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LASER TRANSFORMATION HARDENING OF FIRING ZONE CUTOUT CAMS.(U)
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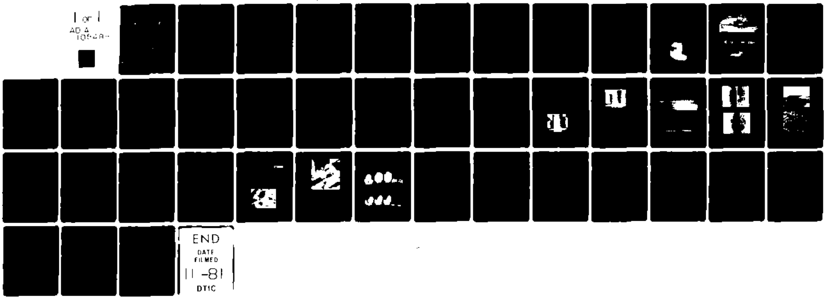

LEVEL II

AD A105498

NAVSEA REPORT NO. S555-79
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LASER TRANSFORMATION HARDENING OF FIRING ZONE CUTOUT CAMS

FINAL REPORT

A PROJECT OF THE
MANUFACTURING TECHNOLOGY PROGRAM
NAVAL SEA SYSTEMS COMMAND

by
ROBERT W. LOWRY

NAVAL SURFACE WEAPONS CENTER
DAHLGREN, VIRGINIA 22448 SILVER SPRING, MARYLAND 20910

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: NAVSEA-S555-79

2. GOVT ACCESSION NO.: AD-A105498

3. RECIPIENT'S CATALOG NUMBER:

4. TITLE (and Subtitle): LASER TRANSFORMATION HARDENING OF FIRING ZONE CUTOUT CAMS.

5. TYPE OF REPORT & PERIOD COVERED: Final

6. PERFORMING ORG. REPORT NUMBER:

7. AUTHOR(s): Robert W. Lowry

8. CONTRACT OR GRANT NUMBER(s):

9. PERFORMING ORGANIZATION NAME AND ADDRESS: Naval Surface Weapons Center (G53), Dahlgren, VA 22448

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: DNS 0055

11. CONTROLLING OFFICE NAME AND ADDRESS: Naval Sea Systems Command (05R), Washington, DC 20362

12. REPORT DATE: Jun[redacted]81

13. NUMBER OF PAGES: 43

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):

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):

Laser Transformation Hardening Cams

20. ABSTRACT (Continue on reverse side if necessary and identify by block number):

This manufacturing technology (MT) project developed techniques to use laser transformation hardening to replace cyanide salt bath nitriding to case harden firing zone cutout cams for the Mk 10 Guided Missile Launcher System (GMLS). These cams, machined of 4340 steel, satisfactorily meet the manufacturing requirements of a case depth of 0.010-0.020 in. and a hardness of R_C 55-67, with minimal distortion, after undergoing laser hardening. The laser transformation, utilizing a beam oscillator and numerical control

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S/N 0102-LF-014-6601

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

391342

20. ABSTRACT (Continued)

stepping procedures to minimize heat buildup, produces a very fine martensitic structure that is hard, typically R_C 62. This hardness is reduced somewhat in the beam overlap regions, but this factor is compensated for by cam pre-heat treatment and sufficient overlap of laser beam passes. The cost of laser hardening is estimated at less than 10 percent of the cost of cyanide nitriding.

FOREWORD

The project reported herein was sponsored by Naval Sea Systems Command, Manufacturing Technology Office (NAVSEA 05R2). The work was funded under Project 4038-79, DNS 555. The purpose of the undertaking was to reduce the cost of surface hardening by developing laser transformation hardening as a replacement for the nitriding process. This project was demonstrated on the firing zone cutout cam of the Mk 10 Guided Missile Launching System (GMLS), but opens the door for laser treating a host of other naval surface weapons and components with the potential for additional cost savings and technological advantages.

The author wishes to acknowledge the following persons for their technical assistance: Robert Retter and Emmett Staples for metallographic analysis and Earl Baird for background information and hardware assistance.

This report has been reviewed and approved by Jerry Hall, Head, Materials Science Branch; Dr. John Thompson, Manufacturing Technology Program Manager; and David Malyevac, Head, Survivability and Applied Sciences Division.

Released by:

CAPT R. P. FUSCALDO
Assistant Head for Weapons Systems
Weapons Systems Department

EXECUTIVE SUMMARY

This manufacturing technology (MT) project developed techniques to use laser transformation hardening to replace cyanide salt bath nitriding to case harden firing zone cutout cams for the Mk 10 Guided Missile Launcher System (GMLS). These cams, machined of 4340 steel, satisfactorily meet the manufacturing requirements of a case depth of 0.010-0.020 in. and a hardness of R_c 55-67, with minimal distortion, after undergoing laser hardening. The laser transformation, utilizing a beam oscillator and numerical control stepping procedures to minimize heat buildup, produces a very fine martensitic structure that is hard, typically R_c 62. This hardness is reduced somewhat in the beam overlap regions, but this factor is compensated for by cam preheat treatment and sufficient overlap of laser beam passes. The cost of laser hardening is estimated at less than 10 percent of the cost of cyanide nitriding.

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INTRODUCTION

OBJECTIVE

The technical objective of this project was to develop production methods for laser processing as an alternative to nitriding as a means of surface hardening firing zone cutout cams for the Mk 10 Guided Missile Launcher System (GMLS). A coincident objective was to reduce the cost of the hardening process, while meeting cam surface requirements. The surface requirements are a case depth of 0.010-0.020 in. and a hardness of R_c 55-67 with minimal distortion.

BACKGROUND

The Naval Surface Weapons Center (NSWC) is currently the design agent for the Mk 10 GMLS firing zone cutout cam (see Figure 1). These items are used aboard ship to confine launcher azimuth and elevation angles in order to prevent firing the missile toward ship structures. Figures 2-5 help illustrate the cam function. Figure 2 is a photograph of the USS BELKNAP (CG 26), which has a Terrier missile launcher (encircled) that uses the Mk 10 firing zone cutout cam. Figure 3, a schematic of a DDG 37 class ship, shows a missile being launched to avoid the ship's superstructure. Figure 4 provides an example of cam contour, while Figure 5 provides a schematic of a typical firing cutout zone. The contour of the cam corresponds to the nonfiring zone profile that is configured to the layout of the ship superstructure. A cam follower (contact pin), when in contact with the cam, tells the launcher not to fire.

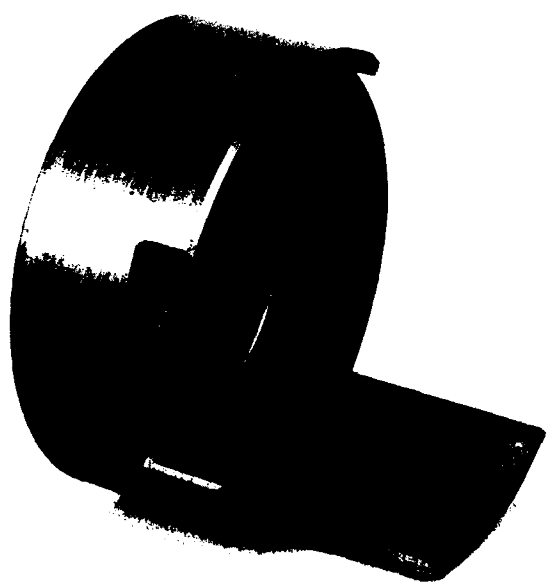

Figure 1. Photograph of Mk 10 Firing Zone Cutout Cam

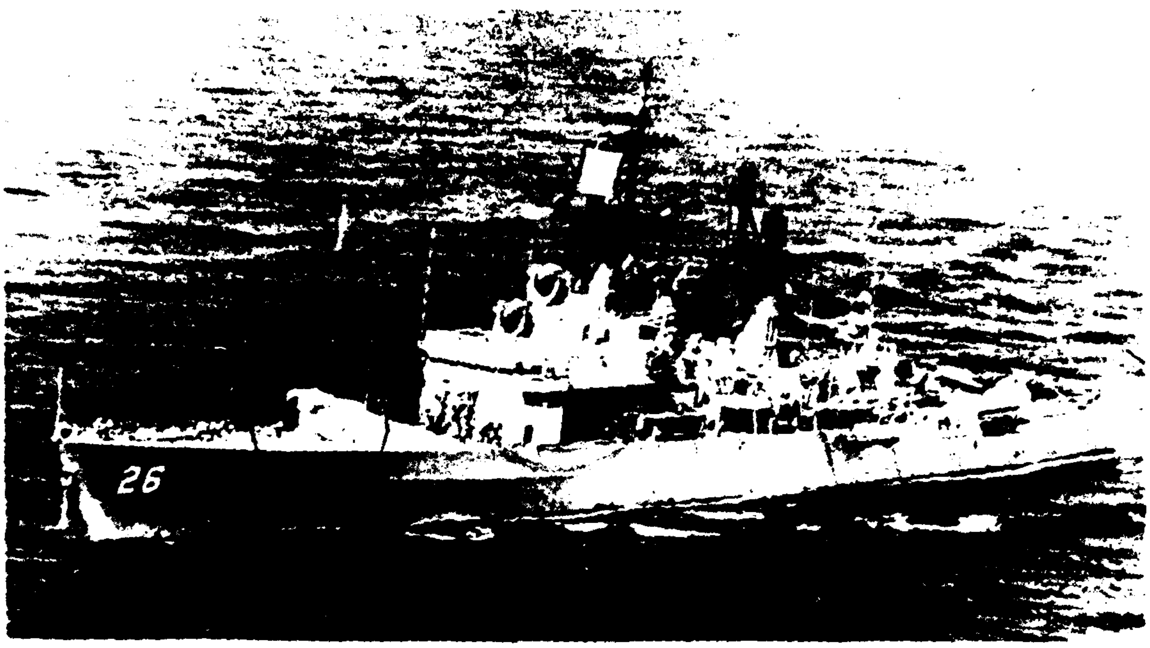

Figure 2. Photograph of USS BELKNAP (CG 26)
Showing Mk 10 Terrier Launcher (Encircled)

