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**LASER METALWORKING
TECHNOLOGY TRANSFER FINAL REPORT**

Contract N00014-82-C-2373

prepared for
THE NAVAL RESEARCH LABORATORY
Washington, DC 20375

by
Ole A. Sanden

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Avco Everett Research Laboratory, Inc.

a Subsidiary of Avco Corporation

2385 Revere Beach Parkway

Everett, MA 02149

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1. INTRODUCTION

The object of the Technology Transfer Program is to assist in the utilization and integration of the laser facility at FMC/NOD into the manufacturing processes of naval ordnance components and systems.

This assistance consists of targeting workpieces and production steps suitable for laser processing in terms of cost effectiveness and quality enhancement, the development of techniques and procedures for such processing and the establishment of processing parameters and other pertinent data.

The work performed under this program has mainly been^{1,5} related to laser surface transformation hardening of steels. The response of a number of frequently used steels to such laser processing has been determined over a wide range of processing parameters, models, and calculator programs for the prediction of laser hardening have been developed and tested, and the necessary thermo-physical constants of the various materials determined by statistical and empirical means.

In addition to the transformation hardening survey, process development work relating to the laser hardfacing of aircraft carrier catapult rails have been performed, and preliminary techniques and processing data established for different combinations of hardfacing alloys/substrate materials.

All the laser processing performed in this program was carried out at Avco Everett Metalworking Laser facilities in Somerville, MA. An Avco HPL[®]-10 CO₂ laser with constant wave output was used throughout. Analysis of processing results was also done at AEML with the exception of some metallography and microhardness survey performed at FMC/NOD.

2. LASER SURFACE TRANSFORMATION HARDENING

2.1 General Considerations

2.1.1. The Process

Laser surface transformation hardening is a relatively new process, made possible by the development of high powered industrial lasers. As in other surface transformation hardening processes, the object of laser surface hardening is to generate a relatively thin surface layer in which the material has undergone martensitic transformation. The process is, therefore, limited to materials that are capable of undergoing such a transformation; or in other words, to hardenable cast irons and steels.

In order for such materials to harden by martensitic transformation, they must be heated to a temperature at which the austenitic phase is stable, followed by very rapid cooling, or quenching, to room temperature.

In surface hardening only the surface region of the workpiece needs to be heated to austenitizing temperatures. It is desirable that this surface heating takes place as rapidly as possible, in order to minimize the effect of heating on the bulk of the material. This requires a very high heat flux to be applied to the workpiece surface. In essence, heat must be applied to the surface at a higher rate than it can be conducted away from the surface towards the cold interior. This makes the laser an ideal heat source for surface hardening of cast irons and steels. In fact, the laser is capable of heating the surface so rapidly that the required subsequent quenching occurs by heat conduction to the still cold interior of the workpiece.

This process, known as self-quenching, is one of the great advantages of laser surface hardening.

When the laser is used for surface transformation hardening, the required power density (flux) is lower and the exposure time longer than in processes such as welding or cutting.

A convenient way of achieving this is to reshape the laser output beam to a broad area beam with uniform power density rather than to the focused beam used for welding and cutting. A typical broad area laser beam, suitable for surface transformation hardening, may have the shape of a square with dimensions of the order 1 cm x 1 cm in the focal plane, and have a power density of 5×10^2 to 5×10^3 w/cm². Hardening is performed by moving such a spot over the workpiece surface at controlled speed. If the processing parameters (power and speed) are appropriate, a strip of surface hardened material is generated by the moving laser spot, and the depth of this hardened case can be controlled through the control of these parameters.

The laser output beam can also be shaped into other suitable broad area beams by means of various optical devices, depending on the specific applications. However, in this program, a square spot with dimensions 1.27 cm x 1.27 cm (0.5" x 0.5") was used throughout.

The absorption of laser radiation from a CO₂ laser (10.6μm) in metals is very low at room temperature. With the relatively low power densities used in surface hardening, it is, therefore, necessary to use energy absorption coatings on the workpiece surface. Many different substances have been used for this purpose, such as manganese phosphate and paints containing graphite,

silicon and carbon black. Since many of the coatings that have been used are quite effective, the choice of a particular coating is dictated not so much by its relative absorption efficiency, as by other considerations such as ease of application and post-processing removal of coating residue. In the work reported here, flat black Krylon #1602 spray paint was used. This coating appears to be 80-90% effective in overall absorption of the 10.6 μm laser radiation. It is easy to apply and is not very sensitive to variation in coating thickness, as long as care is taken to ensure complete coverage. The residue left by this coating after laser processing is also easy to remove.

2.1.2 Metallurgy

In conventional hardening of steel, the workpiece is brought up to austenitizing temperatures at a relatively slow rate, and then allowed to soak at this temperature before quenching. This allows sufficient time for homogenous austenite to form throughout the workpiece, which upon quenching will be transformed to martensite.

In laser surface transformation hardening, the situation is somewhat different because the heating time is very short and no isothermal soak takes place in this process. The very rapid heating and the short time that the workpiece material is kept at elevated temperatures result in several metallurgical effects which must be taken into consideration in analyzing the process.

First of all, rapid heating leads to an increase in the observed transformation temperature¹⁾, which can result in a thinner hardened case than otherwise would

be expected. This effect will, of course, become more pronounced as the laser processing speed increases and the exposure time decreases.

Secondly, if the structure of the workpiece is such that the carbon is unevenly distributed in the micro-structure, the short time the material is at temperatures above the transformation temperature is not sufficient to allow the carbon to redistribute itself uniformly in the austenitic phase. The resulting austenite will, therefore, be of variable carbon content and the structure obtained after self-quenching will not be uniform²⁾. This is not a problem with reasonably fine-grained, medium and high carbon steels, but if the material contains appreciable amounts of free ferrite, such as low carbon steel or some nodular cast irons, laser surface hardening may not be possible in practice. This is particularly so if the material is relatively coarse-grained. Such materials can, however, be laser hardened if they are given a pre-processing quench and temper heat treatment. If the tempering temperature is not too high such a material will have its carbon in a finely dispersed form, and can be laser surface hardened.

Because the laser hardening process takes place under conditions of unsteady heat flow, it is necessary to heat the workpiece surface to temperatures considerably above the normal austenitizing range, in order to obtain useful heat penetration and case depth. The surface will, therefore, experience much higher temperatures than in conventional hardening practices. Care must be taken to prevent the surface temperature from reaching the melting point, particularly in cases where a very deep case is to be generated.

In some cases, localized grain growth may occur if the surface temperature approaches the melting point. Because the maximum temperatures will often occur in the neighborhood of corners and fillets, such grain growth may be very detrimental.

There is also some indication that areas that have been brought to a very high temperature may show excessive amounts of retained austenite after quenching.

The depth of hardened case that can be obtained in laser surface transformation hardening also depends on the hardenability of the material and on the size of the workpiece. A large workpiece, made from a material with good hardenability, can be processed at low speed because a high rate of self-quenching is not required. Hence, there is sufficient time available for deep heat penetration and a deep case can be generated. In SAE 4340 steel, for example, case depths in excess of 0.1" are easy to obtain.

In materials with low hardenability, such as low carbon steel, the laser processing speed must be higher in order to obtain high self-quenching rates. This is particularly true if the workpiece is small and thus is a limited heatsink. A steep temperature gradient must be generated in the workpiece, but because the maximum surface temperature is limited by the melting point of the material, only limited hardened case can be obtained in such materials.

2.1.3 Heat Flow in Laser Surface Transformation Hardening

In order to predict the results of laser surface transformation hardening with a broad area beam, it is necessary to evaluate the time dependent tempera-

ture distribution in the workpiece in the vicinity of of the moving laser spot. Because the boundary conditions are favorable, it is possible to obtain closed solutions to the generalized heat flow equation

$$\alpha \nabla^2 T = \frac{\partial T}{\partial t} \quad 1)$$

that are useful for such prediction. If we consider the semi-infinite body, Equation 1) reduces to

$$\frac{\partial Q}{\partial t} = \alpha \frac{\partial^2 Q}{\partial z^2} \quad 2)$$

where α is the thermal diffusivity; z , the depth below the surface; $Q = -K \partial T / \partial z$ is the flux and K is the thermal conductivity. If the flux at the surface is constant, the boundary conditions are:

The solution to Equation 2) is then³⁾

$$\nabla T = \frac{2Q_1 \epsilon \sqrt{\alpha t}}{K} \operatorname{ierfc} \frac{z}{2\sqrt{\alpha t}} \quad 3)$$

where ΔT at the temperature rise; Q_1 is the applied flux, ierfc stands for the integrated error function compliment and ϵ is the emmissivity of the material, specific to temperature and wavelength of the laser radiation.

This solution is only valid for a semi-infinite body with uniform flux at the surface; i.e., when there is no lateral heat flow so that the heat flow is uni-directional.

This condition is, however, approximately true for the centerline of a broad area laser spot with uniform power distribution, provided the spot is large compared to the characteristic heat diffusion distance

$$d = (\alpha t)^{1/2} \quad 4)$$

where t_D is the dwelltime (exposure time). For a square spot with dimensions $b \times b$, this time is:

$$t_D = b/v \quad 5)$$

where v is the velocity of the laser spot. Hence, if

$$\frac{b}{2} \gg (\alpha t_D)^{1/2} \quad 6)$$

Equation 3) will correctly give the temperature at the centerline of the laser spot. In practice, it is found that if $b \gg 16d/v$, good agreement with experimental data can be obtained. We can then rewrite Equation 3) in the form

$$T_T = T_0 + \frac{2Q_0 E}{K} \sqrt{\alpha t_D} \operatorname{ierfc} \frac{5H}{2\sqrt{\alpha t_D}} \quad 7)$$

where T_T is the transformation temperature, T_0 is the room temperature, and δH is the depth of case.

This equation can also be used to estimate the cooling rate resulting from the self-quenching effect behind the moving laser spot. By the superposition principle, the temperature on the centerline behind the laser spot is approximately:

$$T = T_0 + \frac{2QL\epsilon}{K} \left[\sqrt{\alpha t} \operatorname{erfc} \frac{z}{2\sqrt{\alpha t}} - \sqrt{\alpha(t-t_D)} \operatorname{erfc} \frac{z}{2\sqrt{\alpha(t-t_D)}} \right] \quad (8)$$

where t is the total elapsed time from the start of heating and $(t-t_D)$ is the cooling time. Because of the requirements for minimal lateral heat flow discussed above, this equation can only be used for high speed processing and small values of the cooling time $(t-t_D)$.

If the processing speed is so low that Equation 7) cannot be used; that is, if the heat flow is three-dimensional in the vicinity of the centerline of the laser spot, a more involved analysis is required. An expression, valid for the semi-infinite body with three-dimensional flow around a rectangular spot, is given by Carslaw and Jaeger ⁴⁾. A modification, derived on slightly different principles and valid for a plate with finite thickness was developed in conjunction with this program. The temperature distribution around the moving laser spot under these conditions, was found to be ⁵⁾

$$T = T_0 + \frac{QL\epsilon\alpha}{2KN\sqrt{\pi}} \int_0^{\infty} \sum_{m=-\infty}^{\infty} \exp - \left[\frac{(2mD-z)\alpha}{1-Q} \right]^2 \cdot \left[\operatorname{erf} \frac{(Y+L)\alpha}{1-Q} - \operatorname{erf} \frac{(Y-L)\alpha}{1-Q} \right] \cdot \left[\operatorname{erf} \frac{2(X+B)\alpha^2(1-Q)^2}{2\alpha(1-Q)} - \operatorname{erf} \frac{2(X-B)\alpha^2(1-Q)^2}{2\alpha(1-Q)} \right] \frac{d\alpha}{\alpha^2} \quad (9)$$

where erf stands for the error function and:

$$x = \frac{\sqrt{K}}{2\alpha} \quad B = \frac{vb}{4\alpha}$$

$$y = \frac{\sqrt{K}}{2\alpha} \quad L = \frac{vl}{4\alpha}$$

$$z = \frac{\sqrt{K}}{2\alpha} \quad D = \frac{vd}{2\alpha}$$

b = length of laser spot.

l = width of laser spot.

d = thickness of plate.

In using these models for the prediction of hardened case, it is necessary to know the intensity of the actually absorbed flux, the average value of the thermo-physical constants K and α (thermal conductivity and thermal diffusivity) in the temperature range experienced by the workpiece during processing, and the temperature at which the material will transform to austenite.

The fraction of the applied power that is absorbed into the workpiece (the emissivity ξ), depends among other things on the condition of the workpiece surface. For clean metal surfaces, the emissivity at the wavelength of the CO₂-laser (10.6 μm) is very low. However, by using various absorbing coatings, the emissivity can be increased to the 0.8-0.9 range, even at the relatively low power densities used in surface hardening. In this work, flat black Krylon #1602 spray paint was used as an energy absorber. This increased the absorption to an estimated value of 85%.

The values of the thermal conductivity, K , and the thermal diffusivity, α , for hardenable ferrous materials, changes fairly rapidly with the temperature. Hence, the room temperature values of these variables cannot be used for case depth prediction.

However, in cases where the variation of K and α with the temperature are known, the integral average value can be calculated as:

$$\bar{K} = \frac{1}{T_2 - T_1} \int_{T_1}^{T_2} V(T) dT \quad 10)$$

$$\bar{\alpha} = \frac{1}{T_2 - T_1} \int_{T_1}^{T_2} \alpha(T) dT \quad 11)$$

by means of numerical integration.

