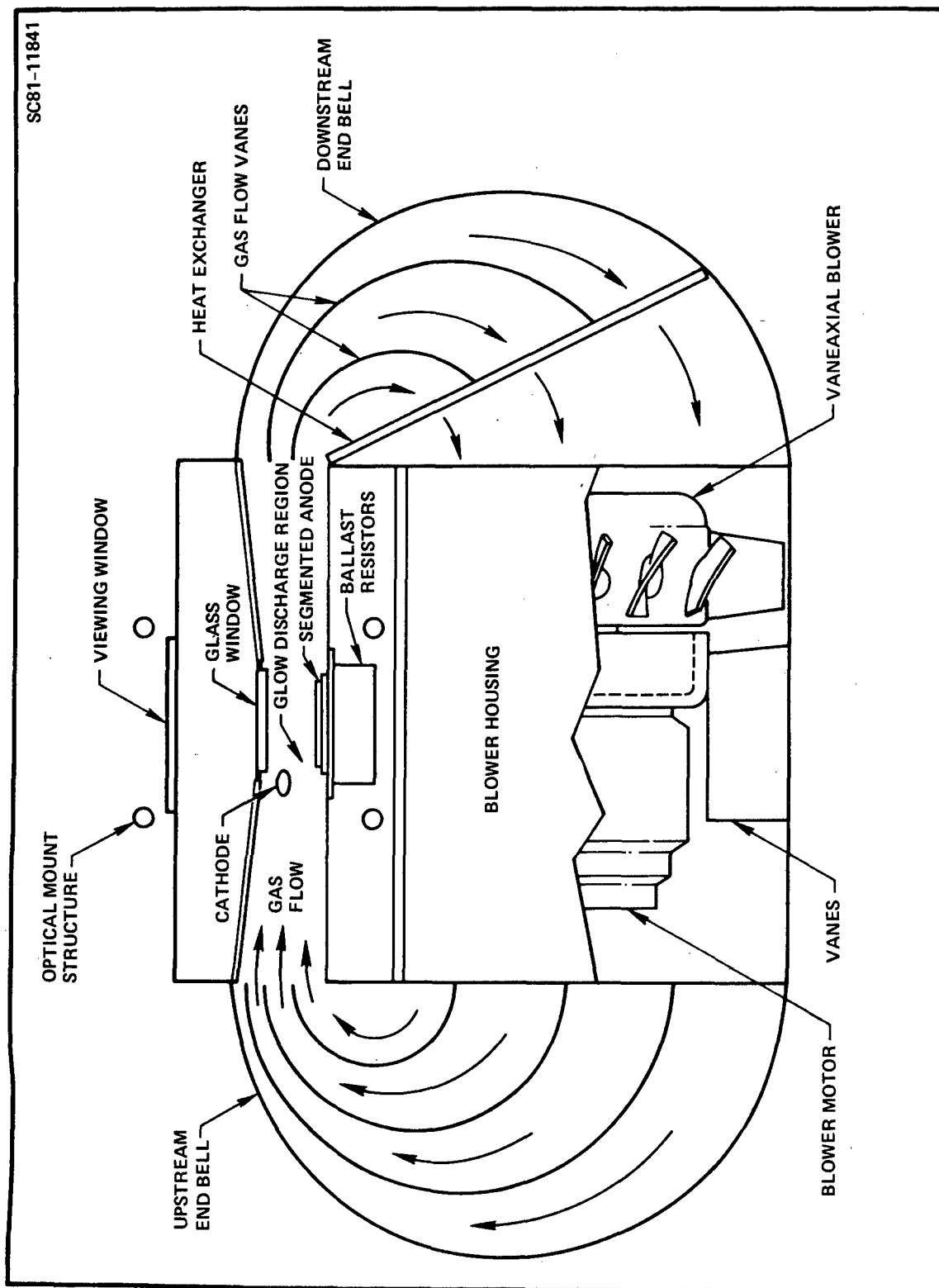


Fig. 29 Schematic cross-section of laser head.

mixture and to improve laser efficiency, that is, by increasing the rate at which CO₂ molecules relax from lower energy levels to ground state, from which they can again be excited by electrical discharge. Figure 30 illustrates schematically the mechanism for emission of 10.6 μm wavelength laser radiation. Light amplification occurs when a photon of proper wavelength emitted by an excited molecule strikes another excited molecule of the same type to stimulate the second molecule to emit a photon of the same wavelength in phase coherence with original photon, thus resulting in two photons. Laser action begins when one or more photons are emitted, moving in precise alignment with the axis of optical cavity. These photons travel back and forth between the cavity mirrors, gaining more stimulated photons with each pass. The process quickly builds up to an intense wave train of coherent optical energy at a wavelength of 10.6 μm . Part of this energy exits through the output coupler.

The optical cavity shown in Fig. 31 consists of an output coupler (made of gallium arsenide) located front, water-cooled copper mirror (spherical concave) located rear, and a pair of water-cooled copper mirrors (flat) for beam folding. The output coupler is partially transmissive to 10.6 μm wavelength laser beam. In operation, the lasing medium (gas mixture) provides a means of optical amplification, and the cavity mirrors provide optical feedback required to form an oscillator. Cathode and segmented anode, located inside optical cavity as illustrated in Fig. 32, are designed to provide uniform electrical glow discharge across the entire length of optical cavity.

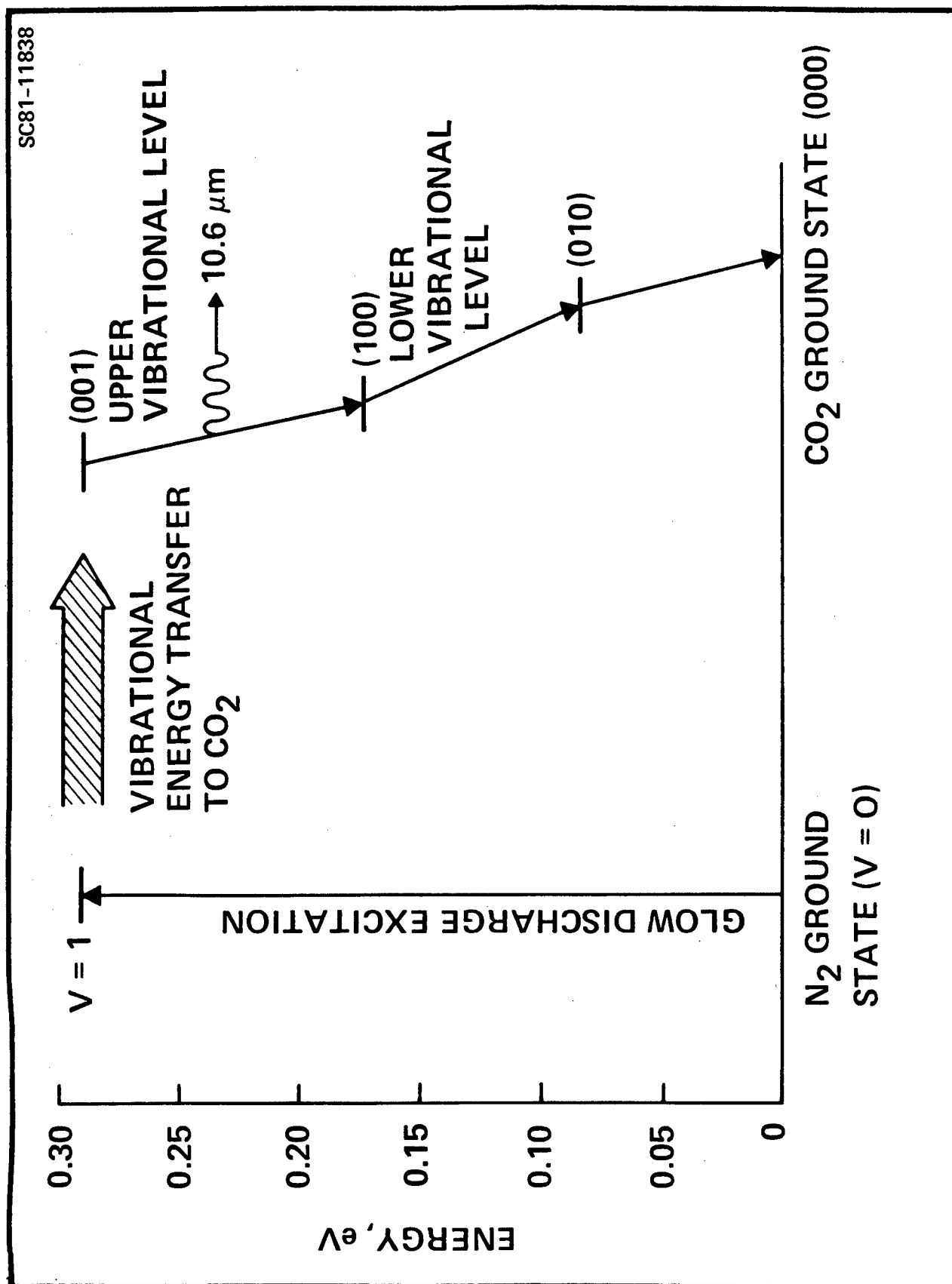


Fig. 30 Mechanism for the emission of 10.6 μm wavelength laser radiation (after Patel⁵).