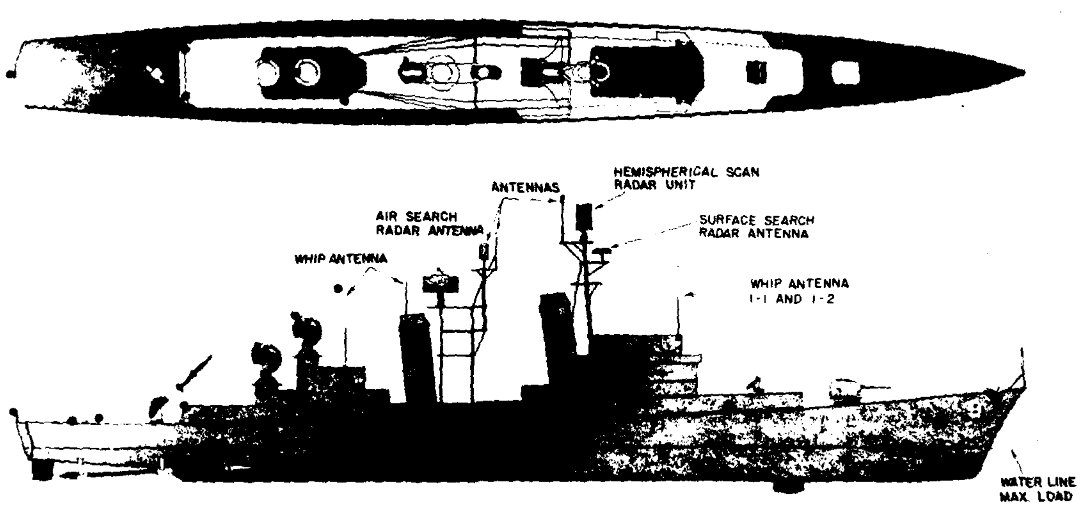

Figure 3. Illustration of Missile Being Fired to Clear
Ship Superstructure (DDG 37 Class)

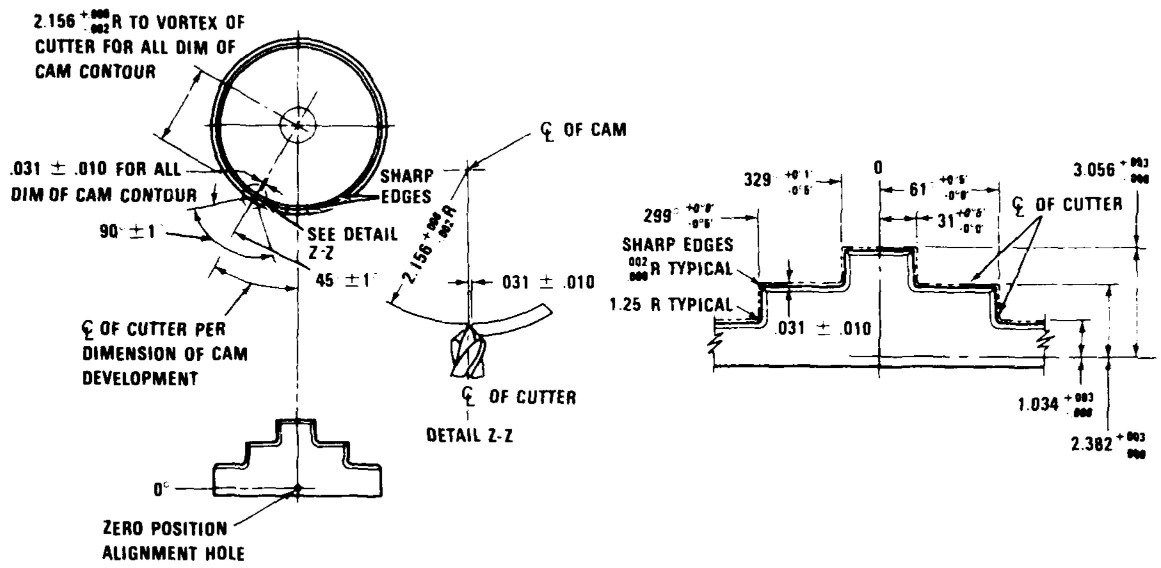

Figure 4. Illustration of Cam Contour

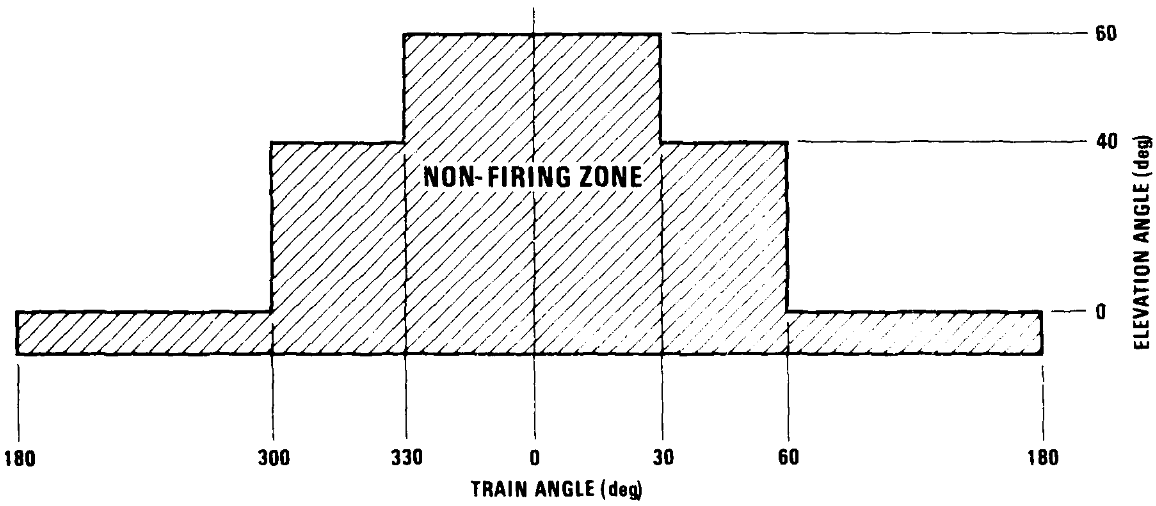

Figure 5. Schematic Illustration of Typical Firing Cutout Zone

The final step in cam manufacture is case hardening. The required quick turnaround (to meet fleet/ship requirements and schedules) is presently being performed by a cyanide salt bath nitriding processing of nitralloy steel cams. This process produces a 55-60 R_c hardness and a case depth of 0.010 in. The requirements are a 55-67 R_c hardness and a case depth of 0.010-0.020 in. One set of two cams has been hardened approximately every 60 days. This method (based on 12 cams/year) costs over $18K per year, which includes the high cost of disposing of toxic cyanide salt waste ($6K/yr) and the total energy consumption of the 60-kW salt bath ($3K/yr) for this energy-intensive operation. These costs are based upon historical data from the 1970s. On a 12 cam/year basis, today's costs would be even higher.

A more cost-effective and less energy-consuming method for surface hardening these parts is laser hardening, which has recently been proven as a practical industrial tool in the manufacture of automobile engine camshafts, gears, and bearing surfaces.[1,2,3] The laser provides very low operating and maintenance costs compared to salt bath nitriding. Specifically, the laser in this application uses approximately 0.29 percent of the electrical energy of the cyanide salt bath. Furthermore, thicker case depths than those being obtained by nitriding are possible by laser hardening.

APPROACH

Originally, it was planned to use the 20-kW laser at the Naval Research Laboratory (NRL) to conduct the surface transformation hardening studies. However, after conducting a preliminary study on nitralloy steel using the NRL laser, it was learned that, because of commitment to other studies, turnaround time and scheduling would be a significant problem. Therefore, it was decided to use a laser from a private contractor. One advantage of this decision will be an early involvement of industry in the manufacturing process. It was also decided, after discussion with Laser Applications Inc., Baltimore, Maryland, that a smaller laser would be sufficient to do the job and that they could satisfy the Navy's cost and turnaround time requirements.

Studies were then initiated using Laser Application's 1.25-kW laser to perform the surface transformation hardening of cams. These studies were directed at determining the effects of laser power (beam intensity), dwell time, cam rotation speed, beam width, and beam oscillation on cam surface hardness and case depth. Hardness measurements were made and samples metallographically examined to assure that the cam cross sections are metallurgically sound and wear resistant. Wear tests, corrosion tests, and tolerance studies were conducted to obtain backup data to assure cam performance, reliability, and laser process repeatability.