In this work, case prediction was performed partially by the aid of Equation 9) and 10), partially by experimental determination of K and α from preliminary runs, as described in Section 2.2.5.

The final datum needed for case prediction is the transformation temperature. This is, of course, not a fixed temperature unless the steel has eutectoid composition. Furthermore, the temperature range over which the transformation occurs is sensitive to the processing speed. In this work, we have used the A_f temperatures from the pertinent IT diagrams as the transition temperature T_T .

2.2 Experimental Work

2.2.1 Equipment and Procedures

The experimental surface transformation hardening was performed with an Avco HPL[®]-10 CO₂ laser. This laser was capable of up to 15 kW output (CW).

The collimated output beam from the laser was directed through ducts to the workstation. In the workstation, the beam - approximately 2.6" in diameter - was shaped to a convergent, square beam by means of an optical integrator, as shown in Figure 1. The square beam had dimensions 1/2" x 1/2" in the focal plane.

Surface transformation hardening was performed on plane specimens by moving the specimens under the beam at controlled speed. The specimens were mounted on a milling machine table in such a way that the focal plane of the optical integrator was located on the specimen surface. The translation speed of the table could be varied steplessly, and speed calibration curves were established prior to start of processing. The correct location of the specimen relative to the beam could be determined by means of a low powered He-Ne laser locator beam built into the laser system to give a visual representation of the location of the actual power beam prior to processing.

The laser power could also be varied steplessly, from approximately 1 kW up to full power. The actual power delivered to the workpiece was determined by calibration curves, established in advance by means of calorimetric measurements. In addition, the beam quality (sharp edges and even power density) was assessed by making test burns in lucite blocks. Speed and power calibration, as well as beam quality, was checked periodically during processing of the samples. Figure 2 shows schema-

BEAM INTEGRATOR

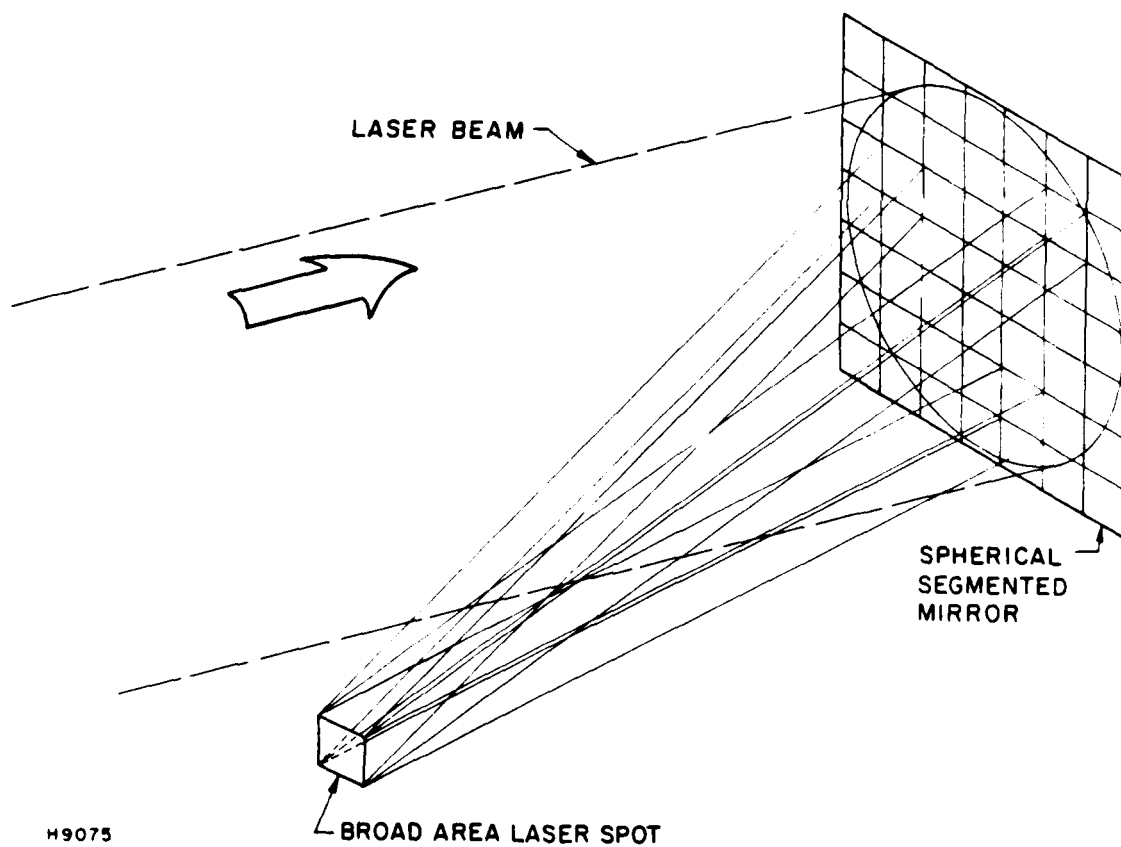
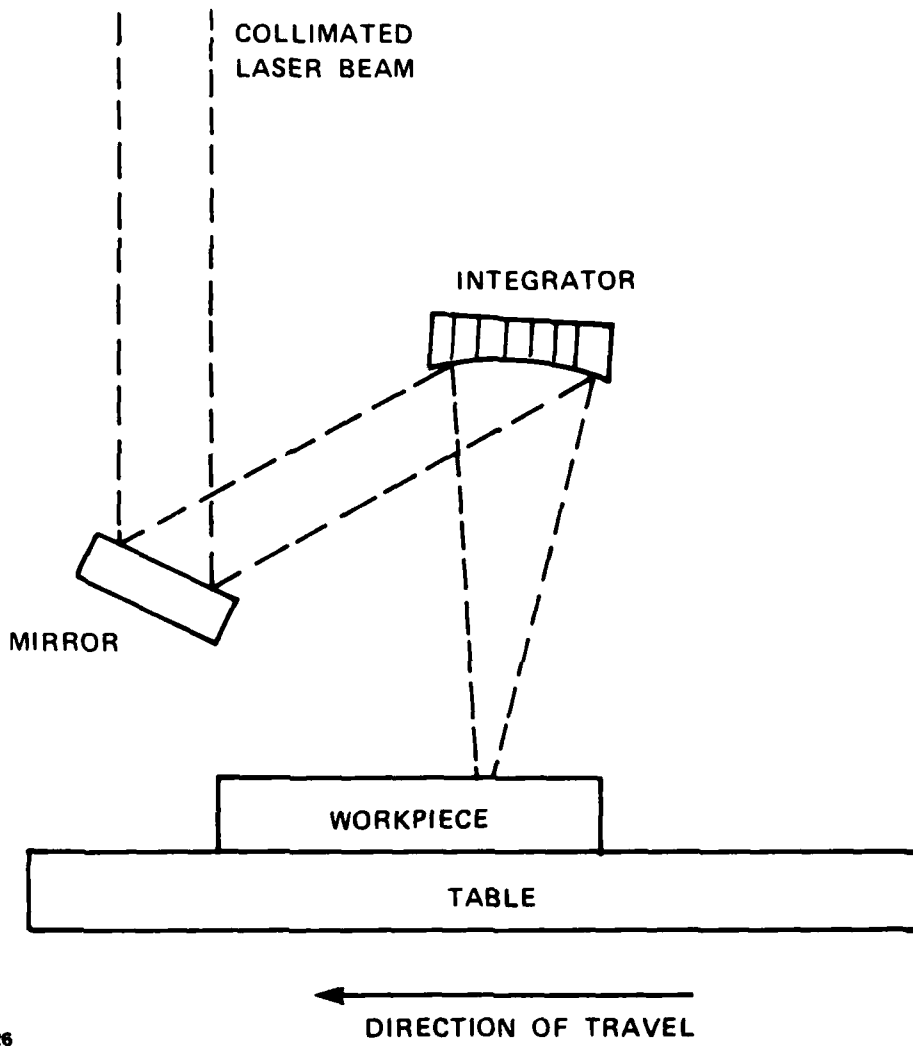


FIGURE 1 FORMING A BROAD AREA LASER SPOT BY MEANS OF AN OPTICAL INTEGRATOR



M2526

FIGURE 2 SETUP FOR LASER TRANSFORMATION HARDENING OF FLAT PLATES

tically the experimental setup used for this program.

Prior to processing, the workpiece surfaces were prepared by coating with flat black Krylon #1602 spray paint. This was done in order to enhance the absorption of the laser radiation (10.6 μm) into the workpiece surface. Previous experience has shown that this treatment results in approximately 85% absorption of the CO₂ laser radiation, even at relatively low power densities. Furthermore, this type of coating is easy to put on, leaves little residue for post-processing cleanup, and is not very sensitive to small variation in application technique. No protective atmosphere was used during processing, but a fan blowing crosswise over the beam/workpiece interaction zone was used to dissipate the smoke resulting from pyrolysis of the coating.

The results of the laser processing were evaluated by metallography and micro-hardness testing, using a Knoop Indenter with 500g load.

2.2.2. Case Prediction by One-Dimensional Heat Flow Model

Prior to the experimental laser processing, the processing parameters were estimated, using a calculator code built on one-dimensional heat flow considerations, as discussed in Section 2.1.2.

The program was written for use on a Texas Instrument TI 59 programmable calculator/printer. This program predicted maximum surface temperature and depth of case based on processing parameters (speed and power density), thermophysical constants and transition temperature of the material.

Originally, this program did not contain any cut-off for processing parameters that fell outside the range where the one-dimensional heat flow model was valid. The

predicted case depth did not, therefore, show reasonable agreement with experimentally obtained data for low processing speed. The program was, subsequently, rewritten to reject input data of this kind. The program could also be used to predict cooling rates during self-quench, based on Equation 8), Section 2.1.3.

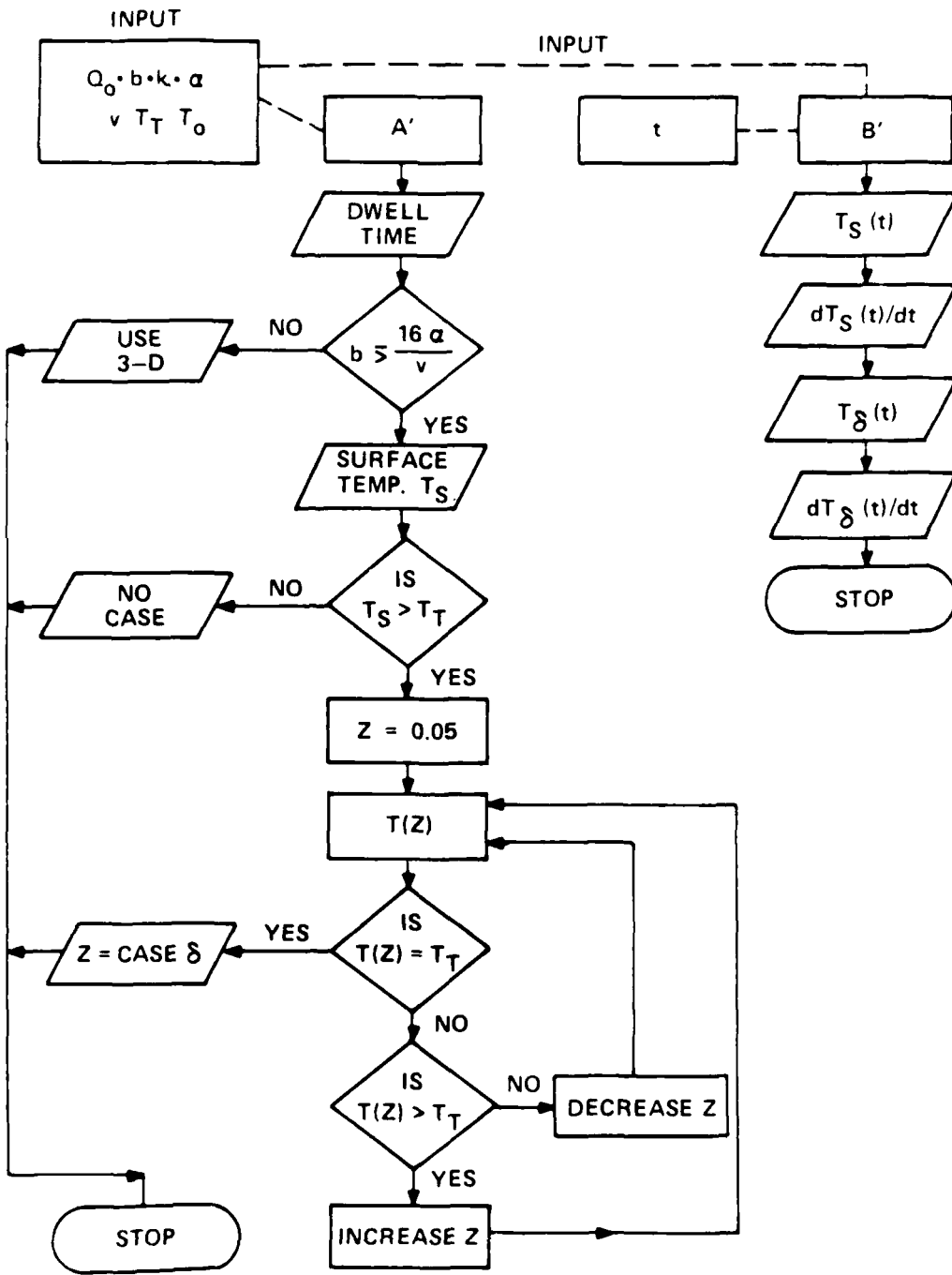
The flow sheet of the program is shown in Figure 3, and the complete program with user information is listed in Appendix I.