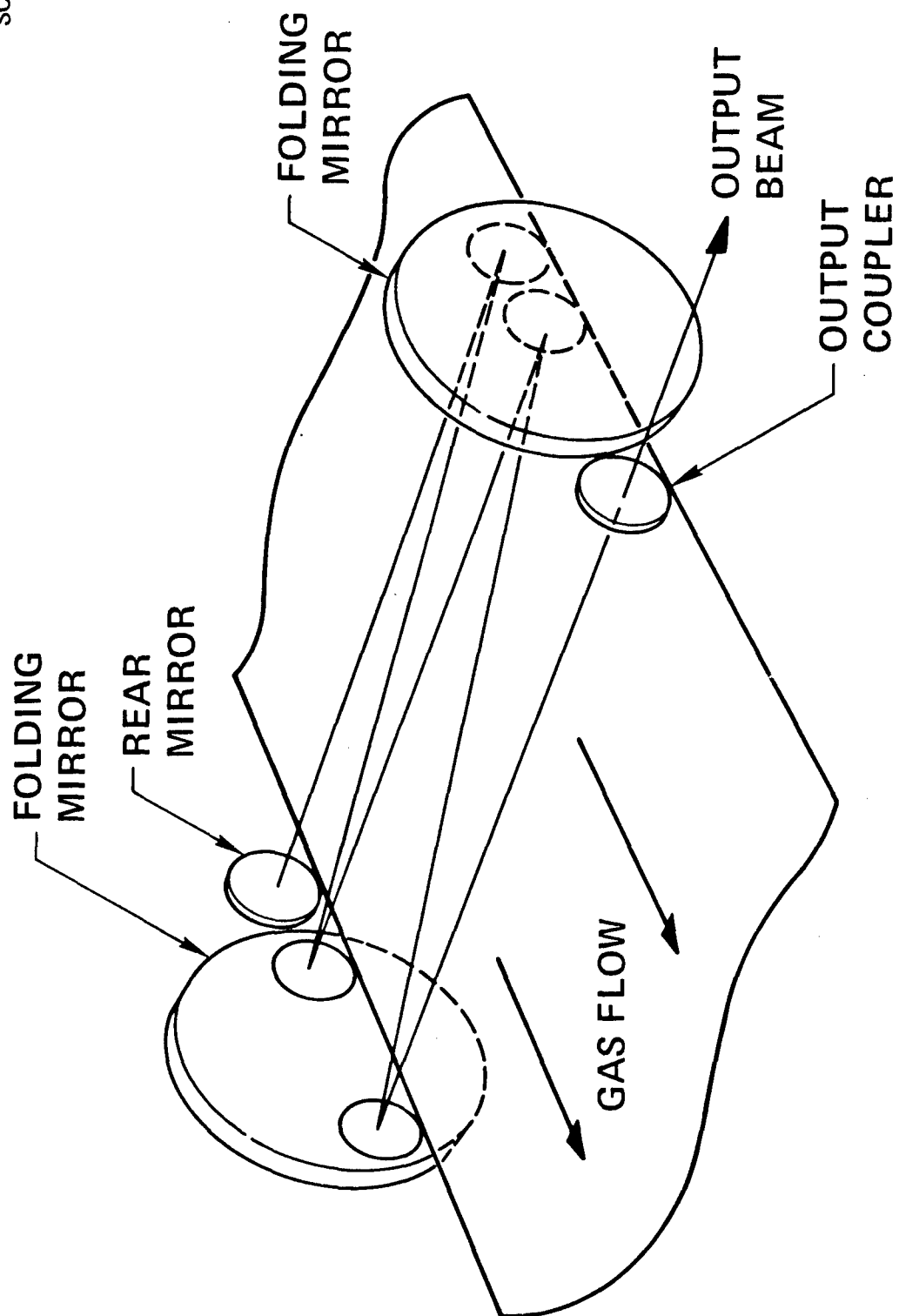


Fig. 31 Mirror arrangement inside optical cavity.

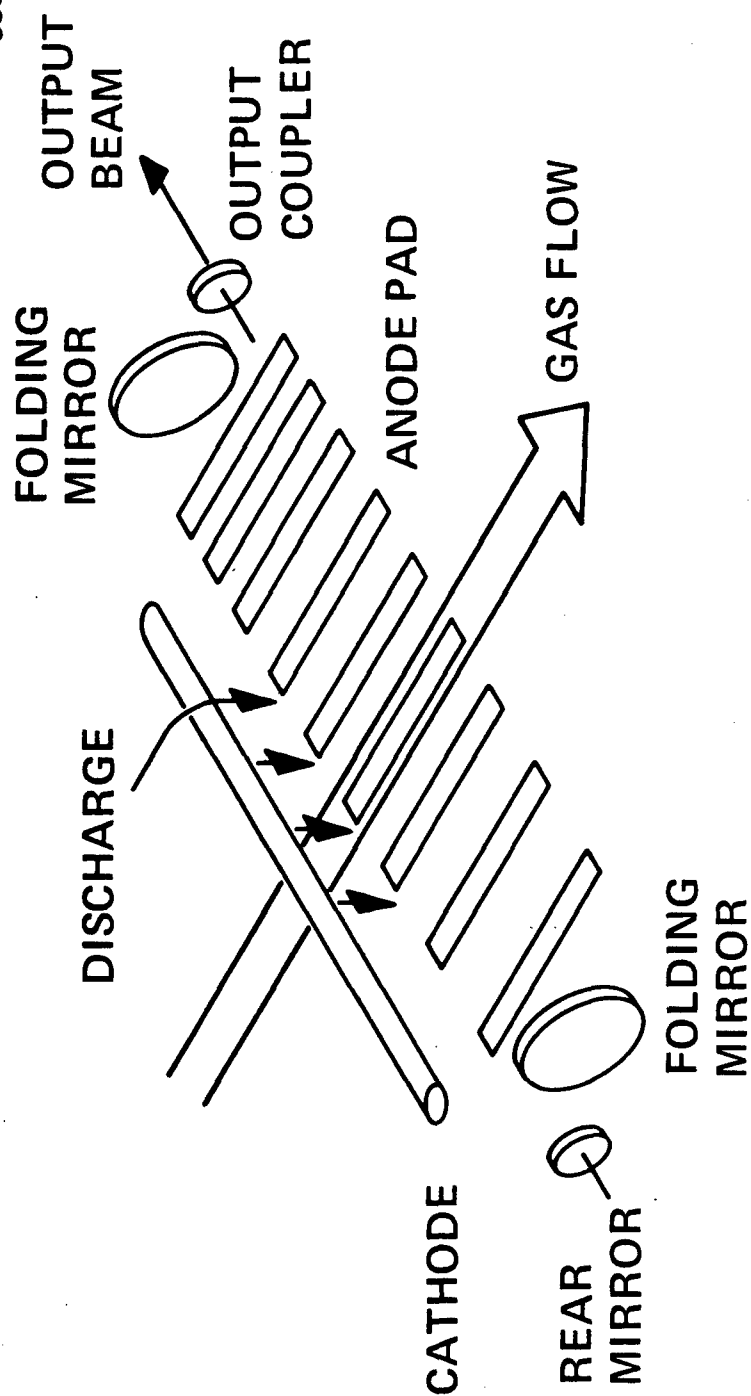


Fig. 32 Electrode arrangement inside optical cavity.