It is anticipated that the laser transformation hardening production method will be implemented following completion of this manufacturing technology program. Laser equipment at Laser Applications, Inc., may be used. It is anticipated that 12 cams per year will be manufactured for approximately eight more years.

MATERIALS

Four steels were considered suitable for laser transformation hardening to the desired hardness: nitralloy 135 modified, 4340, 1045, and 11L41 steels. The chemical compositions of these steels are shown in Table 1. The nitralloy 135 modified steel was examined early in the program because of its immediate availability as the current nitriding steel on stock. This material was found to be unsuitable because of surface eruptions and roughness upon laser impingement. AISI 4340 steel was selected because of hardenability, contractor experience, and surface smoothness after laser transformation hardening. The 1045 steel was selected as a low-cost alternative to 4340, and 11L41 was considered as a relatively low-cost material with good machinability.

Table 1. Typical Chemical Compositions (Percent Weight) of Cam Steels

Element	Nitralloy 135 Mod	AISI 4340	AISI 1045	AISI 11L41
Carbon	0.41	0.40	0.45	0.41
Manganese	0.55	0.70	0.75	1.50
Silicon	0.30	0.30	0.22	
Chromium	1.60	0.80		
Aluminum	1.00			
Molybdenum	0.35	0.25		
Nickel		1.85		
Phosphorus	0.04 max.	0.04 max.	0.04 max.	0.04 max.
Sulphur	0.05 max.	0.05 max.	0.05 max.	0.08-0.13
Lead				0.25

The two primary steels (4340 and 1045) were laser treated in both the as-received (hot rolled) and the heat-treated (called "preheat treatment" throughout the text) conditions. Preheat treatment is required to obtain proper hardness for the cam hobs. In addition, preheat treatment helps reduce the effect of tempering, which occurs at overlapping laser beam passes, and helps reduce warpage during laser heat treatment.

Important material properties for laser surface hardening are density, specific heat, thermal conductivity, and thermal diffusivity. Approximate property values for the steels tested are as follows:

- Density = 7.87 g/cc
- Specific Heat = 0.11 cal/g·°c

• Thermal Conductivity = 9.7×10^{-2} cal/cm•s•°c

• Thermal Diffusivity* = 0.21 cm^2/sec

These values determine depth of penetration and will not be discussed in detail here but are covered in the literature.[4]

BASICS OF LASER HEAT TREATMENT

LASER is an acronym standing for Light Amplification by Stimulated Emision of Radiation. Important laser properties are listed below.

1. Monochromaticity. Light energy from a laser is produced at a much narrower bandwidth and at a considerably higher intensity than energy produced by other light sources.

2. Coherence. Waveforms are regular and predictable with the same frequency, phase, amplitude, and direction.

3. Divergence. Waveforms are very parallel and, thus, energy remains intense over long distances.

4. Intensity. Output from well-collimated laser light can be focused to a very small spot with high energy concentration.

Regions of laser operations with regard to power density and interaction time is illustrated in Figure 6. The power required for laser hardening (heat treating) is in the region of 10^3 - 10^5 W/cm^2. An interaction time on the order of 10^{-1} - 10^{-2} sec is necessary.

The general concept of laser heat treating by the use of oscillating laser beams is illustrated in Figure 7. In this procedure, the laser beam is oscillated back and forth as the material is rotated or translated to provide a wider area of heat treatment. The material is heated very quickly above the transformation temperature (of a hardenable steel or alloy) and self-quenches rapidly to produce a largely martensitic (hard) microstructure.

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* Thermal diffusivity is thermal conductivity x heating rate. The value shown is for a composition close to that of 4340 steel.

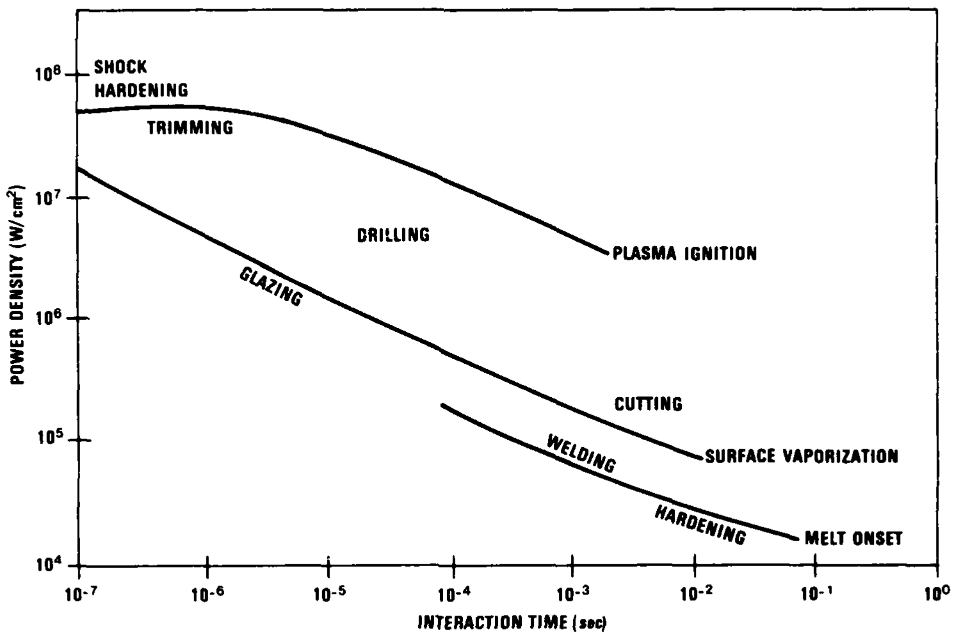

Figure 6. Regions of Laser Power Density and Interaction Time*

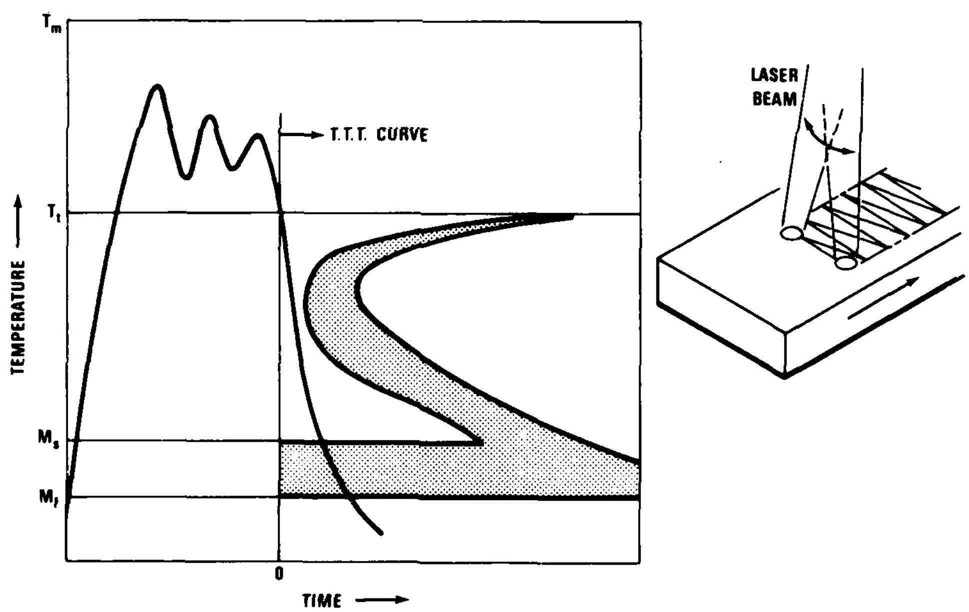

Figure 7. General Concept of Laser Heat Treating by the Use of Oscillating Laser Beam*

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Laser heat-treating patterns are shown in Figure 8 for (a) defocused beam, single pass, (b) defocused beam, overlapping passes, and (c) oscillating beam, single pass. It should be noted that there is a small over-tempered zone of a few thousandths of an inch wide at the periphery of a pass and at the interface between two passes. These overlapping areas will be discussed in more detail with reference to the cams in a later section.