The thermophysical constants used in the preliminary phase were calculated from published data ⁶⁾, as described in Section 2.1.3. The constants for the materials surveyed in the preliminary phase are given in Table I.

2.2.3. Preliminary Evaluation of Laser Hardening Parameters

In this preliminary evaluation phase, the response of six different materials to laser surface hardening was surveyed. The materials were SAE 1045 in the quenched and tempered condition (Q/T), SAE 1045 in the hot-rolled condition (H.R.), SAE 4140 in the Q/T and H.R. condition, SAE 1020 in the H.R. condition and SAE 4340 in the cold-rolled condition (C.R.). Samples of these materials were supplied by FMC/NOD in the form of plates with minimum dimensions 1/2" thick by 2" wide by 8" long.

These specimens were laser processed as described earlier, making single, well separated straight laser runs on the surfaces of the specimens. The processing parameters (power and speed) were varied within limits, calculated to give case depths in the range 10 to 120 mil (0.025 to 0.305 cm). The predicted case was calculated in advance in each case, using the calculator program described in Section 2.2.2.



L4240

FIGURE 3 PROGRAM FOR PREDICTION OF CASE DEPTH AND COOLING RATE

TABLE I

THERMOPHYSICAL CONSTANTS (Estimated) FOR VARIOUS STEELS

Material	Thermal Cond. K (w/cm-C°)	Thermal Diff. α (cm ² /sec)	Transition Temp. T _T C°
SAE 1020	0.38	0.087	850
SAE 1045	0.36	0.085	790
SAE 4140	0.33	0.072	780
SAE 4340	0.30	0.063	750

The processed specimens were analyzed at FMC/NOD for case depth and surface hardness. The results are given in a preliminary report⁷⁾ from FMC/NOD, and are summarized in Tables II, III, IV and V. Due to the limits set by the total available laser power, large areas cannot be laser hardened without some form of multiple-pass technique. It is, however, of interest to look at the best way of achieving this. Several straight abutting and overlapping laser runs were made on samples of SAE 4140 (Q/T), and the discontinuity of hardened case in the zones between the runs assessed by surface hardness measurements. The results are shown in Figures 4, 5 and 6.

2.2.4 Discussion of Preliminary Results

The results of the preliminary processing, as given in Tables II through V, show good agreement between predicted and measured case for medium processing speed. The correlation is, however, poor for very high speed (60 in/min, 2.54 cm/sec) and for very low speed (5-10 in/min, 0.21-0.42 cm/sec). For the high speed runs the case depth is much higher than predicted; while for low speed, the reverse is the case. The latter observation can be attributed to the fact that the one-dimensional heat flow model used is not valid at these low speeds. Hence, the actual temperatures reached by the workpiece surface are much less than those predicted, due to lateral heat flow in the workpiece.

The underestimation of case depth for the high speed runs is unexpected and difficult to explain. If anything, a shallower depth than predicted would not be surprising in this case because the heating rate is so rapid that the kinetics of the process could be expected to influence the results. Lacking any rational explanation for this phenomenon, it is, therefore, assumed that some

$\alpha = 0.072 \text{ cm}^2/\text{sec}$
 $T_T = 780^\circ \text{ C}$

SAE 4140

1.15% OF THEORETICAL
 STANDARD DEVIATION
 59.68

CONDITION	POWER (kW)	SPEED (in/min)	CALCULATED CASE (mil)	MEASURED CASE (mil)	% OF THEORETICAL	CALCULATED SURFACE TEMP. (C°)	SURFACE HARDNESS (Rc)
Q/T	2.5	30	49	47	96	1203	57
Q/T	2.5	40	29	37	128	1045	56.5
Q/T	2.5	60	8	18	225	856	57.5
Q/T	2.0	15	88	77	88	1369	55.5
Q/T	1.7	15	66	63	95	1174	56.5
Q/T	1.5	15	48	45	94	1045	55.5
Q/T	1.4	10	95	56	59	1275	56.5
H.R.	2.5	30	49	48	98	1203	43.5
H.R.	2.5	40	29	40	138	1045	45.0
H.R.	2.5	60	8	22	275	856	27.0
H.R.	2.0	15	88	71	81	1369	37.0
H.R.	1.7	15	66	54	82	1174	31.5
H.R.	1.5	15	48	45	94	1045	31.5
H.R.	1.4	10	95	53	57	1275	37.5

$\alpha = 0.085 \text{ cm}^2/\text{sec}$
 $T_T = 790^\circ \text{ C}$

SAE 1045

1448 OF THEORETICAL
 STANDARD DEVIATION
 90.18

CONDITION	POWER (kw)	SPEED (in/min)	CALCULATED CASE (mil)	MEASURED CASE (mil)	% OF THEORETICAL	CALCULATED SURFACE TEMP. (C°)	SURFACE HARNESS (Rc)
Q/T	2.5	30	51	50	98	1198	55
Q/T	2.5	40	30	38	127	1040	57
Q/T	2.5	60	7	24	342	853	55.5
Q/T	2.5	28	57	67	118	1239	55.5
Q/T	2.3	60	NIL	16	-	769	55.5
Q/T	2.1	40	13	20	154	882	55.5
Q/T	3.0	40	51	51	100	1278	54
H.R.	2.5	30	51	46	90	1198	47.5
H.R.	2.5	40	30	34	113	1040	50
H.R.	2.5	60	7	24	342	853	44
H.R.	3.0	40	51	51	100	1278	50

83% OF THEORETICAL
STANDARD DEVIATION
8.3%

SAE 1020

$$\alpha = 0.087 \text{ cm}^2/\text{sec}$$

$$T_I = 850^\circ \text{ C}$$

CONDITION	POWER (kw)	SPEED (in/min)	CALCULATED CASE (mil)	MEASURED CASE (mil)	% OF THEORETICAL	CALCULATED SURFACE TEMP. (C°)	SURFACE HARDNESS (Rc)
C.R.	1.9	30	6	NIL	-	887	31
C.R.	2.1	30	18	17	94	975	40
C.R.	2.3	30	29	25	86	1062	43
C.R.	2.45	30	38	27	71	1150	46
C.R.	2.6	30	47	38	81	1273	46.5

86.7% OF THEORETICAL
STANDARD DEVIATION
24.3%

SAE 4340

$\alpha = 0.063 \text{ cm}^2/\text{sec}$
 $T_T = 750^\circ \text{ C}$

CONDITION	POWER (kw)	SPEED (in/min)	CALCULATED CASE (mil)	MEASURED CASE (mil)	% OF THEORETICAL	CALCULATED SURFACE TEMP. (C°)	SURFACE HARDNESS (RC)
C.R.	2.4	30	49	45	92	1190	49.5
C.R.	2.3	40	27	26	96	992	51
C.R.	2.3	60	7	10	143	814	48.5
C.R.	1.6	10	110	75	68	1393	53
C.R.	1.6	15	63	54	86	1141	53
C.R.	1.4	15	45	40	89	1007	48.5
C.R.	1.9	15	85	73	86	1341	55
C.R.	1.3	10	78	55	71	1148	48
C.R.	1.0	5	116	57	49	1175	52.5

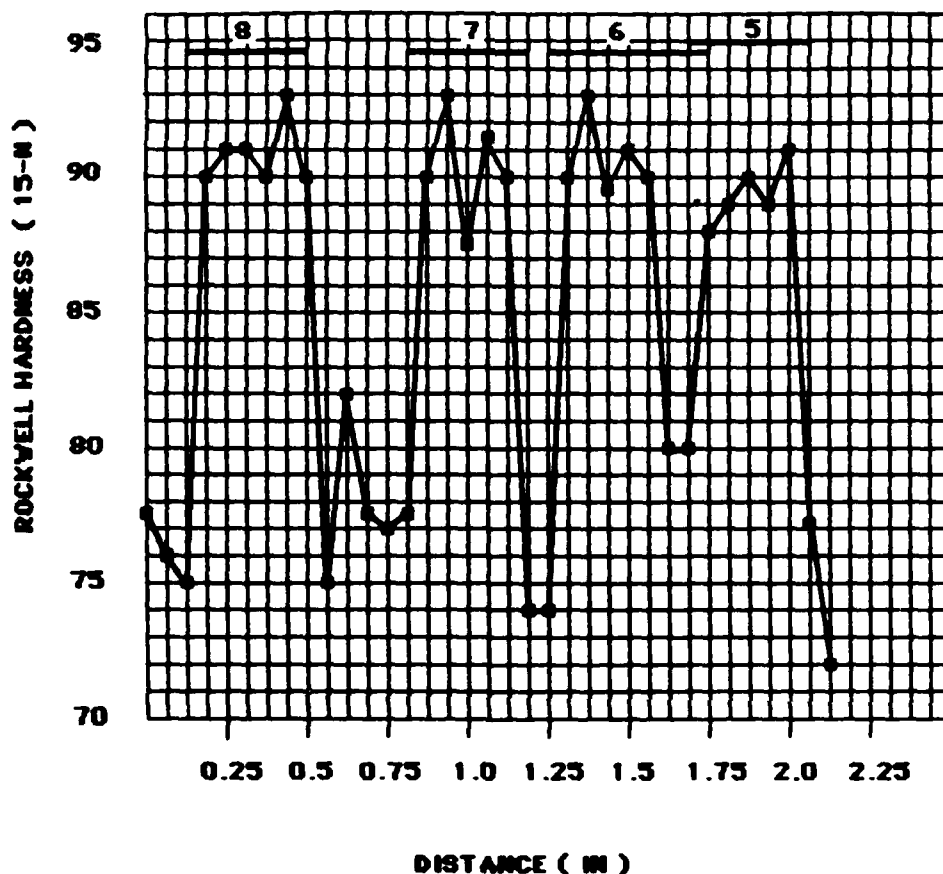


FIGURE 4.

**SURFACE HARDNESS OF OVERLAPPING RUNS ON
SAE 4140 STEEL (H.T.)
POWER DENSITY 1290 W/cm²
PROCESSING SPEED 40 IN/MIN
RUNS 5-8**

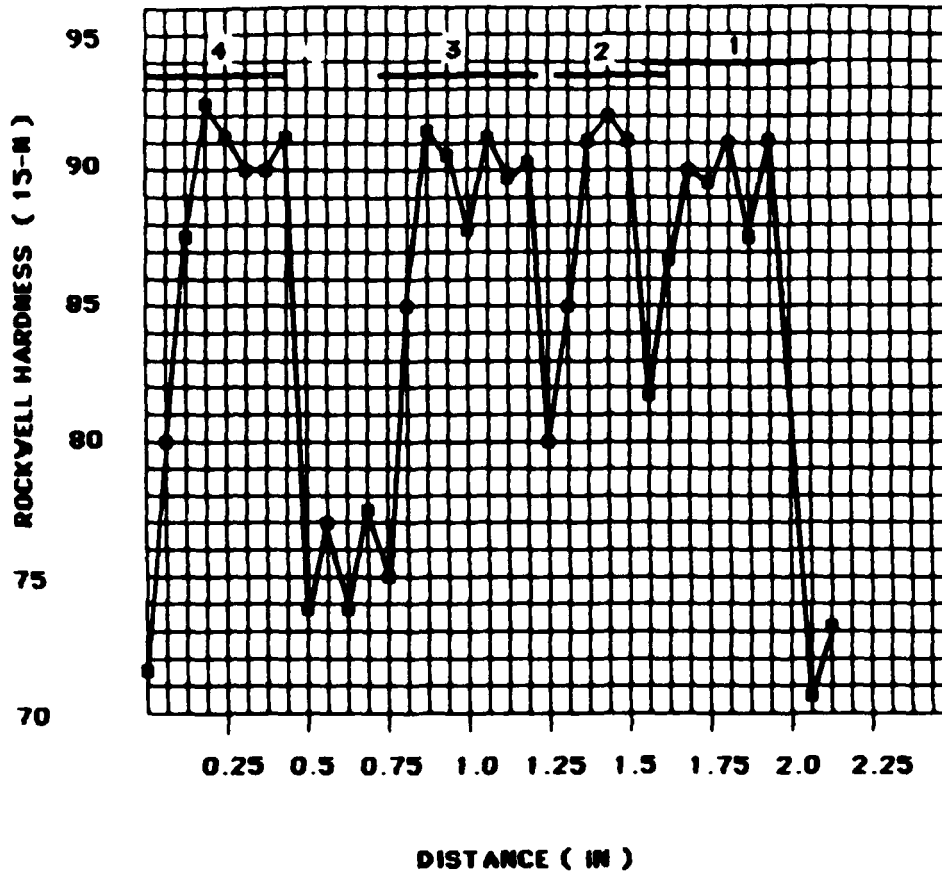


FIGURE 5

**SURFACE HARDNESS OF OVERLAPPING RUNS ON
SAE 4140 STEEL.
POWER DENSITY 1290 ν/cm^2
PROCESSING SPEED 30 IN/MIN.
RUNS 1-4.**