Vaneaxial blowers circulate the gas mixture at a velocity of 60 m/s across optical cavity. In order to provide a smooth flow of gas across this cavity, and therefore a uniform electrical discharge, the upstream and downstream end bells contain several flow-directing vanes. A heat exchanger located at each downstream end bell cools the hot gas mixture after it exits the optical cavity. Viewing windows are located at the top and side of laser head to provide full access for viewing electrical glow discharge in optical cavity. A He/Ne alignment laser provides a coaxial visible beam for alignment of CO₂ beam with workpiece. A continuous on-line power monitoring meter is used for real time laser power output readings. A shutter/power dump assembly provides turn-on and turn-off of laser beam while allowing uninterrupted internal laser operation. This assembly contains a movable beam absorber that functions as a shutter. When this assembly is actuated, CO₂ laser beam is intercepted by the shutter and is absorbed by a water-cooled surface.

6.3.2 Power Supply Cabinet

Power supply cabinet contains high voltage circuits, gas and pressure control system, and system operating controls and indicators. The high voltage power supply converts 3-phase prime input power to high voltage direct current for the discharge electrodes in optical cavity of laser head. The power supply is a current-controlled device, and therefore no adjustment is provided for control of its output voltage. Actual output voltage of the supply is a function of discharge current, gas pressure, and gas mixture.

martensitic up to 3 mm. Initial laboratory tests indicate that abrasive wear resistance of laser heat treated end connector specimen was better than that of an untreated specimen.

- Center guides' wearing surfaces were heat treated to a depth of 3.65 mm with hardness ranging between Rc 50 and 54. Laser power (on work-piece) was 5000 W, and heat treatment time was 70 s to cover total area of 2840 mm². Case microstructure was predominantly martensitic up to a depth of 3.5 mm. Abrasive wear resistance of laser heat treated center guide specimen was comparable to an induction hardened specimen.

- Preliminary estimates on laser heat treating cost of an end connector is \$0.60 and of a center guide is \$0.69. Further development aimed at refining laser heat treating procedures can minimize heat treatment times and/or costs.

- Preliminary specifications for a prototype laser heat treating facility require a work station, beam delivery system, and a 5000 W cw CO₂ laser system.

Preliminary estimates indicate a prototype heat treating facility with a 5000 W CO₂ laser would cost \$423,000 (FY 1979 dollar figures). This facility when operating at 90% uptime can heat treat 103,680 end connectors or 89,856 center guides in a single year (i.e., 2080 h).

- Preliminary quality assurance specifications are proposed to control case depths and hardness profiles from part to part. Some of these specifications consider energy absorbing coatings, laser beam power, laser beam size, laser beam quality, travel speed, and core microstructure of track components.

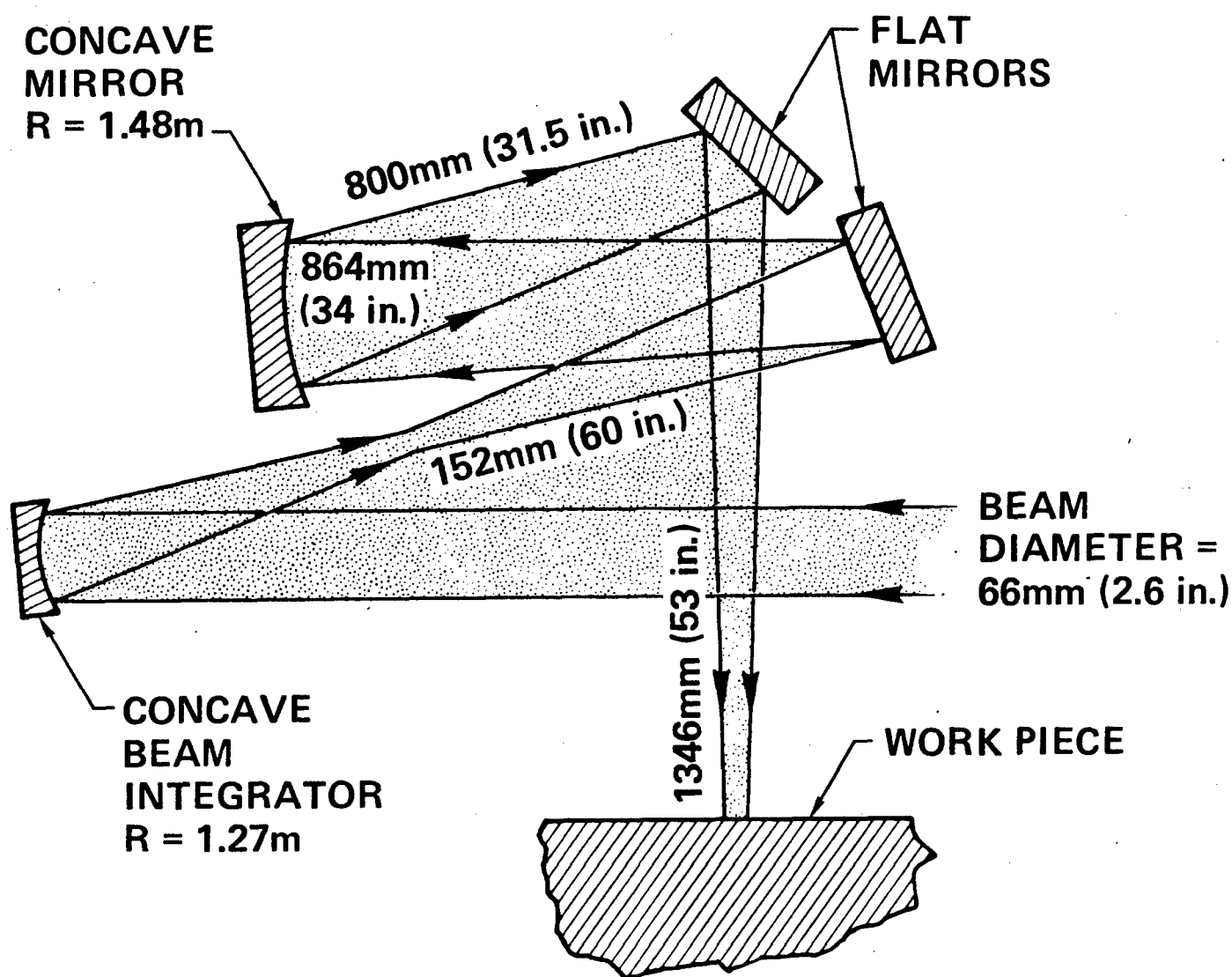
- A 9 mm thick AISI 4140 steel plate (tempered martensitic core with hardness of Rc 38) was laser heat treated to a depth of 6.5 mm. Hardened casing was free from surface melting and cracking. This casing was obtained with 4000 W of laser power (on workpiece) and travel speed of 2.5 mm/s, and without using an external quenching medium (self quenched).

8.0 REFERENCES

1. D. S. Gnanamuthu, C. B. Shaw, Jr, W. E. Lawrence, and M. R. Mitchell, "Laser Transformation Hardening," Laser-Solid Interactions and Laser Processing-1978, American Institute of Physics, New York (1979), p. 173.
2. H. S. Carslaw and J. C. Jaeger, eds., Conduction of Heat in Solids, Second Edition, Oxford University Press, London (1978), p. 270.
3. A. Rose and V. Strassburg, "Demonstration of the Formation of Austenite in Hypoeutectoid Steels by means of TTT Heating Diagrams," Stahl und Eisen, 76, 976 (1956).
4. "Cooling Transformation Diagram for AISI 4140," Atlas of Isothermal Transformation and Cooling Transformation Diagrams, American Society for Metals, Metals Parks, Ohio (1977), p. 390.
5. C. K. N. Patel, "High Power Carbon Dioxide Lasers," Scientific American, 219 (2), 22 (1968).