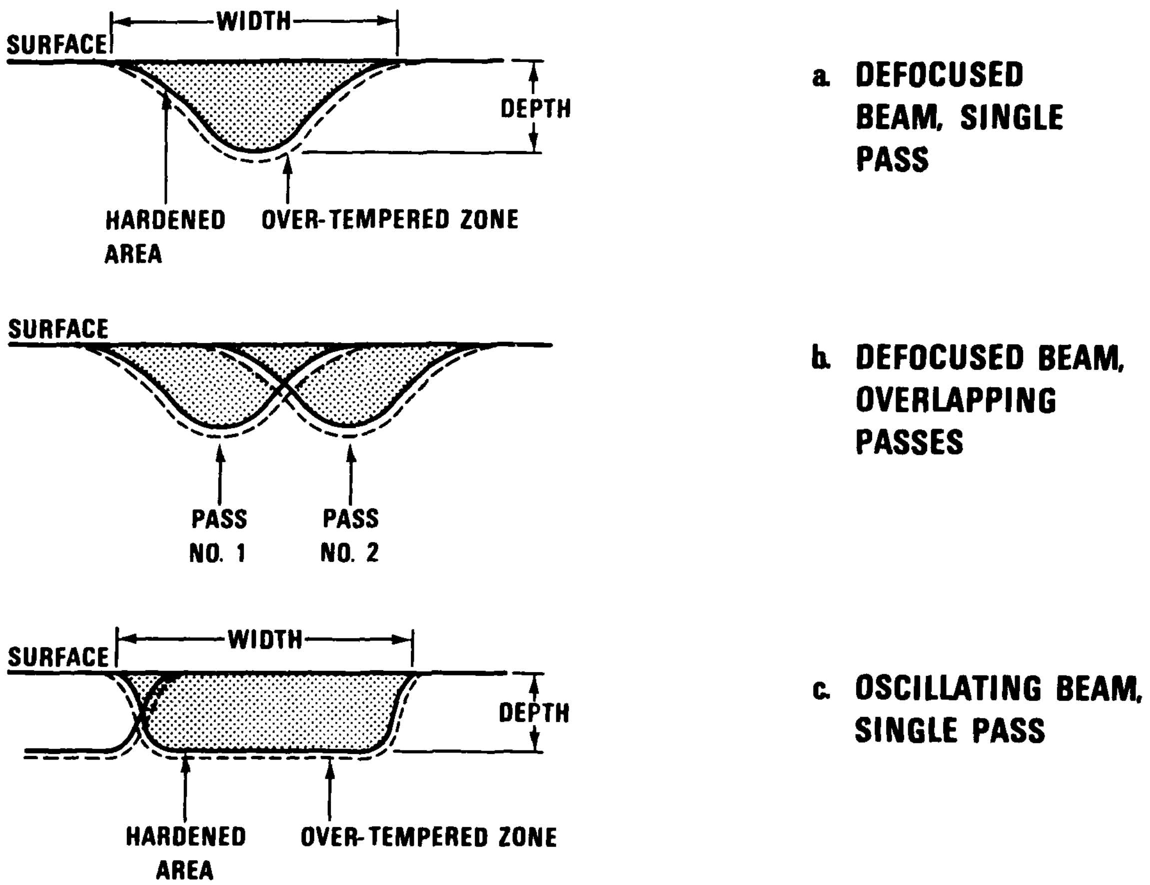

Figure 8. Laser Heat-Treating Patterns*

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EQUIPMENT AND PROCEDURE DEVELOPMENT

Three basic pieces of equipment were used in conjunction with the tooling and fixtures required to manipulate the cam during heat treatment: (1) a 1.25-kW CO_2 laser (10.6-μm wavelength) and (2) a laser beam oscillator (Model 447), both manufactured by Photon Sources, Inc.; and (3) a computerized numerical control (CNC) unit produced by Aerotech, Inc. The laser, of course, is the heat source, the oscillator provides rastering of the beam, while the CNC unit provides programmable automatic rotation and stepping of the cam.

Three different methods were tried in the development of the laser heat treatment of the cam:

1. Defocused beam with manual tilt (45°) for bevels

2. Focused beam with oscillation

3. Focused beam with oscillation; cam stepped with the CNC unit

The first method did not employ the laser beam oscillator and required a 45° manual tilt of the cam in order to harden the beveled surface of the cam. Although the heat treatment/hardening results were acceptable using this method, the manual tilt required time and precision in alignment of the laser beam on the beveled surface. Also, without oscillation, more laser passes were required to heat treat the cam outer surface than with the wider laser passes obtained with the oscillated beam (methods two and three). The width of the oscillated passes was approximately 0.25 in. compared to 0.10 in. for the non-oscillated beam. The use of oscillation in the second method eliminated the tilt and decreased the operation time. Use of an aluminum insert heat sink with thermal coat was required to reduce heat buildup and control distortion in the relatively thin-walled (approx. 0.33 in.) cam. The third and final method employed stepping the cam with the CNC unit to further control heat input distortion especially on the highest lip of the cam. This required programming of the CNC unit. Stepping of the cam is illustrated in Figure 9, a schematic of the cam showing the laser passes--lined off and numbered in order of the stepping sequence.

A comparison of the steps in nitride versus laser treatment for a batch of four cams is provided in Table 2. The time-consuming factors for the nitride process are the startup and shutdown of the salt bath, disposal of cyanide salt wastes, and the actual 24-hour nitride heat treatment itself. The most time-consuming task unique to the laser process is the preparation and checkout of the CNC computer program (2 hours). The total time for the nitride process is two weeks (including startup and shutdown) while that for the laser operation totals 10 hours (including transportation to laser). The laser surface treatment requires about 15 minutes to conduct per cam, which includes 5-7 minutes dwell time for the laser. Therefore, the actual run time for the laser is only 8-10 minutes per cam (32-40 minutes per batch of four cams). The salt bath operates at 60 kW while the laser operates at 1 kW. Therefore, the nitride process uses approximately 345 times the kilowatt-hours compared to the laser.

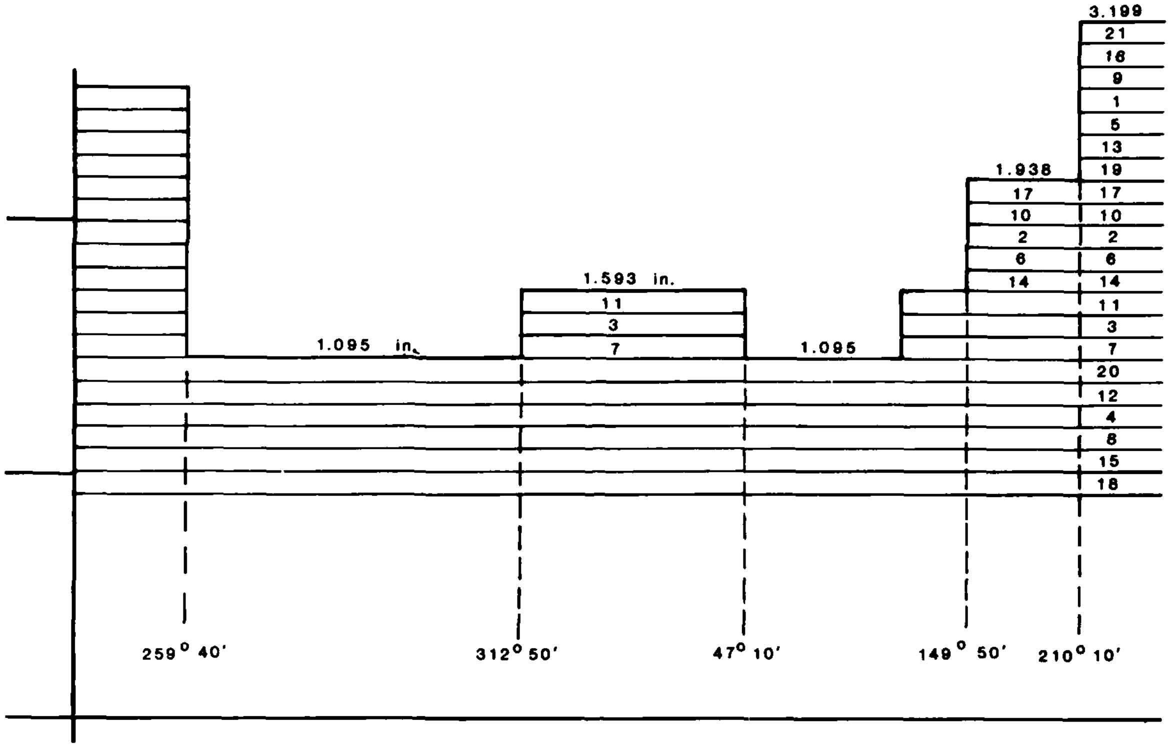


Figure 9. Laser Beam Step Pattern (Sequence)

Table 2. Nitride Versus Laser Treatment (Batch of Four Cams)

Nitride	Laser Treatment
• Clean cams	• Clean cams
• Preheat treat cam	• Preheat treat cam
• Mask off hobs	• Check out parameters (power, mode, etc.)
• Prepare cyanide salt bath	• Prepare and check computer program
• Nitride (24 hr/batch of four cams)	• Insert heat sink into cam
• Clean cams (shot peen)	• Spray graphite coating
• Check case depth	• Set beam oscillator parameters
• Check case hardness	• Laser surface treatment (~15 min./cam)
• Shut down salt bath	• Clean cam (wipe off)
• Cyanide salt waste disposal	• Check hardness
• Gage cams	• Check case depth
	• Gage cams
Total time 2 weeks	Total time 10 hours

It should be noted in Table 2 that a carbon spray coating was applied to the cam surface to provide heat coupling for the laser energy to the steel. Otherwise most of the light (approximately 90 percent) would be reflected and not absorbed.

Laser characteristics and parameters are listed below.

- Power: 1000 W
- Standoff: 8.75 in.
- Spot size: ~ 0.070 in.
- Focal length: 7.5 in.
- Rotation rate: 30 in./min.
- Oscillator rate: 100 Hz, 2 V, sine wave
- Scan length: 0.250 in.
- CNC program: 17-21 steps
- Run time: 15 min. (approx.)

Included in this list are the oscillator parameters. These parameters applied to the cams produce the results described in the next section. These are the final process parameters after process development. These parameters were varied over a considerable range during development.

RESULTS

SUMMARY

A summary of the results is provided below.