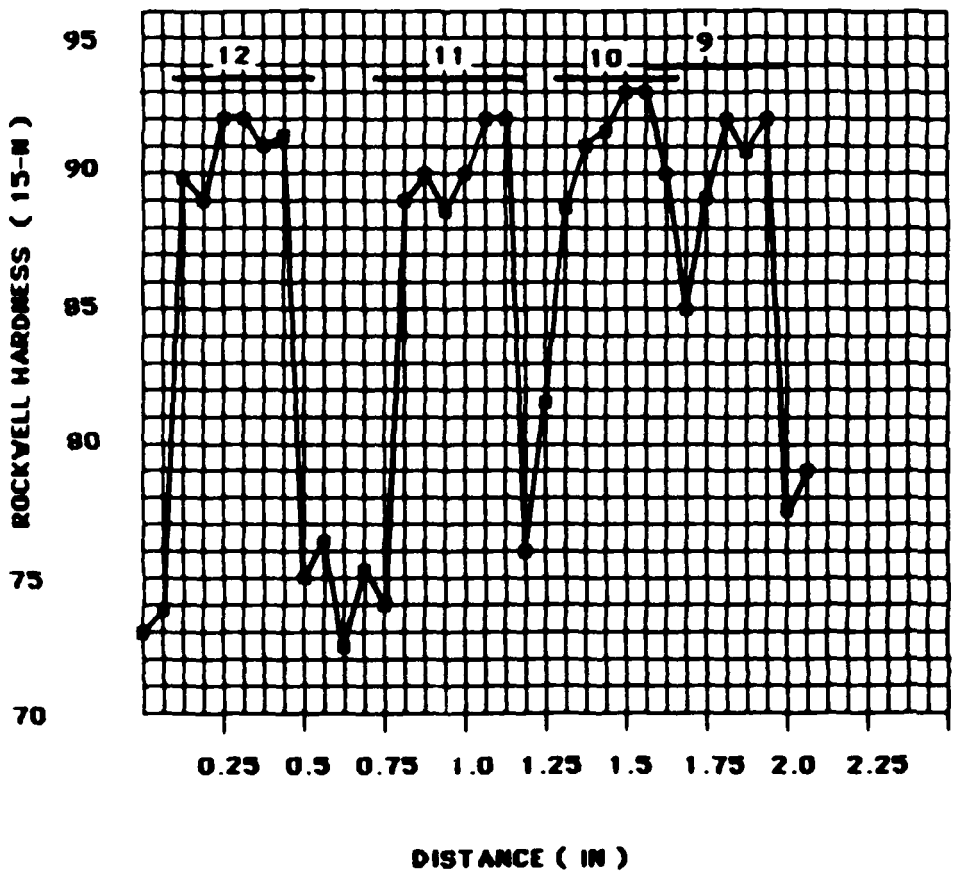


FIGURE 6.
SURFACE HARDNESS OF OVERLAPPING RUNS ON
SAE 4140 STEEL (H.T.)
POWER DENSITY 790 W/cm²
PROCESSING SPEED 15 IN/MIN.
RUNS 9-12

error was made in the power setting, or more possible in the speed calibration curve, in such a way that the actual translation speed was lower than the assumed speed.

For most of the materials, the limit of effective case was taken to be the depth at which the hardness had decreased to Rockwell C 45. In SAE 1020, this criterion could not be used, since the maximal hardness at 100% martensite is about equal to this. Hence, in this case, Rockwell C 35 was used as limit of effective case.

Several of the materials, in particular SAE 4140 (H.R.) and SAE 1045 (H.R.), showed very low surface hardness. This was due to some surface decarburization in these materials. Both materials showed full hardness at greater depth below the surface.

These preliminary studies show the need for the following improvements in the procedures used for the materials response survey:

- elimination of decarburized surface layers in the test specimens,
- improved model for case prediction, including better data for the thermophysical constants,
- closer control of processing parameters, particularly processing speed.

The results of the overlap runs, given in Figures 4, 5 and 6, show that uniform hardened case across the specimen surface cannot be obtained with parallel, multiple laser runs. If the runs are overlapping, some backtempering will occur in the overlap zone. The minimum hardness in this zone is, however, well above the

bulk hardness. Hence from the criterion of surface hardness alone, overlapping runs appear to be more effective than abutting or adjacent runs.

2.2.5 Improved Model for Prediction of Case Depth

As explained in Section 2.1.2., it is possible to obtain a closed solution to the heat flow equation, even if the conditions for one-dimensional heat flow are not met. The solution to the three-dimensional heat flow around a rectangular laser spot on the surface of a finite plate, Equation 9), is, however, very complex and time-consuming to use for practical purposes. It can be simplified somewhat by assuming the workpiece to be infinitely thick. (This is a valid assumption for the range of processing parameters used in this work, provided the actual plate thickness is not less than 1/4"). Furthermore, since a square spot is used in this work and we can limit our calculations to points on or below the centerline of the laser spot, we can rewrite Equation 9) in the form:

$$T = T_0 + \frac{2Q_0 \epsilon \alpha}{2K_1 \sqrt{\pi}} \int_0^1 \exp - \left[\frac{z \alpha}{1 - \alpha} \right]^2 \cdot \left[\operatorname{erf} \frac{L \alpha}{1 - \alpha} \right] \cdot \left[\operatorname{erf} \frac{z(x+B) \alpha^2 + (1 - \alpha)^2}{2 \alpha (1 - \alpha)} - \operatorname{erf} \frac{z(x+B) \alpha^2 + (1 - \alpha)^2}{2 \alpha (1 - \alpha)} \right] \frac{\alpha \alpha}{\alpha^2} \quad (12)$$

This is still a formidable expression to evaluate because the numerical integration requires some 50 to 100 ordinate evaluations in order to give sufficient accuracy. Furthermore, we are interested in finding the maximum value of the temperature relative to the laser spot, and

we have no a priori knowledge where this maximum occurs. To make the model more readily useful, the following procedure was adopted. First, the temperature maximum on or directly below the centerline was evaluated for various paired values of the parameters B and Z in the speed region where three-dimensional heat flow dominates.

Secondly, by comparing these results to those obtained through the use of the one-dimensional heat flow equation (Equation 2), it was found that the ratio f between these two values

$$f = \frac{T(3-D)}{T(1-D)} \quad 13)$$

could be expressed with good accuracy as a polynomial in the form:

$$f = (a_1 B^2 + b_1 B + c_1) \left(\frac{Z}{B}\right)^2 + (a_2 B^2 + b_2 B + c_2) \cdot \left(\frac{Z}{B}\right) + (a_3 B^{-2} + b_3 B^{-1} + c_3) \quad 14)$$

provided the range of B values in each case was not too large. By dividing the range of B values between 0.5 and 4 into three intervals, the constants in Equation 14) could be found by regression analysis.

For values of B > 4, f is unity; i.e., the one-dimensional heat flow model is valid. A calculator program, incorporating Equation 14), could then be written in such a way that case depth values could be predicted for the entire range of processing parameters used in this work. The flow sheet of the program is shown in Figure 7, and the complete program with used instructions is listed in Appendix II.

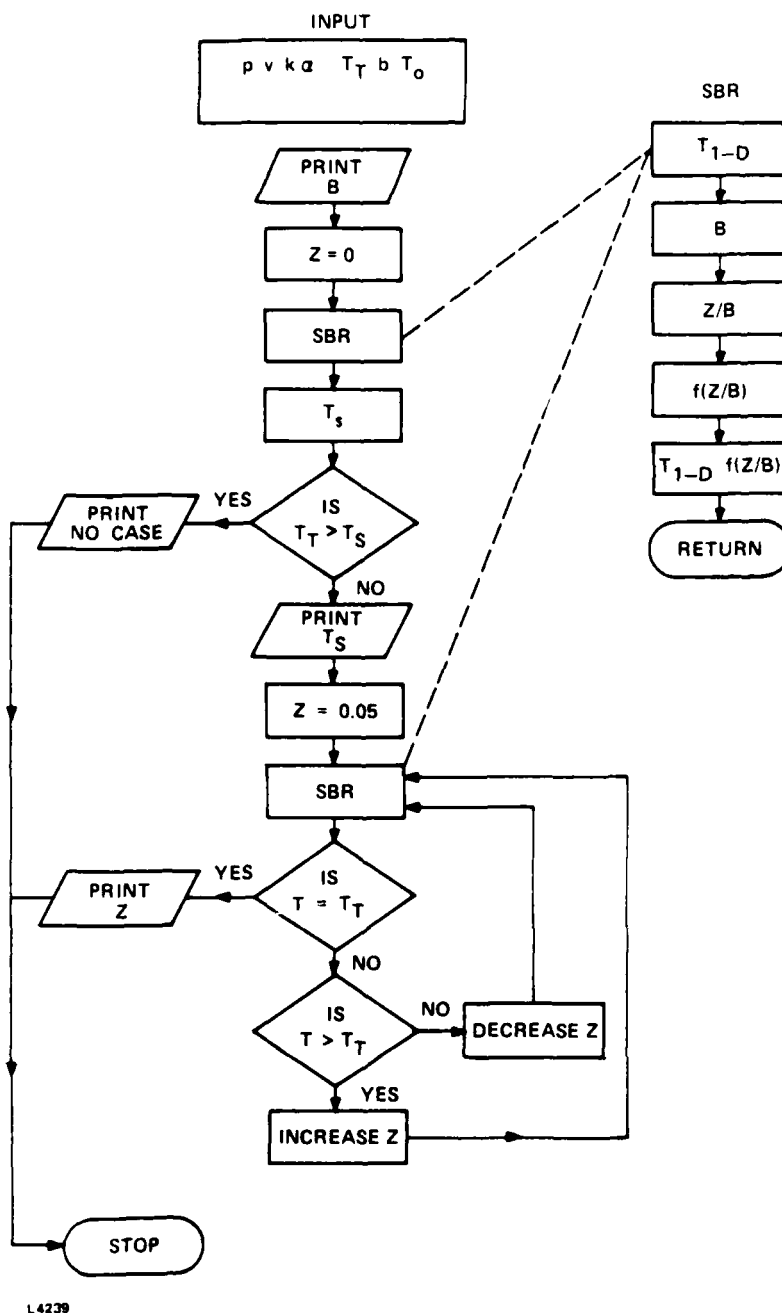


FIGURE 7 IMPROVED PROGRAM FOR CASE DEPTH PREDICTION

2.2.6. Experimental Evaluation of the Thermophysical Constants

As discussed in Section 2.1.2., the thermophysical constants K and α can be estimated for the purpose of case depth prediction, by calculating the integral average of these constants over the approximate temperature range of processing. Unfortunately, however, adequate data for the variation of K and α with the temperature is only available for a few steels. This is particularly true for the diffusivity α . To obtain more general and realistic values for K and α , the following procedure was adopted for the final phase of this work.

- 1) The thermal conductivity K was determined as before by calculating the integral average over the temperature range of processing, using published data and Equation 10). For materials where only the room temperature conductivity was available, the average value of K was estimated from this datum, relative to materials for which complete data was known.
- 2) A number of trial laser runs were made, using processing speeds sufficiently high to ensure predominantly one-dimensional heat flow. The resulting case depths were measured by means of micro-hardness testing, and the value of the diffusivity α for each material was then found by least mean square analysis, using the experimentally determined case depths and the value of conductivity K , (found from step 1) in Equation 7). Due to the transcendental nature of this equation, the analysis had to be done by numerical methods. This method of determining the average thermal

diffusivity is phenomenological and is not intended to represent anything else but an empirical parameter for practical work. The method has the advantage of expressing the value of α based on actual processing, and an error in the estimation of K will, at least in part, be compensated for due to the fact that the results obtained through Equation 7) are more dependent on the ratio of K and α than on their individual values. The values of K and α used in the final part of this work are given in Table VI. Some of the values for K, given in Table I, have been recalculated over a larger temperature interval and are, therefore, somewhat smaller. Here, it is noticeable that the new values of α , found by experimental methods, are significantly lower than the earlier values found by integral averaging.

2.2.7. Final Evaluation of Processing Parameters

In this final phase, steels in various heat treated conditions were laser processed over a wide range of processing parameters. The sample materials consisted of SAE 1045 in the annealed (ANN.) condition, the quenched and tempered (Q/T) condition and in the hot-rolled (H.R.) condition, SAE 4140 in the ANN., Q/T and H.R. condition, SAE 4340 in the ANN., Q/T and H.R. condition, SAE 8620 in the ANN. and Q/T condition, and Hyten B 3X in the ANN. and Q/T condition. Samples of SAE 1020 and SAE 4130 were also supplied by FMC/NOD, but these materials were not suited for parameter development work, as explained in Section 2.2.8 below. The samples consisted of plates and bars, none with thickness less than 1/2". All samples were processed in the same manner described in Section 2.2.1. In each case, the expected case depth was

TABLE VI

THERMOPHYSICAL CONSTANTS

MATERIAL	THERMAL COND. K (w/cm - c°)	THERMAL DIFF. α (cm ² /sec)	TRANSITION TEMP. T _r (c°)
SAE 1045	0.36	0.068	790
SAE 4140	0.31	0.049	780
SAE 4340	0.28	0.047	750
SAE 8620	0.28	0.050	840
HYTIN D3X	0.30 (cst.)	0.049	760 (cst.)

predicted in advance, using the improved calculator program discussed in Section 2.2.5 above. The results of the processing are given in Tables VII through XI.