APPENDIX A

Results on the heat treatment of T-142 end connectors and center guides, using an AVCO HPL cw CO₂ laser, are illustrated in Figs. A1 to A9. AVCO laser is rated at 15000 W of laser output power at a wavelength of 10.6 μm .



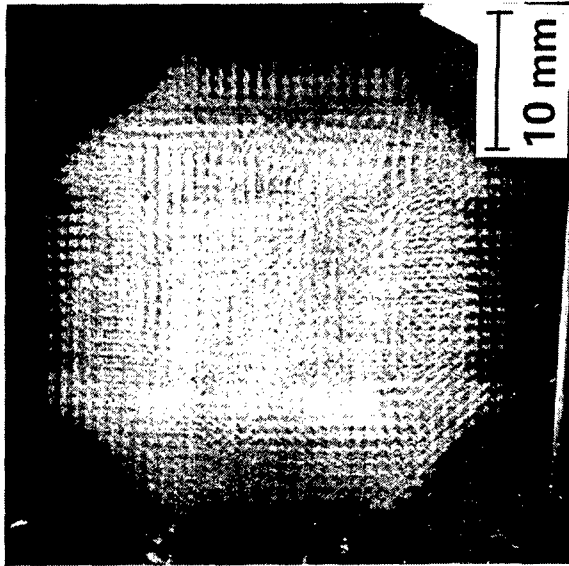
FOCAL RATIO = $f/23.3$

MAGNIFICATION = 1.9

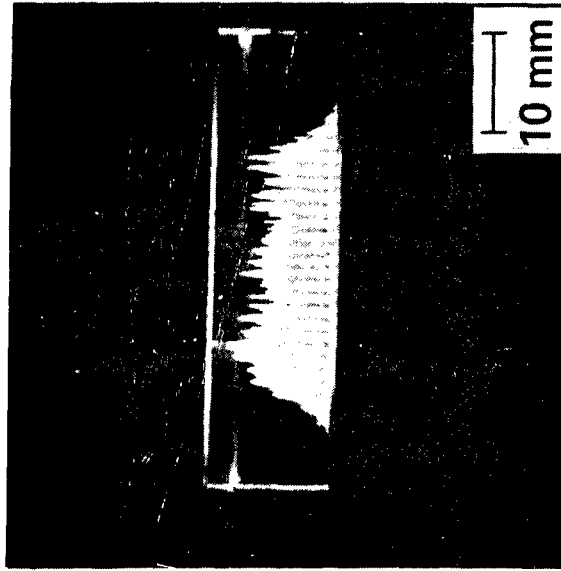
BEAM SIZE ON WORK SURFACE = 24 x 24 mm

Fig. A1 Optical tooling used in conjunction with an AVCO laser to provide suitable beam size for heat treatment of track components. (A total of 8 mirrors were used for collimating, directing, and beamshaping).

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TOP VIEW



LONGITUDINAL VIEW

Fig. A2 Intensity distribution of CO₂ laser beam (shaped by optical tooling illustrated in Fig. A1) as revealed by "burn patterns" in Lucite.

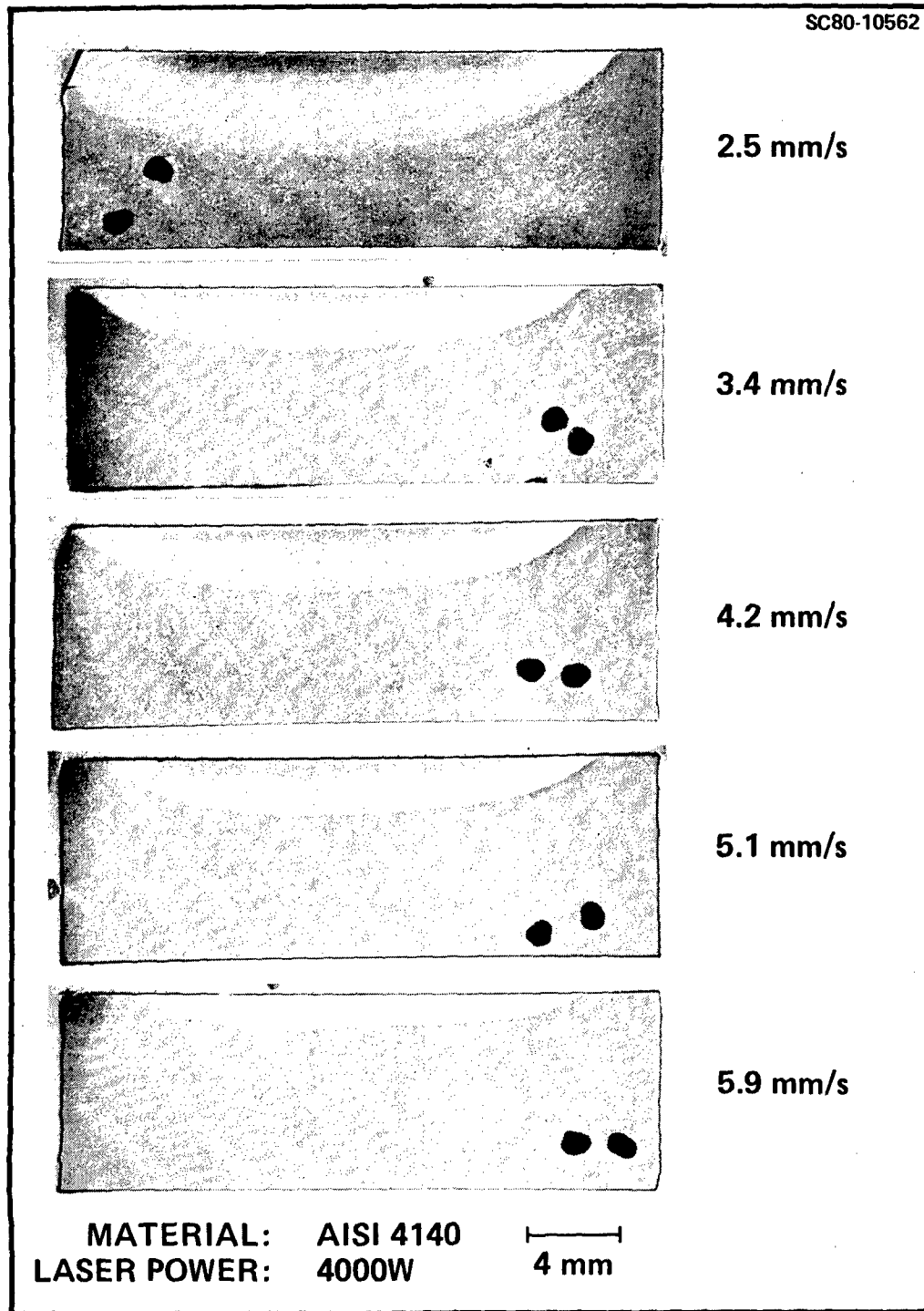


Fig. A3 Cross-sectional views of steel plates heat treated with 4000 W of laser power from an AVCO laser and optical tooling illustrated in Fig. A1. Plates were nickel plated during metallographic preparation for edge retention. Note microhardness impressions along heat treated casings.