- Hardness: Profile = 62 R_C; Overlap = 51 R_C (very narrow band)
- Depth: Profile = 0.015-0.017 in.; Overlap = 0.009-0.010 in.

  (Can get 0.025 to 0.030 in. with more heat but with warpage and melt)
- Tolerance: Within 4 min. train / Within 0.001 in. elevation } Acceptable
- Microstructure: Highly refined martensite
- Wear: ~0.0001 in.

The results show that the requirements of R_C 55-67 and 0.010-0.020 in. depth of penetration with minimal distortion can be met. These values represent the best results obtained to date. A larger data base is required to determine the repeatability of tolerance control. This information will be collected on fleet cams as they are processed by laser heat treatment. The microstructure is basically a highly refined martensitic microstructure yielding a hard yet tough microstructure suitable for good wear resistance. The actual wear resistance compares favorably with that of nitrided cams.

Problems encountered in laser heat treatment of cams are (1) somewhat reduced hardness in the narrow overlap bands between laser passes, (2) potential for heat buildup causing tolerance distortion in outer members (lips), and (3) rounding of bevel edges/corners caused by incipient melt, which provides gaging difficulties. Each of these problems was addressed in this project. Tolerance distortion is the most significant problem and will be discussed in detail.

METALLURGICAL ANALYSIS

Hardness

Hardness results for cams made of 4340 and 1045 steels are compared in Figure 10. Both steels hardened to nearly the same peak hardness (R_C 62) but the 4340 steel hardened more consistently to a greater depth. AISI 4340 steel is a deep-hardening steel and provides a smooth laser-hardened surface.

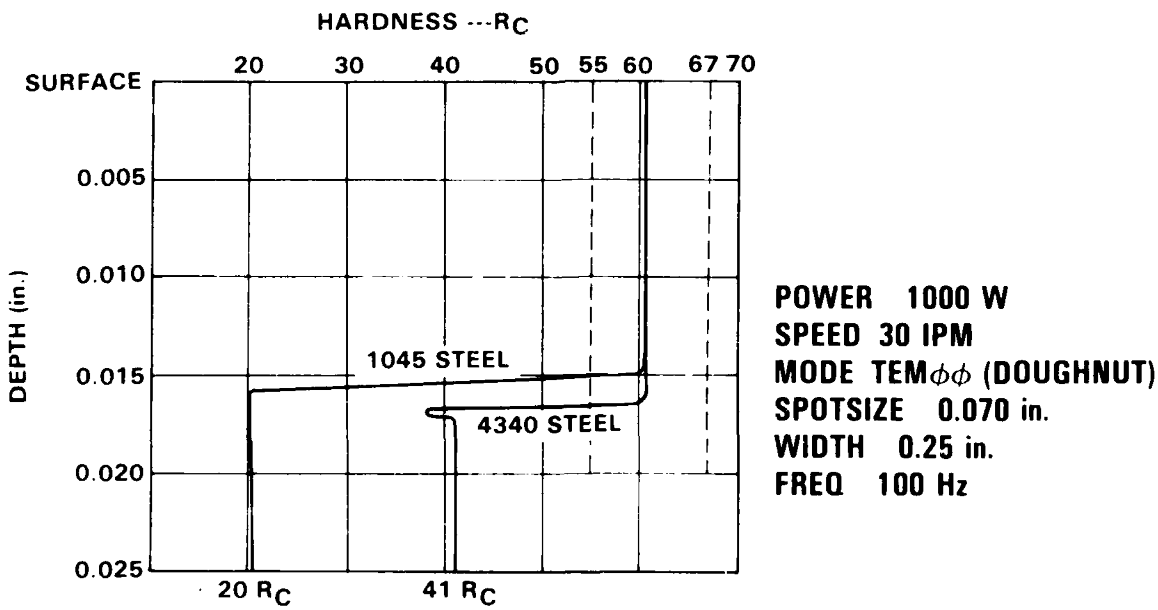


Figure 10. Hardness Profile, 4340 Steel

Initially, one problem encountered in obtaining uniform surface hardness was the overtempered zone or softening that occurs at laser beam interfaces of overlapping passes. These soft zones are very narrow in width (on the order of a few thousandths of an inch wide or a few hundredths of a millimeter). The hardness in these zones varies from 45-54 R_C for the 4340 steel, which was prehardened to 41 R_C. The 1045 steel was not prehardened in this particular case and the overlap hardness dropped off to the base hardness of R_C 20. In another case, the 1045 steel was prehardened to about 35-38 R_C which did improve the soft band hardness somewhat but not to the level of 4340 steel. Another problem with 1045 steel was poor machinability, both in the hot-rolled (as-received) condition and the hardened condition. The 4340 steel was both easier to machine and to laser harden from a penetration and surface-smoothness standpoint. As a result of prehardening and improvements in carbon spray coating, combined with proper laser pass overlapping, the soft bands have been nearly eliminated. They are very difficult to locate with a hardness tester.

Photographs of laser-hardened cams are shown in Figures 11 and 12. The thin lines (indicated by arrows) are the overlap zones between laser passes. Figure 11 shows 0.100-in.-wide (2.54 mm) laser passes without oscillation and Figure 12 shows the wider 0.300-in.-wide (6.4 mm) laser passes with beam oscillation.

Figure 11. Laser-Treated Cam (Defocused Beam, 0.100-in. Passes)

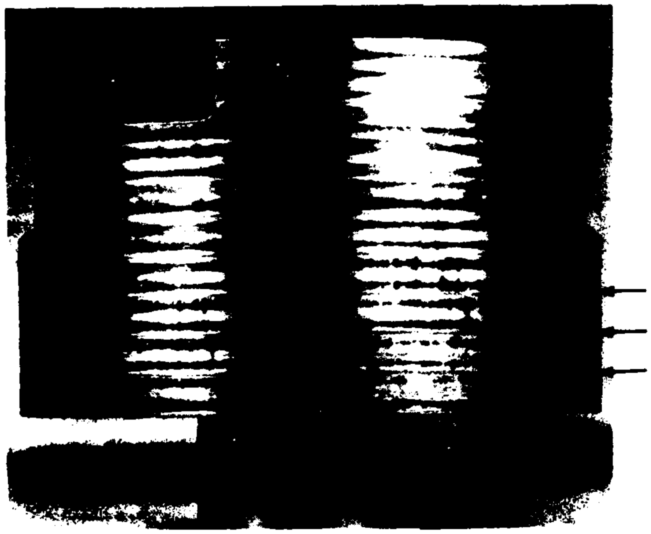


Figure 12. Laser-Treated Cam (Oscillated Beam, 0.300-in. Passes)

Metallography

Macrographs of cam sections showing laser-hardened zones produced with and without laser beam oscillation are shown in Figures 13 and 14, respectively. Note the excellent coverage of the bevel (right side of macrograph) in Figure 13. The oscillated beams provide wider (plateau-like) and, therefore, fewer passes than the bell-shaped nonoscillated beam. Micrographs are provided in Figures 15-18 and show details of the laser-transformed microstructure. The white zones in Figures 15-17 are the laser-transformed microstructures while the dark zones are the parent metal microstructures. Figure 15 shows a 0.017-in. (0.43 mm) laser-hardened zone on a straight circumferential surface of a 4340 steel cam. Figure 16 shows laser penetration on the corner of a cam at the bevel. Laser penetration at cam corners is extremely good because of the cam geometry. It should be mentioned here that the cam bevels, edges, and corners are very important from a hardness standpoint because of cam follower impingement on them. Figure 17 shows overlap between two laser passes providing good laser coverage at the interface. This interface will possess adequate hardness because of the overlap and depth attained by the laser.

A closeup view of the laser-transformed microstructure is shown in Figure 18. This structure is a very fine tempered martensite with some bainite. This microstructure is very hard and should be durable because of its toughness.

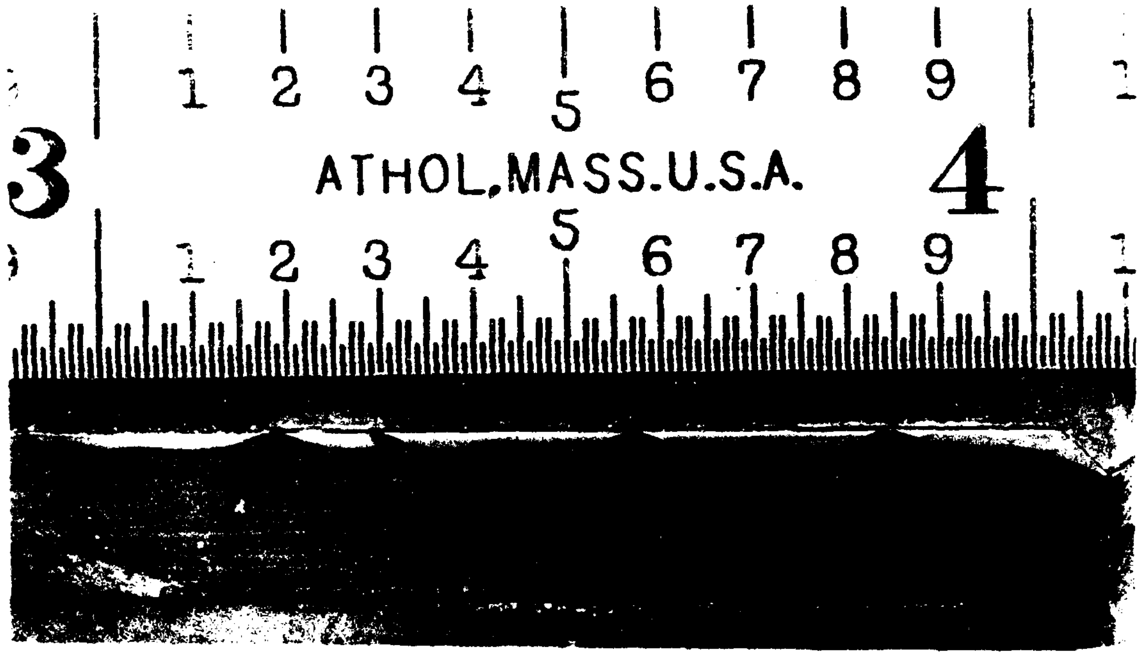


Figure 13. Laser-Treated Cam Cross Section (Multiple Oscillated Passes, 4340 Steel)