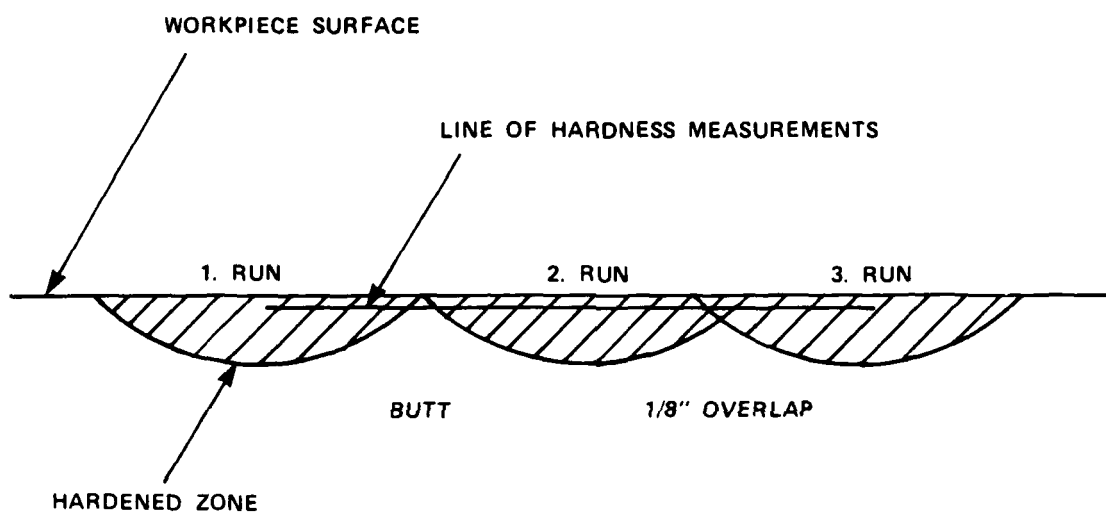
In addition, adjacent and overlapping runs in the pattern shown in Figure 8, were made on samples of SAE 8620 and Hyten B 3X. The results of these runs are shown in Figures 9 through 16. The hardness profiles shown in these figures were not obtained by surface hardness measurements, but by micro-hardness measurements taken 10 mils below the surface on samples cut normal to the processing direction.

2.2.8. Discussion of Results

The overall correlation between calculated and measured case is in the range of $\pm 20-30\%$ average over the entire range of processing speed and power used. The results for low speed processing of SAE 4140 and SAE 4340 are generally in even better agreement with the calculated values. This is clearly an improvement upon the results obtained in the preliminary survey.

- The values of the thermophysical constants used appear to be about right, with the exception of SAE 4340, where the value $\alpha = 0.047$ appears to be a little high.
- The surface hardness is somewhat low for most of the specimens, although full hardness is mostly achieved at ~ 10 mils below the surface.

This is not uncommon in laser hardening, and it has been suggested that this is due to a lower cooling rate at the surface. However, it is easy to demonstrate that this cannot in fact be the case, as the time for cooling from A_f to M_s is shorter at the surface than in the



M2525

FIGURE 8 PROFILE OF OVERLAPPING RUNS

SAE 1045
 $a = 0.068 \text{ cm}^2/\text{sec}$
 $T_T = 790^\circ \text{C}$

95.7% OF THEORETICAL
 STANDARD DEVIATION
 20%

CONDITION	POWER (kw)	SPEED (in/min)	CALCULATED CASE (mil)	MEASURED CASE (mil)	% OF THEORETICAL	CALCULATED SURFACE TEMP. (C°)	SURFACE HARDNESS (RC)
ANN	2.5	40	18.6	20	108	952	54.5
Q/T	2.5	40	18.6	21	113	952	56
H.R.	2.5	40	18.6	19	102	952	60
ANN	2.3	40	10.8	8	74	877	50
Q/T	2.3	40	10.8	13	120	877	52.5
H.R.	2.3	40	10.8	12	111	877	56
ANN	3.0	40	35.2	33.5	95	1139	57
Q/T	3.0	40	35.2	36	103	1139	56
H.R.	3.0	40	35.2	32	91	1139	59.5
ANN	2.5	30	36.6	24.5	67	1096	56
Q/T	2.5	30	36.6	28.5	78	1096	56
H.R.	2.5	30	36.6	31	85	1096	58
ANN	3.0	60	13.5	12.5	93	933	56
Q/T	3.0	60	13.5	13	96	933	54.5
H.R.	3.0	60	13.5	20.5	152	933	55
ANN	3.5	40	48.6	36.5	75	1325	56.5
Q/T	3.5	40	48.6	37.5	77	1325	57

100% OF THEORETICAL
STANDARD DEVIATION
28.6%

SAE 4140

$\alpha = 0.049 \text{ cm}^2/\text{sec}$
 $T_s = 780^\circ \text{ C}$

CONDITION	POWER (kW)	SPEED (in/min)	CALCULATED CASE (mil)	MEASURED CASE (mil)	% OF THEORETICAL	CALCULATED SURFACE TEMP. (C°)	SURFACE HARDNESS (Rc)
ANN	2.3	40	8.9	12.5	140	865	52
Q/T	2.3	40	8.9	16.5	185	865	52
H.R.	2.3	40	8.9	6.0	67	865	48.5
ANN	2.3	30	23.7	16.5	70	996	57
Q/T	2.3	30	23.7	29.0	122	996	51.5
H.R.	2.3	30	23.7	16.5	70	996	52
ANN	1.4	15	13.8	17.5	127	860	53.5
Q/T	1.4	15	13.8	17.0	123	860	53.0
H.R.	1.4	15	13.8	12.5	91	860	51.5
ANN	1.6	15	31.4	22.5	72	980	52
Q/T	1.6	15	31.4	34.5	110	980	52.5
H.R.	1.6	15	31.4	22.5	72	980	52
ANN	1.7	15	39.1	32	82	1040	55.5
Q/T	1.7	15	39.1	43.5	111	1040	52
H.R.	1.7	15	39.1	34.5	88	1040	54
ANN	3.1	60	13.5	15	111	950	53.5
Q/T	3.1	60	13.5	18.5	137	950	51.5
H.R.	3.1	60	13.5	9	67	950	51.5
ANN	2.0	10	76.2	71	93	1306	53.5
Q/T	2.0	10	76.2	84.5	111	1306	52
H.R.	2.0	10	76.2	55.5	73	1306	54
ANN	1.7	5	103.7	102.5	99	1371	56.5
Q/T	1.7	5	103.7	83.5	81	1371	52.5
H.R.	1.7	5	103.7	105	101	1371	52

$\alpha = 0.047 \text{ cm}^2/\text{sec}$
 $T_T = 750^\circ \text{ C}$

SAE 4340

90.28 OF THEORETICAL
 STANDARD DEVIATION
 23.38

CONDITION	POWER (kw)	SPEED (in/min)	CALCULATED CASE (mil)	MEASURED CASE (mil)	% OF THEORETICAL	CALCULATED SURFACE TEMP. (C°)	SURFACE HARDNESS (Rc)
ANN	2.2	40	14.8	21.5	145	897	54
Q/T	2.2	40	14.8	13	88	897	53.5
H.R.	2.2	40	14.8	7	47	897	47.5
ANN	2.9	40	35.5	44	124	1176	55
Q/T	2.9	40	35.5	33	93	1176	54.5
H.R.	2.9	40	35.5	31	87	1176	52
ANN	2.3	40	33.5	32.5	97	1078	53
Q/T	2.3	40	33.5	26	78	1078	57
H.R.	2.3	40	33.5	23	69	1078	53.5
ANN	1.5	15	37.8	29	77	996	55
Q/T	1.5	15	37.8	25.5	67	996	53
H.R.	1.5	15	37.8	28.5	75	996	51.5
ANN	1.7	15	52.9	53	100	1126	54
Q/T	1.7	15	52.9	34	64	1126	54
H.R.	1.7	15	52.9	42	79	1126	51
ANN	2.8	60	14.6	22	151	931	54.5
Q/T	2.8	60	14.6	13	89	931	51.5
H.R.	2.8	60	14.6	12.5	86	931	52.5
ANN	1.9	10	86.1	83.5	97	1353	53.5
Q/T	1.9	10	86.1	73	85	1353	50.5
H.R.	1.9	10	86.1	72	84	1353	51
ANN	1.4	5	91.0	104	114	1238	53
Q/T	1.4	5	91.0	71.5	79	1238	51.5
H.R.	1.4	5	91.0	81.5	90	1238	49.5

95.5% OF THEORETICAL
STANDARD DEVIATION
29.08

SAE 8620

$\alpha = 0.05 \text{ cm}^2/\text{sec}$
 $T_T = 840^\circ \text{ C}$

CONDITION	POWER (kw)	SPEED (in/min)	CALCULATED CASE (mil)	MEASURED CASE (mil)	% OF THEORETICAL	CALCULATED SURFACE TEMP. (C°)	SURFACE HARDNESS (RC)
Q/T	2.3	40	12	15	125	965	41
ANN	2.3	40	12	7	58	965	35
Q/T	2.0	30	14.2	21	148	969	41
ANN	2.0	30	14.2	12.5	88	969	38
Q/T	2.4	30	30.9	33	107	1159	40
ANN	2.4	30	30.9	31	100	1159	46.5
Q/T	1.6	15	36.3	34	94	1094	39
ANN	1.6	15	36.3	23	63	1094	44.5
Q/T	1.4	5	74.7	67.5	90	1258	41.5
ANN	1.4	5	74.7	63.5	85	1258	43.5
Q/T	2.9	60	11.7	16	137	993	40.5
ANN	2.9	60	11.7	6	51	993	37.5

102.5% OF THEORETICAL
STANDARD DEVIATION
25.9%

HYTEN B 3X

$\alpha = 0.049 \text{ cm}^2/\text{sec}$
 $T_I = 760^\circ \text{ C}$

CONDITION	POWER (kW)	SPEED (in/min)	CALCULATED CASE (mil)	MEASURED CASE (mil)	% OF THEORETICAL	CALCULATED SURFACE TEMP. (C°)	SURFACE HARDNESS (RC)
Q/T	2.8	60	10.8	13	120	888	56.5
ANN	2.8	60	10.8	6	56	888	55.5
Q/T	2.2	40	10.2	15	147	855	57
ANN	2.2	40	10.2	11	108	855	55
Q/T	2.8	40	29.1	32	110	1083	57
ANN	2.8	40	29.1	33	113	1083	57.5
Q/T	3.5	40	45.4	44.5	98	1349	57.5
ANN	3.5	40	45.4	43.5	96	1349	58
Q/T	2.9	30	48.8	44	90	1242	56
ANN	2.9	30	48.8	43	88	1242	56.6

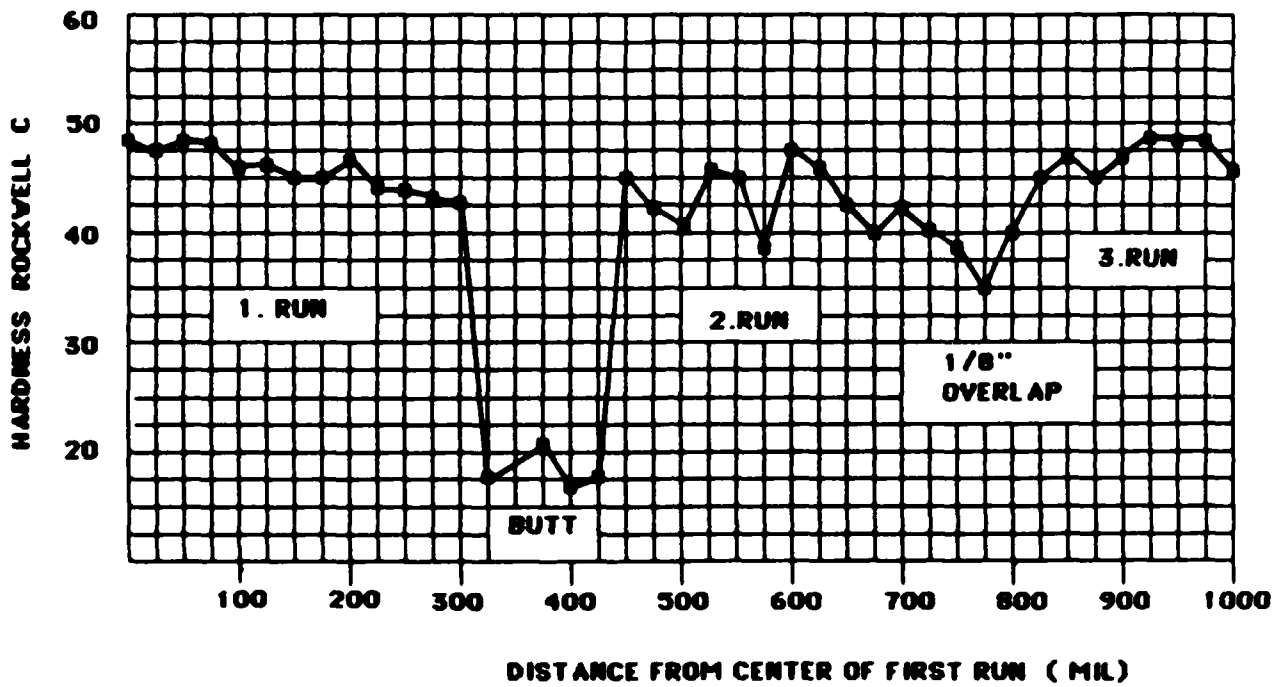


FIGURE 9.

SAE 8620 (HOT ROLLED). LASER HARDENED AT 1.4 KV
AND 5 IN/MIN PROCESSING SPEED.