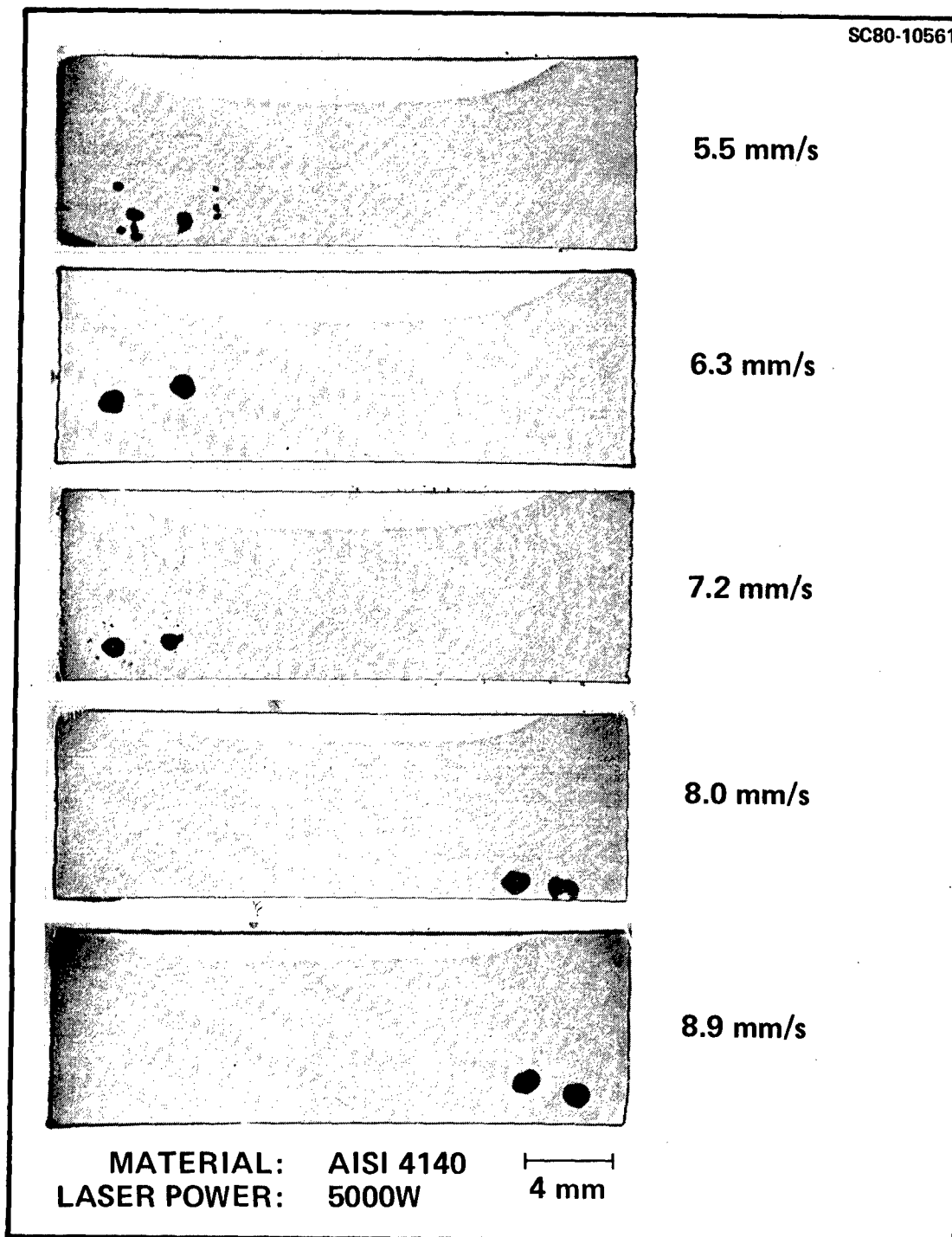


Fig. A4 Cross-sectional views of steel plates heat treated with 5000 W of laser power from an AVCO laser and optical tooling illustrated in Fig. A1. Plates were nickel plated during metallographic preparation for edge retention. Note microhardness impressions along heat treated casings.

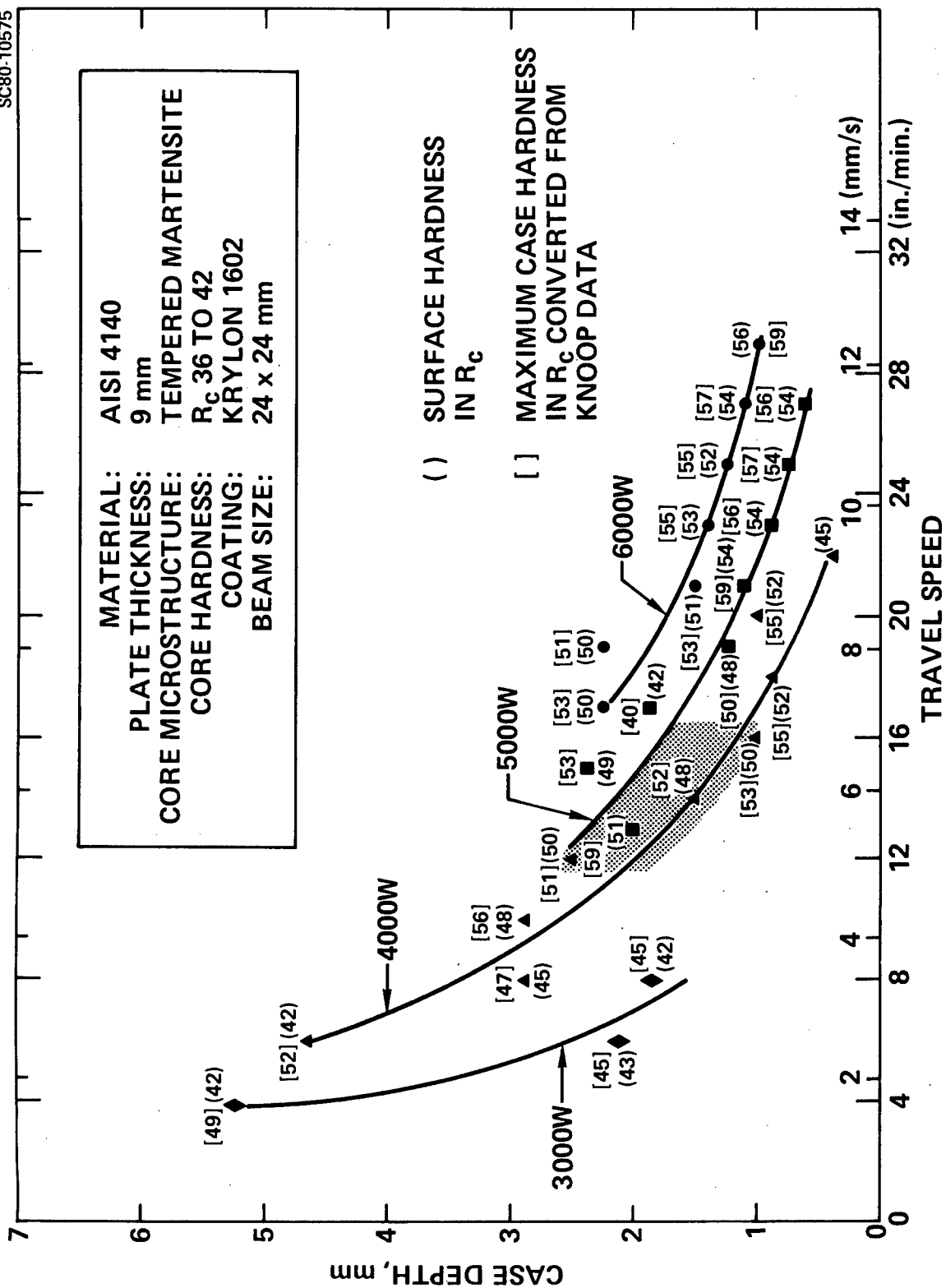


Fig. A5 Variation of case depth vs. travel speed at 3000 W, 4000 W, 5000 W, and 6000 W of laser power, using an AVCO laser.