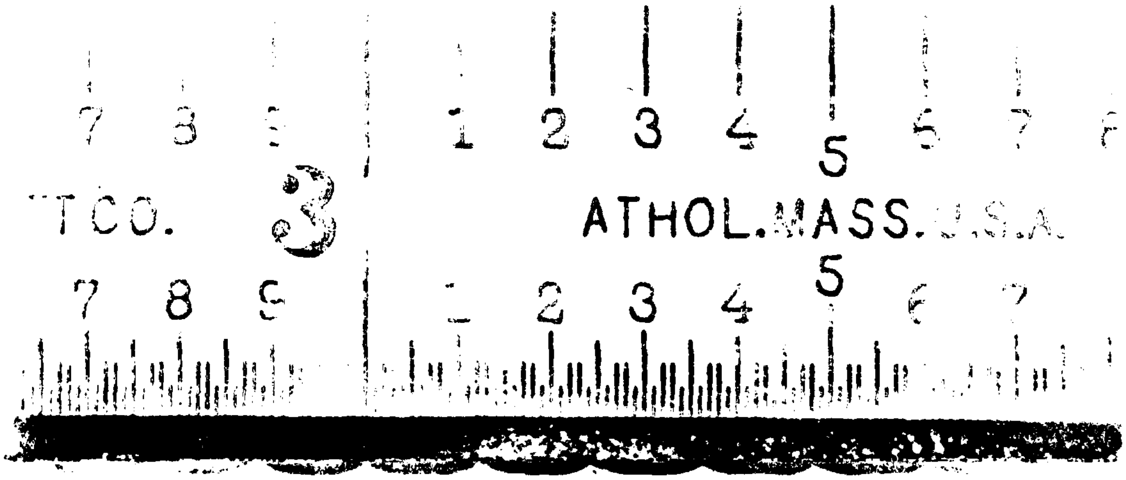
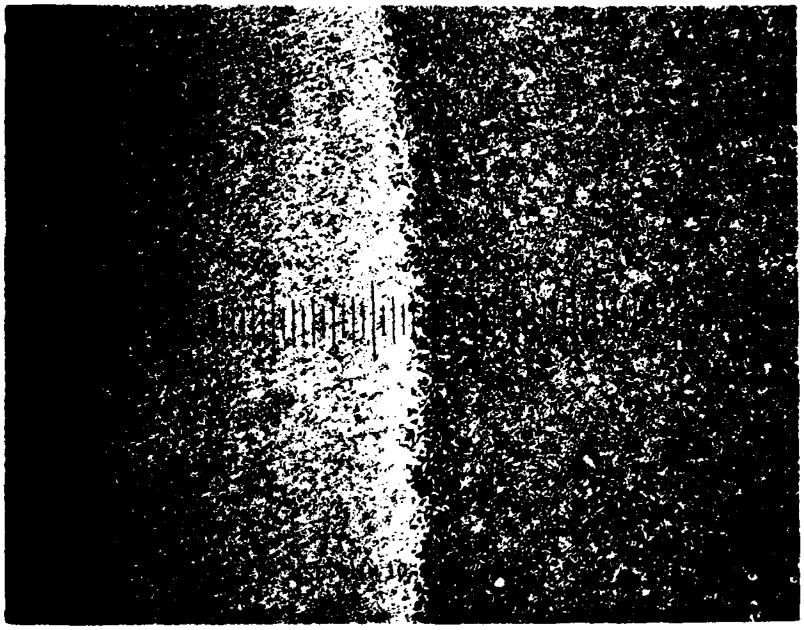
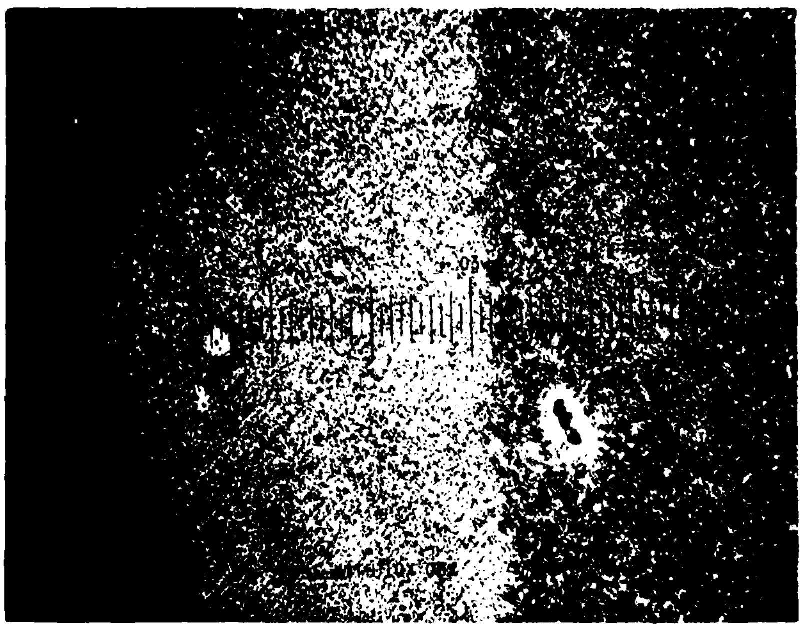


Figure 14. Laser-Treated Cam Cross Section (Multiple Passes, Defocused Beam, No Oscillation, 4340 Steel)



100X

Figure 15. Laser-Transformation-Hardened Cam (Approximately 0.017-in. Penetration, 4340 Steel)

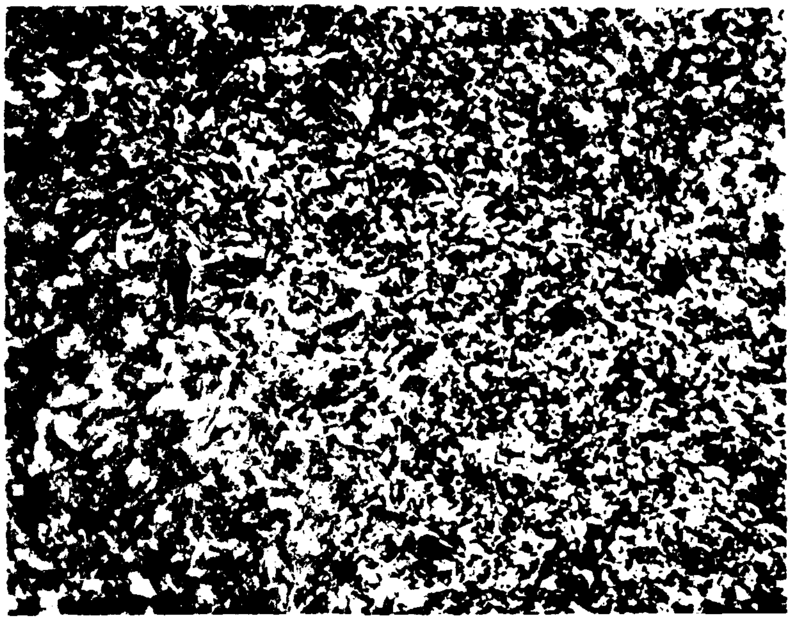


100X

Figure 16. Laser-Treated Cam Bevel (Approximately 0.020-in. Penetration)

50X

Figure 17. Overlap of Two Laser Passes Using Beam Oscillator



800X

Figure 18. Laser-Transformed 4340 Steel Cam
(Microstructure is Fine Martensite)

TOLERANCE CONTROL

One of the problems encountered in laser treating the Mk 10 cams was tolerance distortion caused by heat buildup. This occurred primarily on the high lip of the cam. Also, corners and edges, especially at the bevels and the alignment hole, were rounded because of the high heat intensity, causing difficulties in gaging the necessary dimensions. The distortion occurred as heat gradually built up in the relatively thin cam body as the number of laser passes increased. Heat buildup can more readily cause a problem in the highest lip of the cam where there is only a small amount of mass to dissipate heat. Rounding of corners and bevel edges, caused by incipient melting, occurred because of the effect of laser heat intensity being increased by the edge geometry.

The heat buildup problem in the cam body and high lip was resolved by providing the appropriate dwell time between passes and stepping the laser to distribute the heat from one location to another. Except for the first few passes, which were made without dwells, the dwell time was 30 sec. It was especially important to keep from concentrating heat in the high lip. The second problem, incipient melt, was handled by wiping off the thermal spray coating of carbon precisely on the edges and corners. This reduced the heat intensity on these areas to the appropriate level.