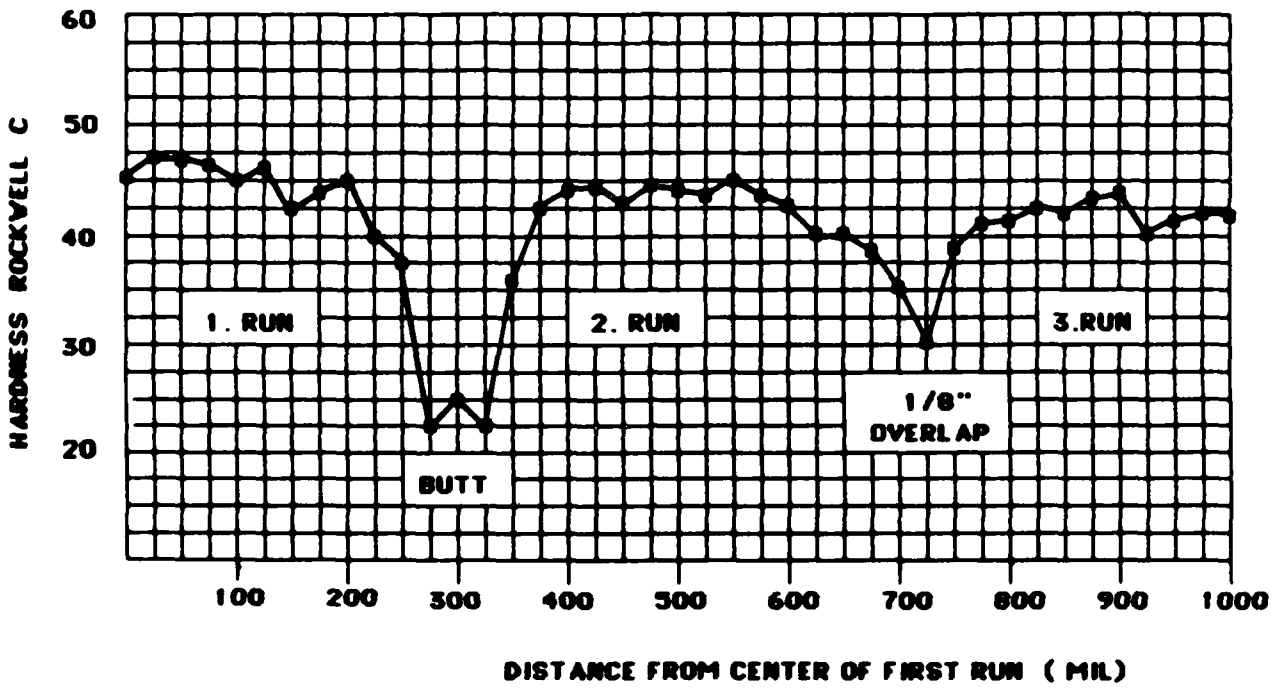


FIGURE 10.

SAE 8620 (QUENCHED AND TEMPERED). LASER HARDENED AT 1.4 KV AND 5 IN/MIN PROCESSING SPEED.

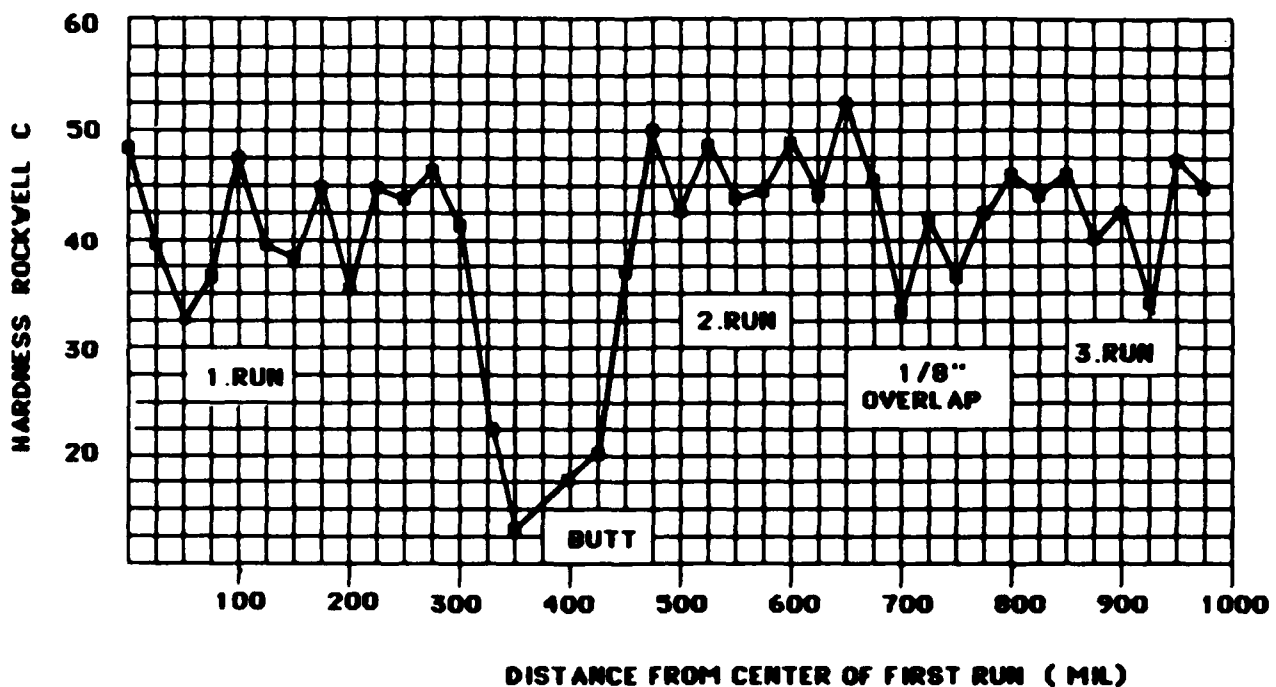


FIGURE 11.

SAE 8620 (HOT ROLLED). LASER HARDENED AT 2.4 KV AND 30 IN/MIN PROCESSING SPEED.

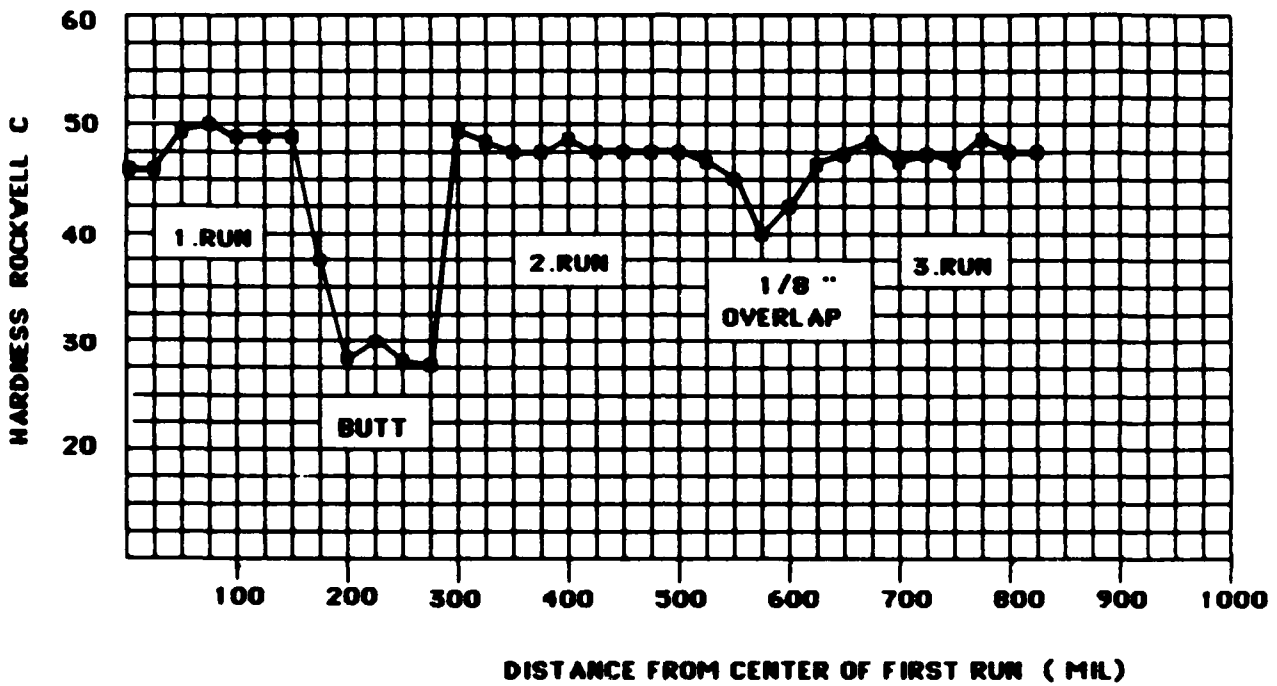


FIGURE 12.

SAE 8620 (QUENCHED AND TEMPERED). LASER HARDENED AT 2.4 KV AND 30 IN/MIN PROCESSING SPEED.

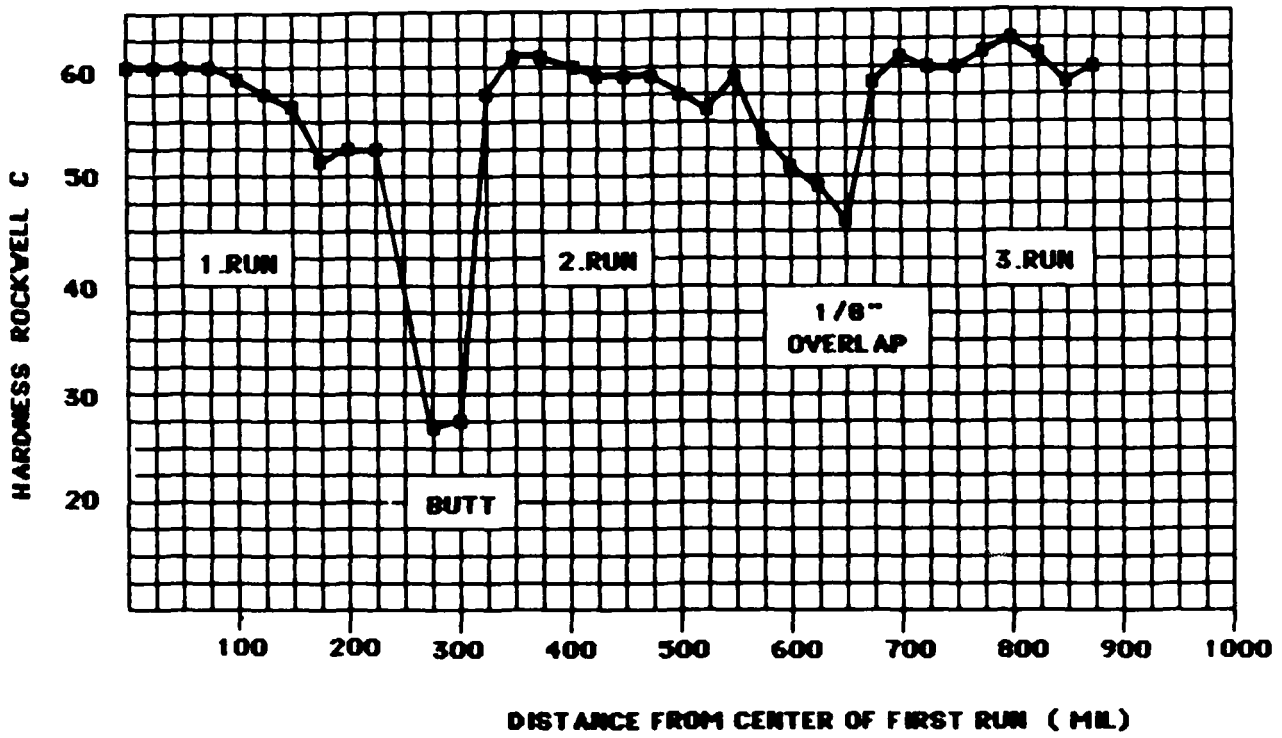


FIGURE 13.

HYTEN B 3X (QUENCHED AND TEMPERED). LASER HARDENED AT 1.2 KV AND 5 IN/MIN PROCESSING SPEED.