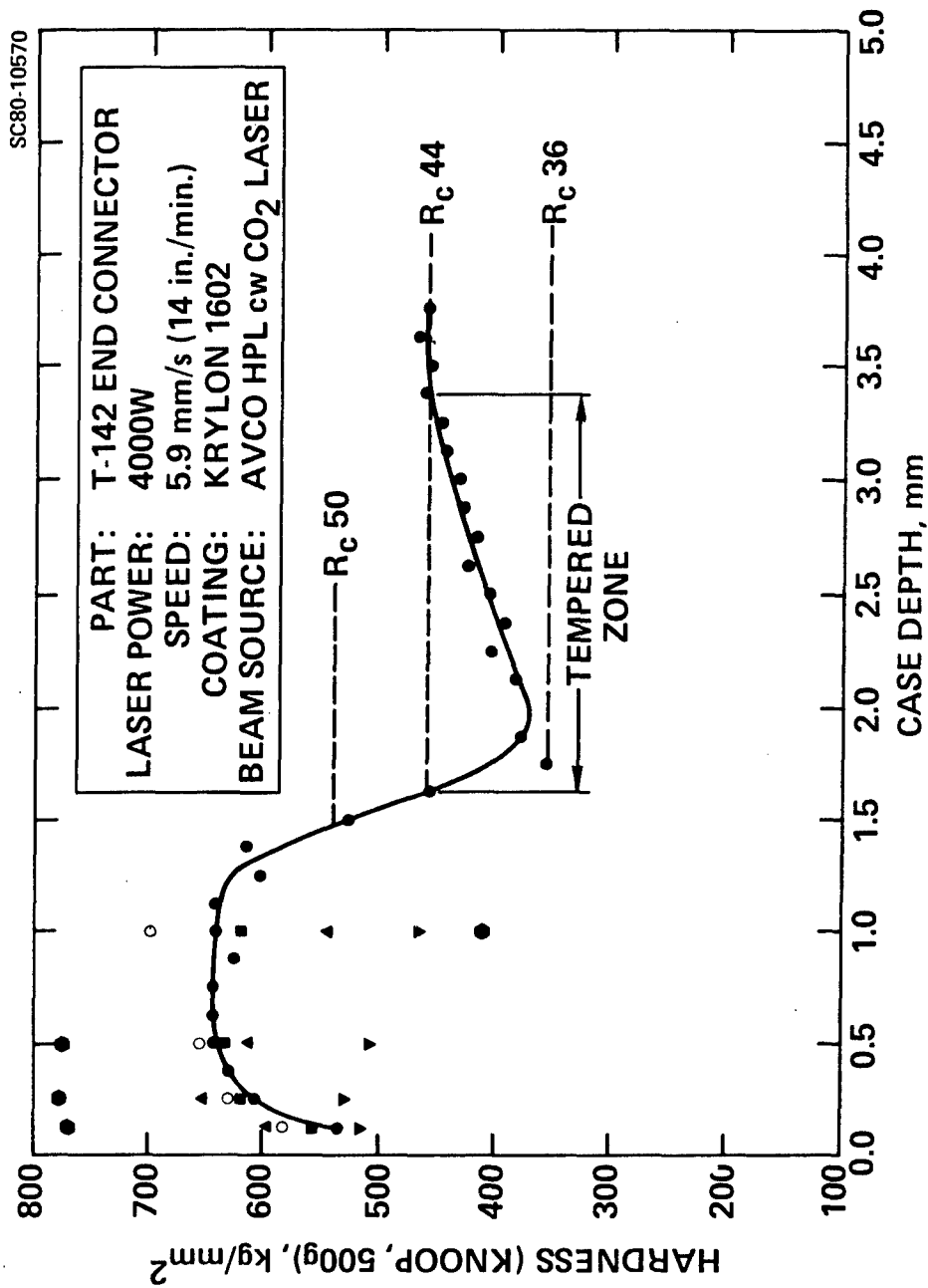


Fig. A6 Hardness profile along a heat treated casing in an end connector. Microhardness measurements at 0.1 mm, 0.2 mm, 0.5 mm, and 1.0 mm below surface of six separate heat treated casings in an end connector show microhardness variations observed at these locations. Casing with the highest hardness (780 kg/mm²) observed, had cracks along the surface, while the other casings were crack free. Variations in case depth and hardness from one heat treat pass to another may be due to variations in travel speed and/or thickness of energy absorbing coating.

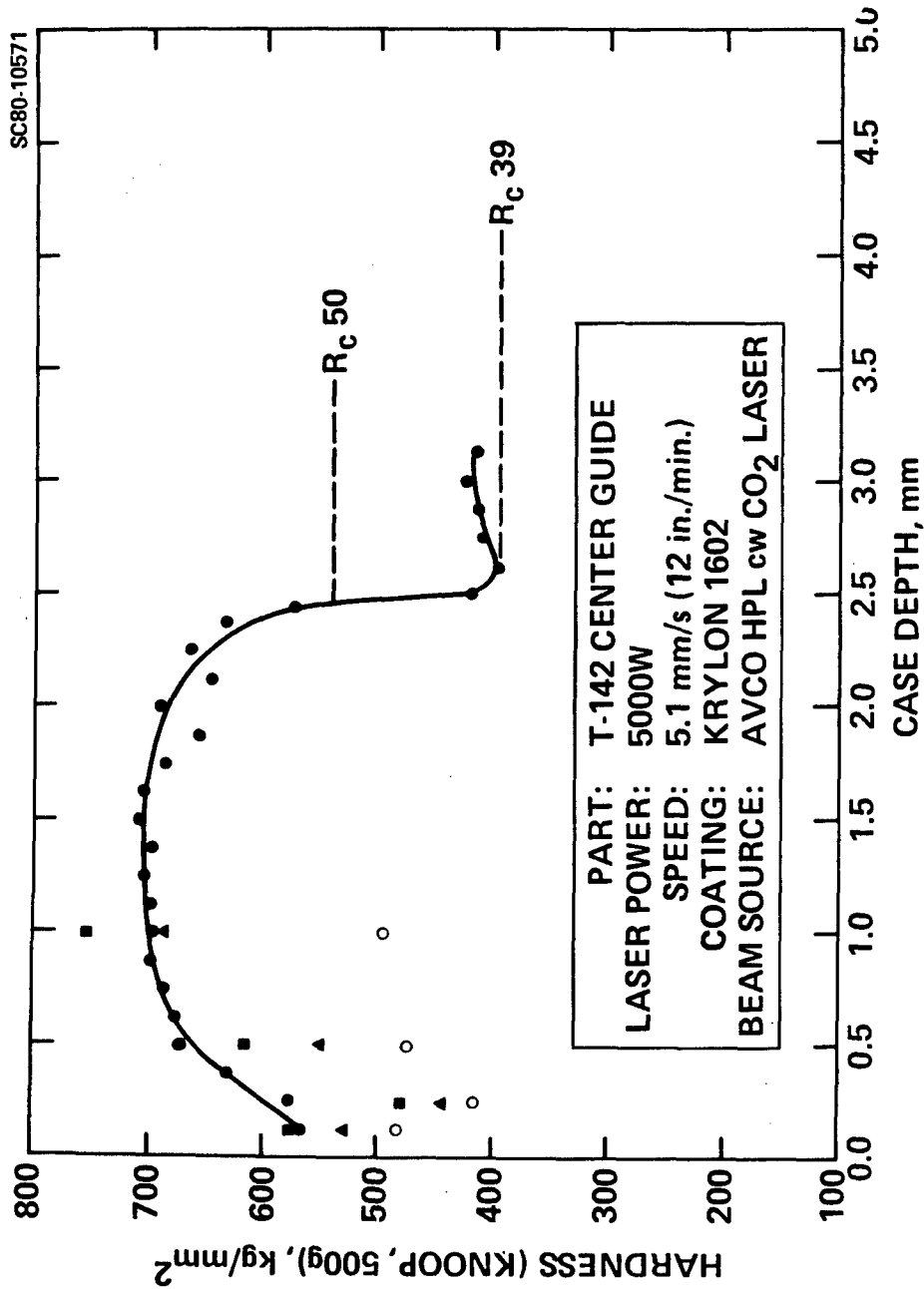
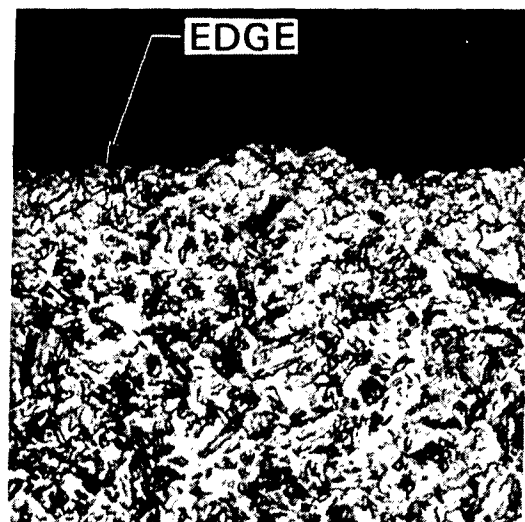


Fig. A7 Hardness profile along a heat treated casing in a center guide. Microhardness measurements at 0.1 mm, 0.2 mm, 0.5 mm, and 1.0 mm below surface of four separate heat treated casings in a center guide show microhardness variations observed at these locations. Variations in case depth and hardness from one heat treat pass to another may be due to variations in travel speed and/or thickness of energy absorbing coating.