A total of eleven 4340 steel cams were laser processed during the project and were used for tolerance evaluation. Tolerance data are provided in Table 3 and 4. (For an example of measurement locations, see Figure 5.) Cam tolerance requirements are 5 min on the train angles and $^{+0.003}_{-0.000}$ in. on the elevation heights. An additional ±2 min for train angle and ±0.001-in. elevation is allowed for operator error in measurement. Observation of Tables 3 and 4 shows that three cams were within or close to the dimensional/tolerance requirements.

Some tolerance distortion and warpage occurred because of the problems already mentioned. It should be mentioned here that rough machining of the cams also is a contributing factor in gaging and tolerance variation. This factor was especially notable for one cam (#10) in which the alignment hole was roughly machined. Additional information on cam tolerances will be collected as cams are produced for the fleet. If any distortion because of heat buildup continues to be a problem, water cooling will be used to reduce overall heat during laser processing. Otherwise, the laser power (wattage) and heat intensity can be reduced somewhat while still achieving surface hardness and penetration depth requirements.

Table 3. Cam Tolerance Chart

Cam Number	Angle (°)	Difference: Train Angle (')		Difference: Elevation (in.)	Requirements: Train Angle (5' ±2)	Requirements: Elevation (±0.001 oper.)	Accept/Reject (A/R): Train	Accept/Reject (A/R): Elev.
1*	209††	+0.13	(+8)	+0.013	+5	+0.003 -0.000	R	R
(Prehardened**	257	-0.05	(-3)	+0.005	+5		R	R
4340	323	-0.35	(-20)	+0.001	-5		R	A
A-Arm†)	36	+0.07	(+4)	0	+5		A	A
	150††	-0.27	(-16)	+0.001	-5		R	A
2	209	+12		-0.001	+	-0.000 +0.003	R	A
(Prehardened	322	-8		-0.001	-		R	A
4340	37	+10		+0.005	+		R	R
B-Arm)	102	-3		+0.001	-		A	A
	150	-9		-0.001	-		R	A
3	209	+3		+0.002	+		A	A
	322	+9		+0.002	-		R	A
(Prehardened	37	+6		0	+		A	A
4340	101	+8		+0.001	-		R	A
B-Arm)	150	+5		0	-		R	A
4	209	+2		+0.003	+		A	A
	257	+3		+0.004	+		A	A
(Prehardened	322	+2		+0.001	-		A	A
4340	37	-2		+0.002	+		A	A
A-Arm)	150	0		0	-		A	A
5	209	+6		+0.006	+		A	R
	257	+11		+0.007	+		R	R
(Prehardened	322	+5		+0.004	-		R	A
4340	37	-2		+0.001	+		A	A
A-Arm)	150	-4		+0.002	-		A	A
6	209	-3		-0.001	+		R	A
	322	+4		0	-		R	A
(Prehardened	37	+1		0	+		A	A
4340	102	+1		0	-		A	A
B-Arm)	150	+3		0	-		R	A

* There were no cams numbered 8 and 9.

** As a result of preliminary laser processing studies, it was determined that the cams must be prehardened by conventional heat treatment in order to prevent/reduce soft zones at the laser pass overlap interfaces.

† A-Arm and B-Arm designate two different cam configurations. There is a pair of cams (an A- and B-Arm) on each ship with two launchers.

†† The 209° and 150° angles include the high lip, which poses the most difficult tolerance control.

Table 3. Cam Tolerance Chart (Continued)

Cam Number	Angle (°)	Difference: Train Angle (')	Difference: Elevation (in.)	Requirements: Train Angle (5' ±2)	Requirements: Elevation (±0.001 oper.)	Accept/Reject (A/R): Train	Accept/Reject (A/R): Elev.
7	209	-8	-0.006	+	-0.000 +0.003	R	R
	322	-2	-0.007	-		A	R
(Unhardened	37	-2	-0.007	+		A	R
1045	102	-4	-0.006	-		A	R
B-Arm)	150	-3	-0.008	-		A	R
10	209	-11	-0.003	+	+0.003 -0.000	R	R
	322	+4	+0.001	-		R	A
(Prehardened	37	+3	+0.001	+		A	A
4340	102	-3	-0.002	-		A	R
B-Arm)	150	-10	-0.004	-		R	R
11	209	-3	0	+		R	A
	322	+3	0	-		R	A
(Prehardened	37	+1	0	+		A	A
4340	102	+1	0	-		A	A
B-Arm)	150	0	0	-		A	A
12	209	-5	+0.006	+		R	R
	259	0	+0.008	+		A	R
(Prehardened	312	+2	+0.004	-		A	A
4340	47	-9	0	+		R	A
A-Arm)	150	-9	+0.004	-		R	A
13	210	-11	+0.002	+		R	A
	259	-3	-0.002	+		R	R
(Prehardened	313	-2	-0.005	-		A	R
1045	47	-9	-0.003	+		R	R
A-Arm)	150	-8	-0.007	-		R	R

* There were no cams numbered 8 and 9.

** As a result of preliminary laser processing studies, it was determined that the cams must be prehardened by conventional heat treatment in order to prevent/reduce soft zones at the laser pass overlap interfaces.

† A-Arm and B-Arm designate two different cam configurations. There is a pair of cams (an A- and B-Arm) on each ship with two launchers.

†† The 209° and 150° angles include the high lip, which poses the most difficult tolerance control.

Table 4. Cam Tolerance Summary

Cam Number*	Tolerance Evaluation: Ratingt†	Tolerance Evaluation: Train (')/Elev. (in.) (Total Error)**	Comments
1†	Poor	30/0.012	
2†	Fair	19/0.005	Correct angular direction
3†	Fair	18/0	Gaging shift (angles)
4	Acceptable	0/0.001	
5	Poor	14/0.008	
6	Acceptable	10/0.001	
7 (1045 Steel)	(See Comment)	8/0.019	Pos. Gaging shift (angles and elev.)
10 Demo	(See Comment)	20/0.009	Alignment hole not properly machined.
11	Acceptable	7/0	
12	(See Comment)	20/0.010	Pos. Gaging shift (angles and elev.)
13 (1045 Steel)	(See Comment)	26/0.017 Acceptable 10/0.005 Error	Gaging shift (angles and elev.)

* There were no cams numbered 8 and 9.

** Total error is the sum of the error outside the stringent tolerance control range. The sum is for five train angles and five elevations. The 10' total acceptable error for train angle is the sum of a 2' measurement for each of five angles (2' x 5 = 10'). The 0.005-in. total acceptable error for elevation is the sum of a 0.001 measurement error for five elevations (0.001 in. x 5 = 0.005 in.).

† No attempt was made to control tolerances for the first three cams. These cams were used to develop the laser processing technique and laser parameters. Therefore, by eliminating the first three cams from the data, three out of eight cams were acceptable from a tolerance standpoint. Gaging difficulties or machining quality may have prevented cams numbered 7, 10, 12, and 13 from being acceptable. A larger data base for statistics is needed.

†† The ratings are defined as follows: poor - neither train nor elevation requirements were met; fair - either train or elevation requirements were met; and acceptable - both train and elevation requirements were met.

WEAR TEST

A wear test was conducted to determine how well the laser surface held up in contact with the cam follower (shown in Figure 19) in comparison with the nitrided surface.[5] Photographs of the wear test setup are shown in Figures 20 and 21. Figure 20 shows the cam follower in contact with the laser-processed cam, while Figure 21 shows the follower free from the cam surface. The test was set up such that the nitrided cam and laser-treated cam were coupled together on a single shaft and were, therefore, rotated together in contact with two cam followers. (The second follower is not visible in the photographs.) The compressive spring force from each follower was calibrated to 4.7 lb prior to placement in contact with the cams. The cams were rotated at approximately 7 rpm for approximately 80 hr providing about 33,600 total revolutions. These test conditions simulated actual operating conditions for the Mk 10 cam and were equivalent to several years of service. (This test was conducted per Reference 5). Cams have an average life of three years and some see as long as six to seven years of service. No cam has worn out to date. Cams are generally replaced when a new configuration is required.