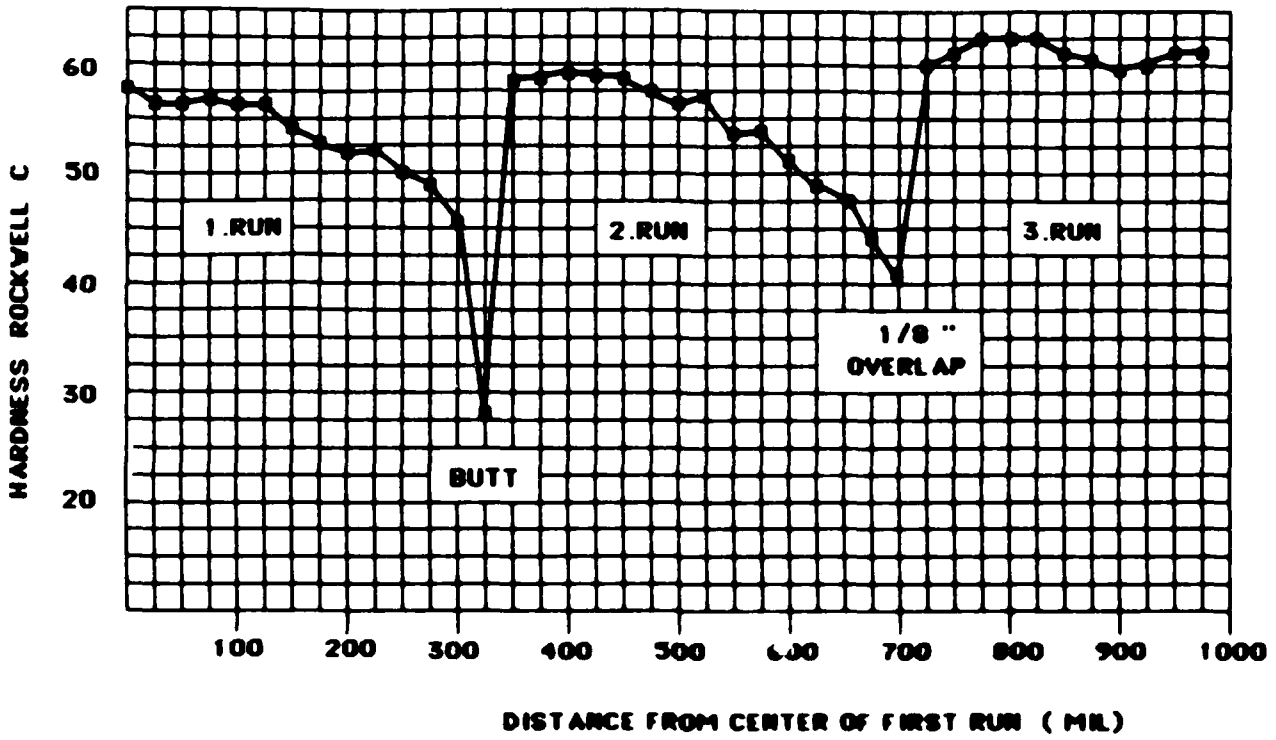


FIGURE 14

HYTEN B 3X (QUENCHED AND TEMPERED). LASER HARDENED AT 1.6 KV AND 5 IN/MIN PROCESSING SPEED.

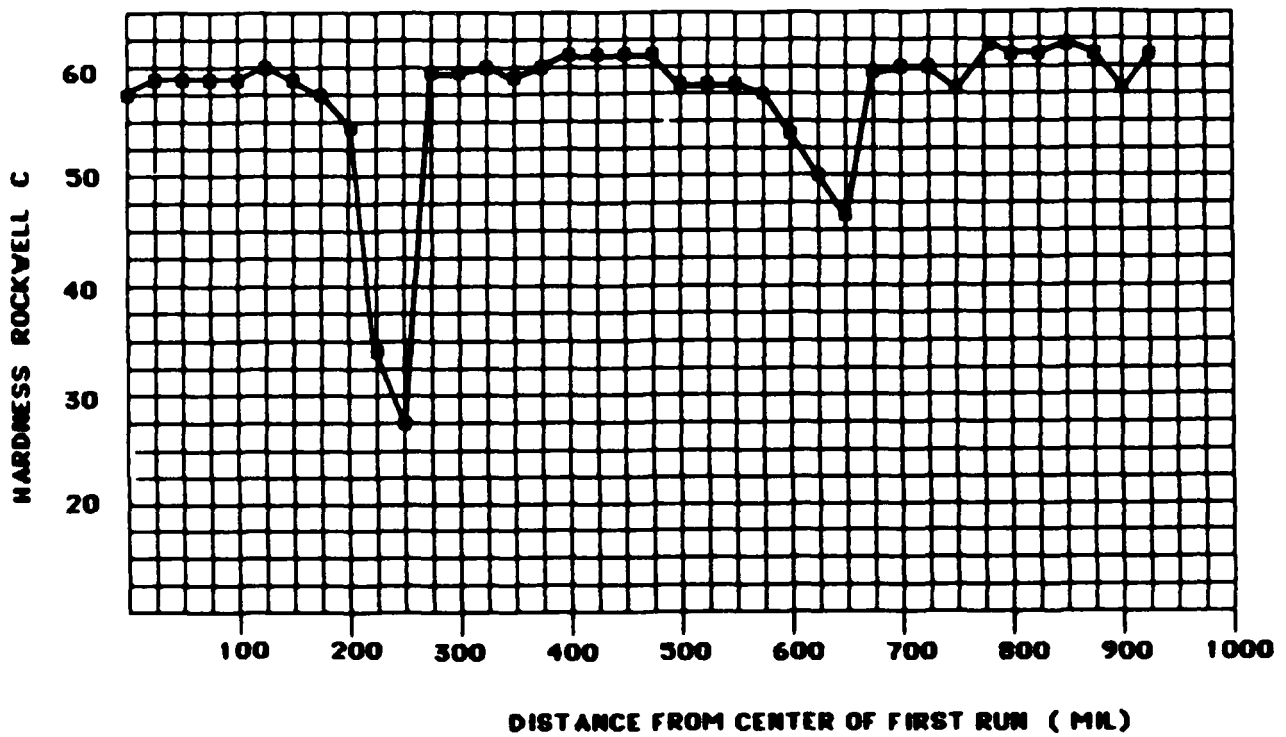


FIGURE 15.

**HYTEN B 3X (QUENCHED AND TEMPERED) LASER HARDENED
AT 2.9 KV AT 30 IN/MIN PROCESSING SPEED.**

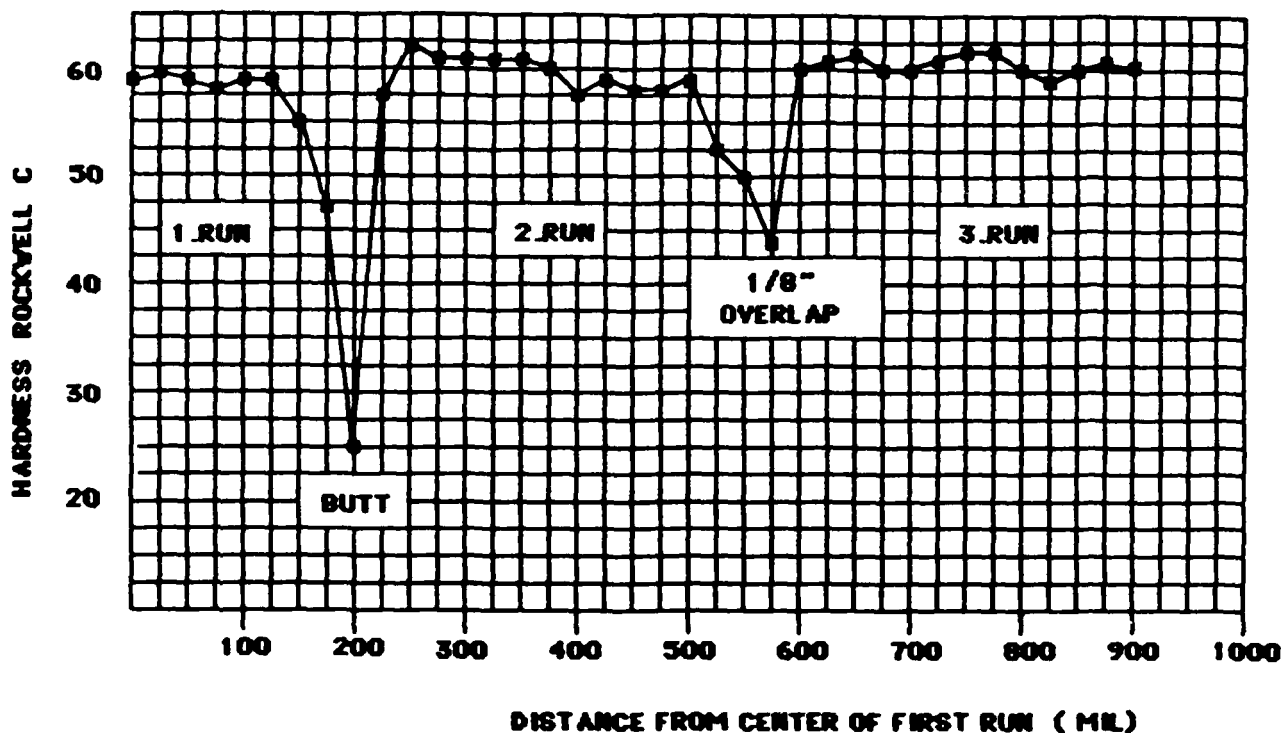


FIGURE 16.

HYTEN B 3X (QUENCHED AND TEMPERED). LASER HARDENED AT 2.9 KW AND 40 IN/MIN PROCESSING SPEED.

interior. It is, however, possible that the surface will tend to contain a higher percentage of retained austenite than the interior, due to the very high temperature reached here during the laser processing. If this is the case, one should perhaps expect a more pronounced softening at low speed/high surface temperature, but this effect may be counteracted by the lower cooling rate occurrence in such cases. An answer to this question could, however, easily be obtained by X ray analysis.

- Overlap results show that positive overlap results in backtempering, but not to the bulk hardness of the material. From the point of view of hardness only, it is clearly more efficient to run overlap rather than butt to butt.

The 1020 samples provided by FMC did not develop an adequate hardened case under any combination of speed and power. From metallographic examination, it appeared that a slight decarburization had occurred at the surface, but removal of 50 mil of material by milling did not improve the hardenability of the material. A 1020 sample from Avco stock was processed for comparison purposes, and this material did harden, as expected. Figure 17 shows the hardness tracks obtained on these two materials at 2.9 kW power and 30 in/min speed. Figures 18 and 19 show the microstructure of the two materials. It is apparent that the grain size of the two materials is different, the FMC sample having the larger grain size; while there appears to be little difference in carbon content between the two. It is, therefore, reasonable to assume that the interaction time available in laser processing (~1 sec) is not sufficiently long to allow

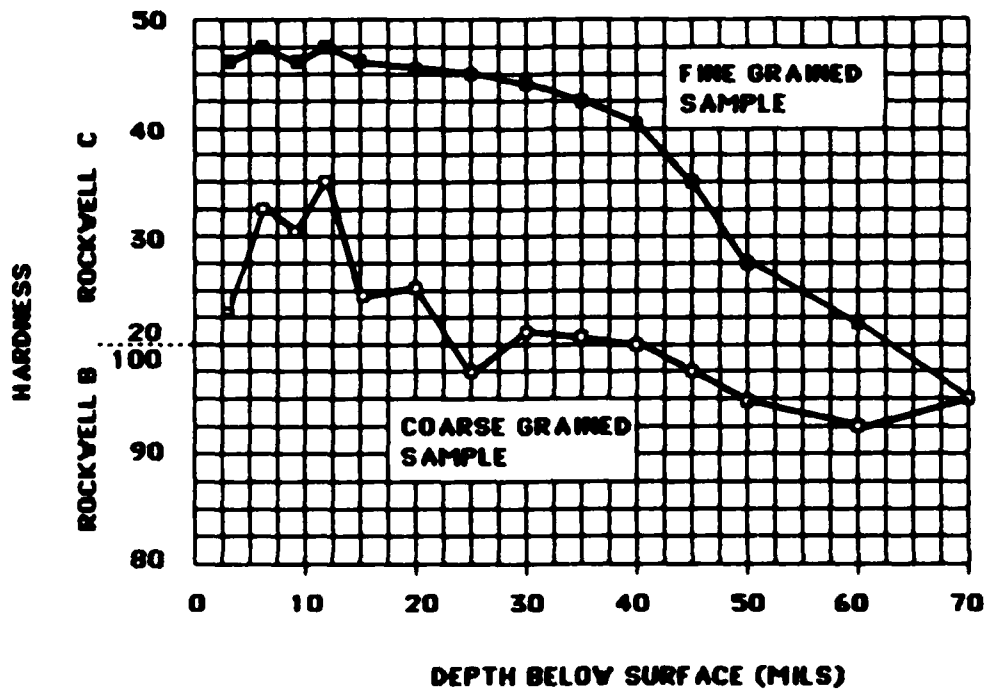


FIGURE 17.

HARDNESS PROFILES IN SAE 1020 STEELS, LASER HARDENED AT 2.9 KV AND 30 IN/MIN PROCESSING SPEED.




FIGURE 18 STRUCTURE OF SAE 1020 (FMC)
500X



FIGURE 19 STRUCTURE OF SAE 1020 (AVCO)
500X

solution and redistribution of the carbon in the γ -phase to form a hardenable austenite in the coarse-grained material. Increased interaction time would give the longer carbon diffusion distances required for the coarse grained sample, but due to the low hardenability of 1020, the resulting self-quenching rates would not be sufficiently high to form 100% martensite. A profiled laser beam with "hot" leading edge would yield better results, but such a device was not available for this work.

The 4130 samples could not be laser processed with any benefit, since these samples already were in the fully hardened, untempered condition. (Bulk Hardness Rc 51). The only results of the laser processing are some softening at the surface, and tempering of the material at the bottom of the heat-affected zone.

3. CLADDING OF CATAPULT RAIL BARS

3.1 Objective

The objective of this phase of the program was to determine the feasibility of laser cladding carrier catapult rails with wear-resistant alloys, and to develop preliminary processing parameters and procedures for such cladding. Specifically, it was desired to develop methods for cladding the rail material with hardfacing alloys having approximately the same hardness as the substrate (approximately Rockwell C 32). Furthermore, the cladding process should be such that sharp edges could be maintained on the finished product. The final objective was to produce representative samples of cladded rail sections.