SURFACE

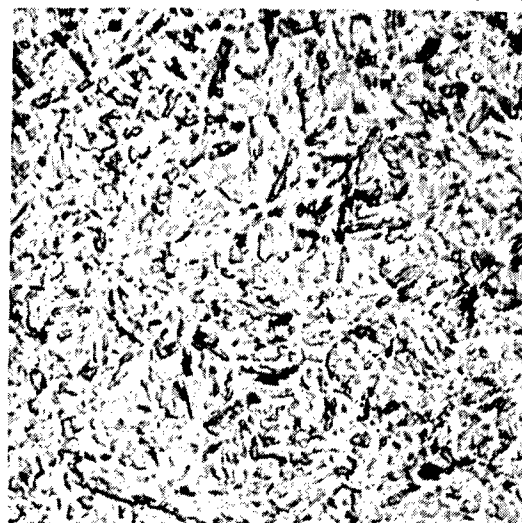
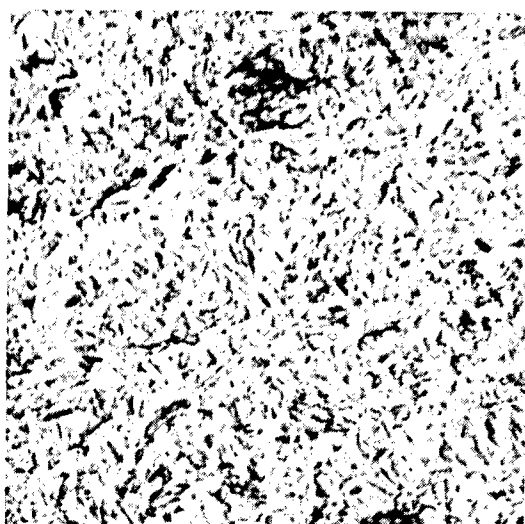
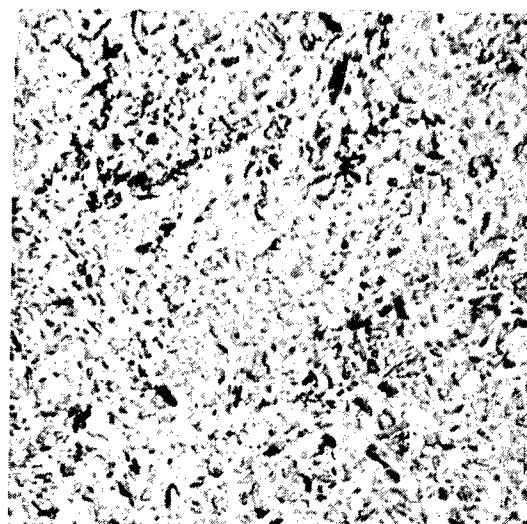
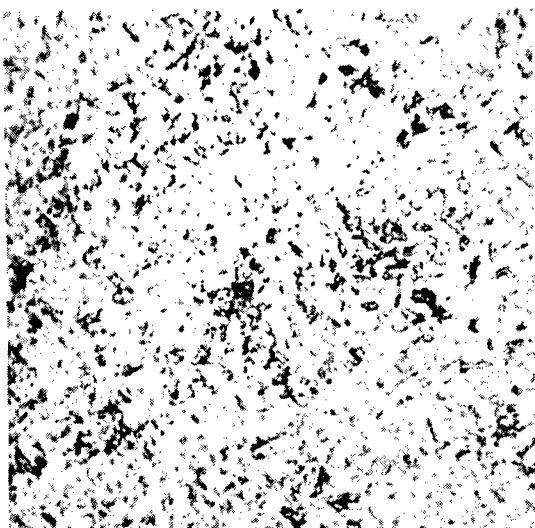
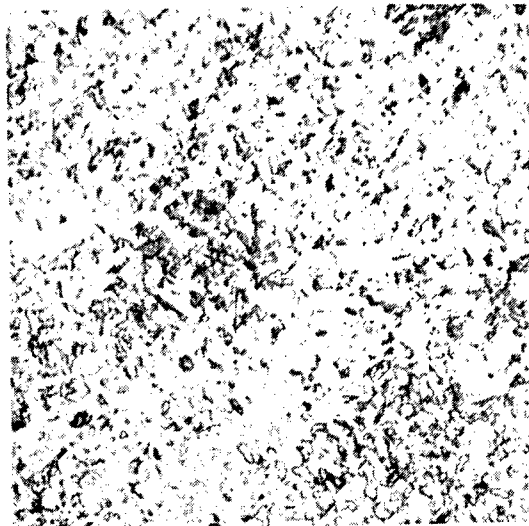
0.3 mm
 R_c 540.5 mm
 R_c 55
10 μ m1.0 mm
 R_c 55

Fig. A8 Microstructures at several locations along a heat treated casing in an end connector. Hardness reading corresponding to each location is illustrated. Martensitic plates near surface are more refined than those illustrated in Fig. 20.

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1.25 mm
 R_c 53

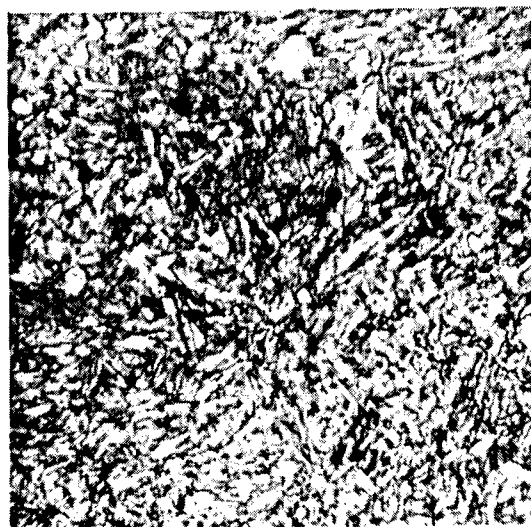


1.5 mm
 R_c 50



1.75 mm
 R_c 36

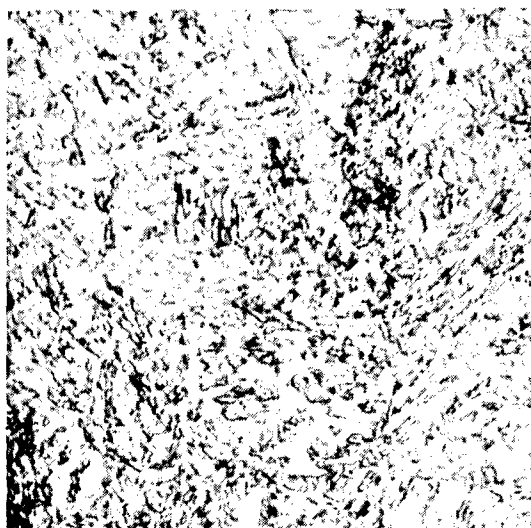
10 μ m



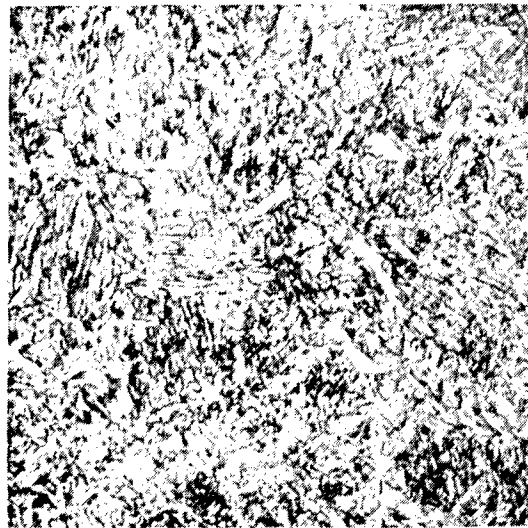
2.5 mm
 R_c 40

Fig. A8 Cont.