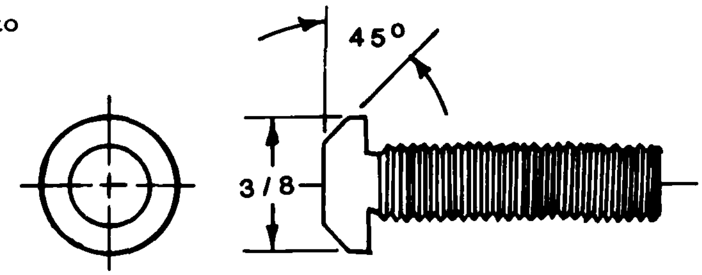


Figure 19. Cam Follower Used on the Mk 10 Type Firing Cutout Cam

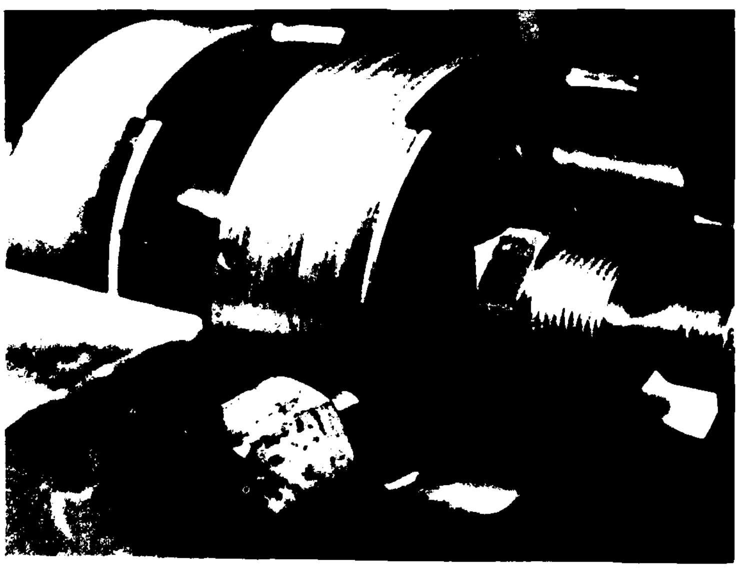


Figure 20. Photograph of Wear Test Setup Showing Laser-Treated Cam (Right) and Nitrided Cam (Left)

Figure 21. Photograph of Wear Test Setup Showing
Follower for the Laser-Treated Cam

The most severe wear on the cam occurs at the initial edge of contact between the follower and the cam. This test was designed to represent the repeated movement of the follower over an edge each time the launcher is loaded (really an overtest). The wear at the edge of the cam was of primary importance in this test. This is so because wear at an edge causes tolerance change and therefore a change in cutout zone. The cams were lubricated at the start of the test as they are when first installed in the launcher. The maximum wear for the nitrided cam edges was 0.000070 in. and that for the laser-treated cam was 0.000100 in. These amounts are insignificant over the lifetime of the cams. The fact that the laser-treated cam edge wore more than the nitrided cam edge is attributed to a more roughly machined surface for the laser-treated cam. It should be noted that the cam follower was placed over a laser overlap "soft" zone (which was previously discussed). No wear at this zone could be observed.

CORROSION TEST

A 48-hour accelerated corrosion salt-spray test was conducted on both nitrided and laser-treated cams and cam sections. Photographs of these sections after salt-spray testing are provided in Figures 22 and 23. Figure 23 simply shows the reverse side of Figure 22. The general result of the accelerated corrosion test was that there was no apparent difference in the corrosion resistance of the five sections shown in Figures 22 and 23. The five sections shown in these figures are nitrided nitralloy steel, parcoluberized-laser-treated 1045 and 4340 steels, and bare-laser-treated 1045 and 4340 steels.

Figure 22. Cam Sections After 48-Hour Salt-Spray Test

Figure 23. Cam Sections After 48-Hour Salt-Spray Test
(Reverse of Figure 22)

One problem interpreting these results lies in the fact that much of the corrosion was caused by salt-spray runoff or spillage from an area where salt water collected. The corrosion appears worse than it normally would and interferes with proper interpretation. It was expected that the nitrided corrosion resistance would be better than untreated steel (non-nitrided). However, it is obvious that the nitrided cam corrodes.

It should be pointed out that no cams have been replaced due to corrosion or wear. The cams are initially lubricated upon installation in the launcher and are sheltered from seawater spray. In other words, the corrosion environment is not severe. (The corrosion test described herein was an overtest.) At any rate, laser-treated cams should be adequate in such an environment.

ADVANTAGES OF LASER PROCESSING

The advantages of laser processing over nitriding of cams are listed below:

1. Shorter times for process/turnaround
2. Lower cost on a quick turnaround basis
3. Better case depth and hardness than salt nitride
4. Deeper penetration on critical bevels and edges
5. No handling of cyanide salt required
6. Less dimensional growth than gas nitride
7. Significantly less energy consumed compared with present bath nitride

Cost Analysis

A comparison of costs for three processes is shown below: (based on a batch of four cams, or a total of 12 cams/yr)

- Salt Nitride*:
  (Present Method)

$$\frac{\$6K/yr\ (salt\ disposal) + \$3K/yr\ (electricity) + \$9K/yr\ (labor)}{12\ cams/yr} = \$1500/cam$$

- Gas Nitride*: $1756/bath of four cams = $439/cam

---

* The estimate for both nitriding processes are based upon having a dedicated run/heat for a quick response.

• Laser Treatment:

$$\frac{\$680(\text{laser})/\text{day} \times 1/2\ \text{day (laser)} + (3.5\ \text{hr} \times \$50/\text{hr})\ \text{computer and engineering}}{4\ \text{cams}} = \$129/\text{cam}$$

The salt nitride process employs the currently used molten cyanide salt bath at NSWC for a 24-hour period (not including preparation). This process is energy intensive and requires disposal of the toxic salts.

The gas nitride process employs cracked ammonia for a 72-hour period. The cost using a nondedicated furnace at Drever Heat Treaters, Baltimore, Maryland, is currently only about $50 per cam. However, because of scheduling and time required, this may not always be practical for a quick response required by the fleet. In addition, some dimensional growth can be expected using the gas nitride process (approximately 0.002-in. growth has been experienced in the past). This can be allowed for by proper machining and the gas nitride process is an entirely acceptable backup process.

The CO_2 laser process can be accomplished in 1-1/2 hr per cam, which includes 15 min or less of actual laser time. The laser (1.25 kW) uses tremendously less energy than either of the nitriding processes. The 1.25-kW laser at Laser Applications, Baltimore, Maryland, is available on a quick-response basis and can process a batch of four cams (the usual requirement) in approximately 6 hr. The cost savings using the laser on a quick-response basis is $1,370 per cam in comparison with the salt nitride and $310 per cam in comparison with the gas nitride process. A large intangible benefit of the laser hardening process is the elimination of cyanide salt handling and disposal.

A summary of the economic analysis required for the MANTECH program is provided in Table 5. This table shows a projected $16.4K savings per year in the outyears and a savings (after payback of the initial investment) of about $80K through FY 1988. (The above cost information in no way binds potential contractors to future prices.)

Table 5. Economic Analysis

	FY 79	FY 80	FY 81	FY 82	FY 83	FY 84	FY 85	FY 86	FY 87	FY 88
A. Scheduled Procurements										
1. Present Method (Nitriding)	12	12	12	12	12	12	12	12	12	12
2. Proposed Method (Laser Hardening)	--	--	12	12	12	12	12	12	12	12
B. Unit Cost-Present Method $1500 per cam			$18K	$18K	$18K	$18K	$18K	$18K	$18K	$18K
C. Unit Cost-Proposed Method $129 per cam			$ 1.6K	$ 1.6K	$ 1.6K	$ 1.6K	$ 1.6K	$ 1.6K	$ 1.6K	$ 1.6K
D. Gross Savings $1,370 per cam			$16.4K	$16.4K	$16.4K	$16.4K	$16.4K	$16.4K	$16.4K	$16.4K
E. Investment-Proposed Method										
1. Manufacturing Technology		$50.5K								
2. Other	0									
3. Carried Forward	0									
4. Total		$50.5K								
5. Payback						$15.1K	$16.4K	$16.4K	$16.4K	$16.4K

NOTE: Funding received late FY 79.

Applicability of Laser Processing to Other Navy Programs

The potential of the laser as applied to processing of naval weapons and components is immense as well as the potential dollar savings using the laser. This is so because of the versatility of the laser (surface hardening, cutting, welding, glazing, alloying, cladding, drilling, softening) and the speed of laser processing. Listed below are several programs and weapons systems and components to which the laser can be applied and which would be a direct outgrowth of this program.

1. Laser processing of Vertical Launch System (VLS) components:

    - Welding of steel plenum and uptake structures, canisters, etc.
    - Heat treatment of cams, bearings, shafts, etc.
    - Cutting and drilling of sheet metal

2. Laser surface treatment of depleted uranium and tungsten penetrators:

    - Glazing to improve penetrator surface resistance to corrosion
    - Hardening to improve penetrator performance

3. Laser transformation hardening of cams, bearings, shafts, etc. for gun mounts (Mk 75-76mm)

4. Laser transformation hardening, alloying, cladding of gun barrels and liners

5. Laser processing of metal matrix composites

6. Laser cutting of Kevlar armor panels and components

7. Laser welding of high-pressure argon/coolant bottles for the 5" Guided Projectile

8. Laser scoring of warheads and projectiles for controlled fragmentation

9. Laser transformation hardening, alloying, and cladding of Terrier and other missile launcher rails

CONCLUSIONS

1. Laser surface hardening of Mk 10 cams is both a feasible and economical alternative to cyanide salt bath nitriding. The requirements of 0.010-0.020 in. case depth and hardness of 55-67 R_C have been easily met or exceeded using the laser.

2. Cam tolerances can be controlled by proper control of laser power and heat input, through rub-off of carbon spray coating on edges, and through water-cooling techniques if needed.

3. Laser processing of cams can be done on a quick-response basis--one day turnaround if needed.

4. Cost savings using the laser process is $16.4K per year (for 12 cams).

RECOMMENDATIONS

1. Generate a producibility data base of laser-hardened cams to implementation of the laser process.

2. Discontinue use of cyanide salt nitride process and place the furnace on surplus.

3. Pursue the vast potential of the laser in processing naval surface weapon systems and components.

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