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3.5 mm
R_c 44

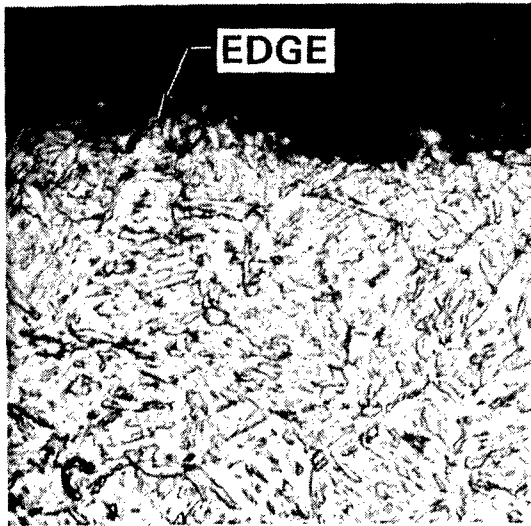


CORE
R_c 44

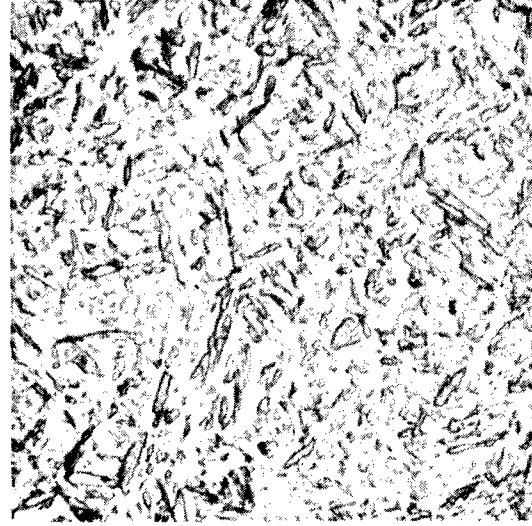
10 μ m

Fig. A8 Cont.

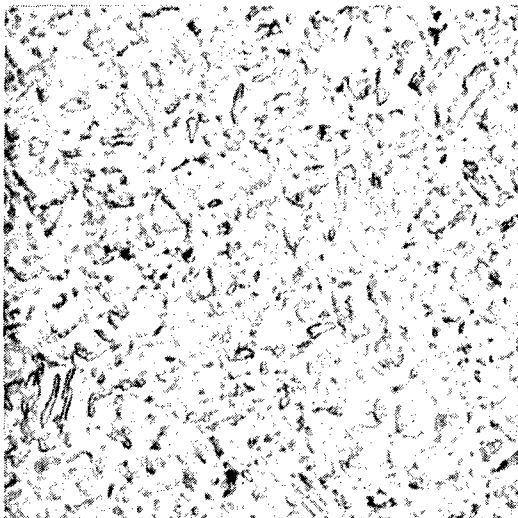
SC81-12521



SURFACE

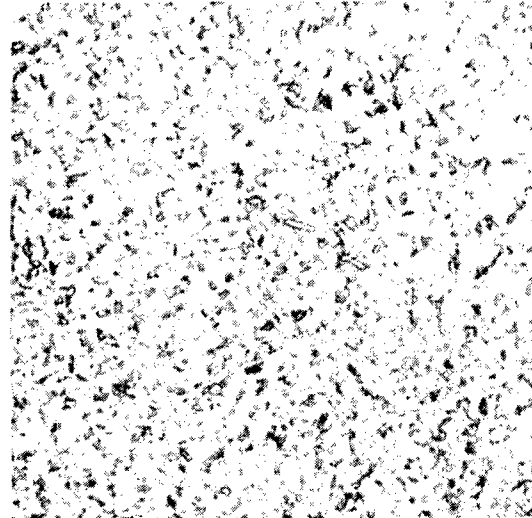


**0.5mm
R_c57**



**1.0mm
R_c58**

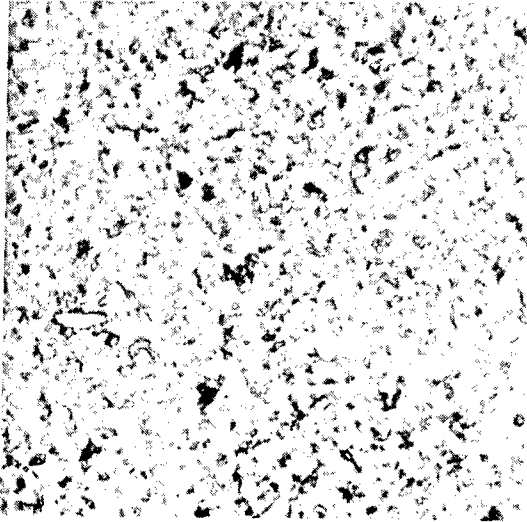
10μm



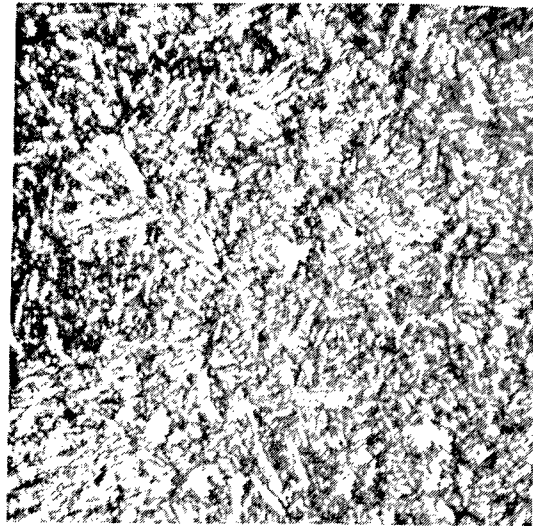
**2.0mm
R_c58**

Fig. A9 Microstructures at several locations along a heat treated casing in a center guide. Hardness reading corresponding to each location is illustrated.

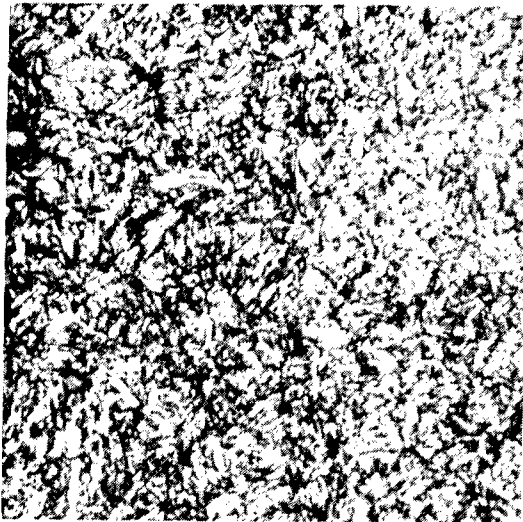
SC81-12522



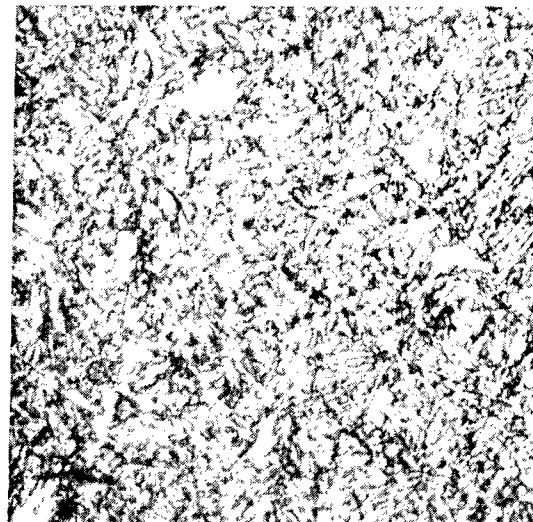
2.4mm
 R_c55



2.6mm
 R_c39



3.0mm
 R_c40



CORE
 R_c40

10 μ m

Fig. A9 Cont.