3.2 Experimental Work

3.2.1. Materials

Sample rails of two different types were provided by FMC/NOD. These consisted of bars made from SAE 4140 and Hy-90 steel, having cross-sectional dimensions 1 1/2" x 2". Two of the rail samples had been flame-sprayed with Stellite #6 E on one face. The other rails were uncoated.

For the laser cladding of the rails, three different types of hardfacing powder were provided. These consisted of Deloro 22, Deloro 35 and Stellite #6 E. In addition, 304 stainless steel powder for dilution of the hardfacing alloys was provided, in order to allow control of the cladding hardness and to lower cracking susceptibility where needed.

3.2.2. Equipment and Procedures

The laser processing was performed with an Avco HPL[®]-10 CO₂ laser with CW output. The laser output beam

was shaped with a square beam by means of an optical integrator, as shown in Figure 1. This beam had dimensions 1/2" x 1/2" in the focal plane. The entire experimental arrangement was essentially identical to the setup used for the heat treatment work discussed in Chapter 2 in this report and shown in Figure 2, with the addition of an argon gas blanket nozzle aimed at the laser spot from the trailing edge side of the spot.

The object of this gas blanket was to protect the molten material in the interaction zone from reaction with the ambient atmosphere. The gas flow through the nozzle was 15 ft³/hr.

The alloy powder was preplaced onto the substrate surface, using 1/16" thick templates to obtain even coverage. Originally, it was the intention to use an automatic powder feeder for delivery of the alloy powder to the substrate, but the alloy powder used in this work did not flow well through this feeder. In particular, the stainless steel powder created problems due to its small grain size (+ 10 μm).

3.2.3. Development of Processing Parameters

Trial runs were made with all three powders at various power levels and processing speeds, ranging from 3 kW/cm² to 6 kW/cm² and 0.211 cm/sec to 0.847 cm/sec (5 in/min to 20 in/min). Both straight alloy powders and alloy powders with various amounts of 304 stainless steel powder added were clad onto 1/2" SAE 4140 steel plates.

It quickly became clear that the Stellite powder needed about 40% stainless steel addition, both to prevent cracking and to lower the hardness to an acceptable level. At this stage, no cracking problem was experienced

with Deloro 22 and Deloro 35. However, stainless steel addition to these two alloys resulted in a clad layer with variable hardness.

Because of this, it was decided to process the two Deloro alloys without stainless steel addition, even though the resulting clad layer had a hardness somewhat in excess of Rockwell C 32.

The following processing parameters gave the best combination of smooth flow, minimal dilution with the substrate, and absence of porosity.

STELLITE #6 E + 40% STAINLESS STEEL

4.65 kW/cm² 10 in/min

DELORO 22

4.65 kW/cm² 8 in/min

DELORO 35

4.65 kW/cm² 10 in/min

Following the determination of the optimal processing parameters, overlapping runs were made (1/8" overlap). No problems with cracking or flow were encountered at this stage, but a tendency for pore formation in the Deloro 35 specimens in the overlap zone was noticed. These pores were predominantly in the surface region and did not appear to be of critical importance.

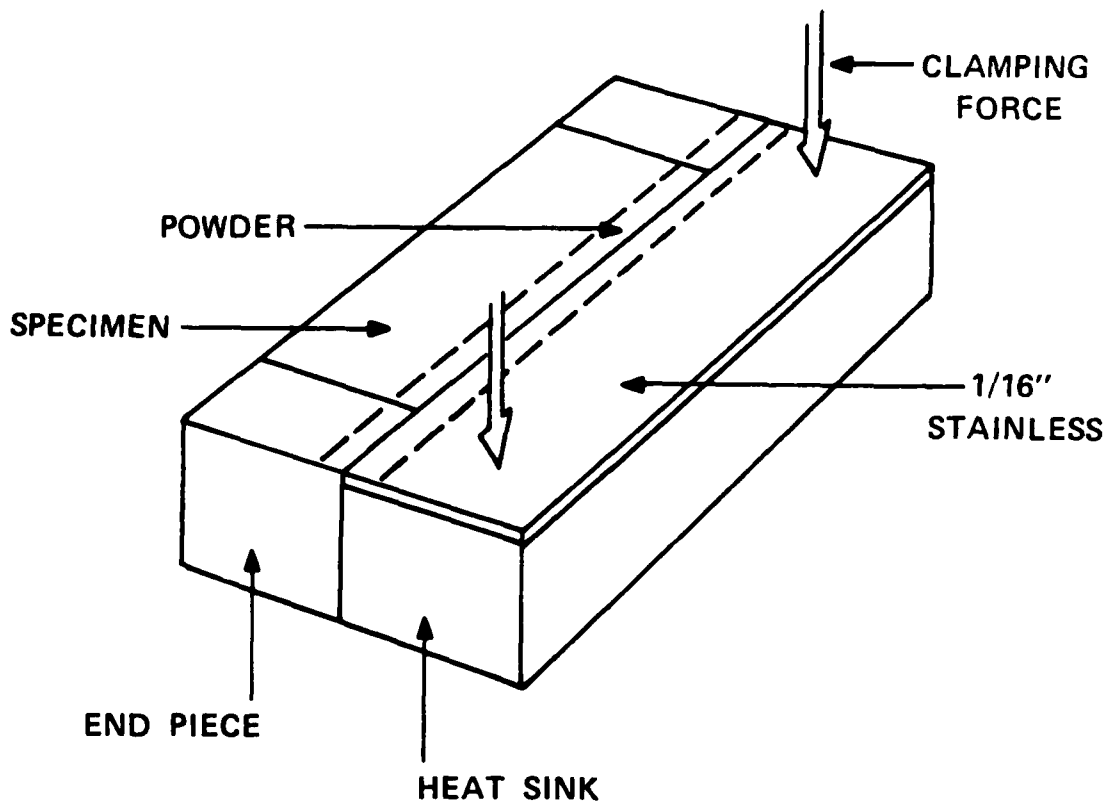
Finally, processing of the flame-sprayed test bars was attempted. This was not a success because the only effect of the laser processing, over a wide range of power and speed, was erosion of the sprayed layer. At power input rates sufficiently high to cause any reaction whatsoever, a veritable shower of sparks was generated. This gave the impression that the sprayed layer was under intense residual stresses.

3.2.4. Edge Control

In order to obtain sharp edges on the clad bars, both at the ends and along the edges, a series of runs were made to find a way to obtain this. The following techniques were found to give satisfactory results.

- To obtain sharp edges at the ends of the bars, two short pieces were cut from the barstock and used as run-on and run-off pieces. The fitup of these pieces must be good enough to allow cladding across the gap without any loss of powder through the gap. If necessary, the gap could be sealed off with a slurry of the alloy powder. (Alcohol or Nicobrazz can be used as a carrier). By starting the cladding at least an inch past the end-gap, a continuous clad deposit could be made. After laser processing, the end-pieces could be knocked off cleanly, or cut by sawing or abrasive wheel.

- To obtain sharp edges along the bar, stainless steel extension surfaces were used. These consisted of 1/16" stainless (304) plates fitting tightly along the edges. These plates were clamped down on another steel bar to provide heat-sinking. It is important that the extension surface is as long as the bar plus the two end pieces, otherwise through-melting will result at the corners. The edge cladding was performed with about half the width of the final run on the bar and the other half on the extension surface. After processing, the stainless steel plate could be cut from the underside, providing a sharp edge. Figure 20 shows the technique of edge control.



L4241

FIGURE 20 EDGE CONTROL IN LASER CLADDING

3.2.5. Preparation of Specimens

Six specimens, each about 2.5" long, were cut from the 1 1/2" x 2" bars, three from SAE 4140 bars and three from Hy-90 bars. These were clad on one of the 1 1/2" faces, using overlapping runs and edge control techniques (as described above) to obtain uniform cladding of about 0.05" thickness over the entire surface. Each of the three alloys were clad onto both SAE 4140 and Hy-90 substrates. Figure 21 shows the shape of the final specimens. (Deloro 22 on SAE 4140).

3.3 Results and Discussion

Both the Stellite #6 E + 40% stainless steel specimens developed cracks at the third overlay pass. These cracks were of the "herring bone" type. The Deloro 35 specimens also showed cracks in the third overlay, but these were normal to the processing direction. In order to prevent cracking, new specimens were made as before, but with stress relief between each cladding run (1200°F for 1 hour). No improvement was observed in the Stellite #6 E specimens, but one of the Deloro 35 (on SAE 4140) was apparently crack-free. Deloro 35 on Hy-90, however, showed the cracks.

The two Deloro 22 specimens showed no cracks, and these were not stress-relieved between runs.

Figures 22 through 24 show the hardness profiles of the six different clad specimens. In all cases, the clad layer is 45 to 50 mil deep, with a hardness ranging from 32 to 42 Rockwell C. The substrates of the specimens clad with Deloro 22 show transformation hardening in the vicinity of the clad/substrate interface. This is absent in the other specimens, due to the stress-relief heat treatment.

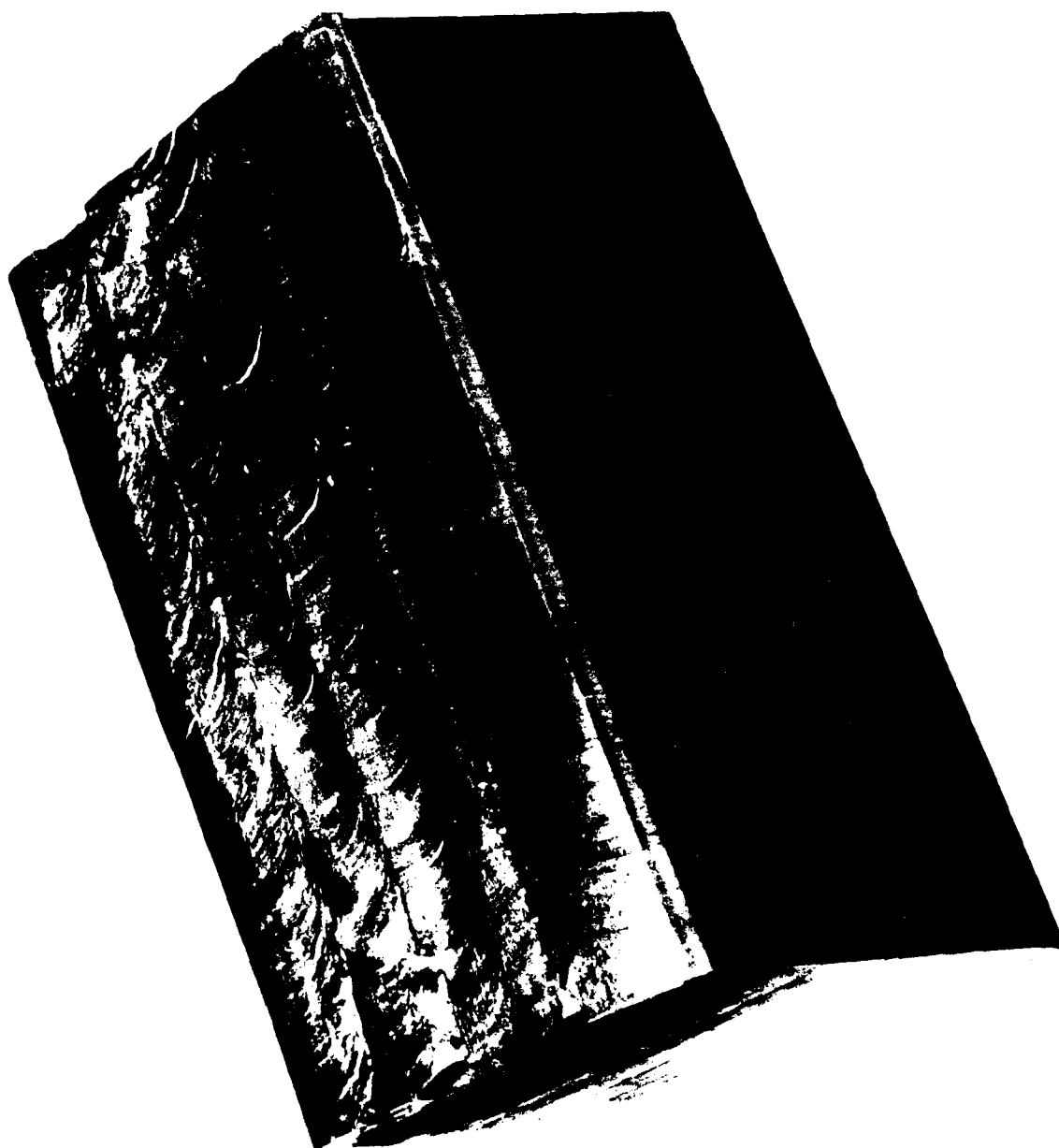


FIGURE 21

SAE 4140 STEEL BAR CLADDED WITH DELORO 22

Cladding of catapult rails with Deloro 22 can be performed easily. The hardness of the overlay is Rockwell C 35 to 40. The 4140 substrate shows transformation hardening to a peak hardness of Rc 51-52. The Hy-90 substrate does not harden to more than Rc 40.

The Deloro 35 and Stellite #6E alloys can probably not be clad onto these steels in a continuous manner without preheating and slow post-processing cooling to prevent cracking.

Remelting of flame-sprayed layers was not successful in this case, but this should be possible if closer control of the spraying process is exercised.

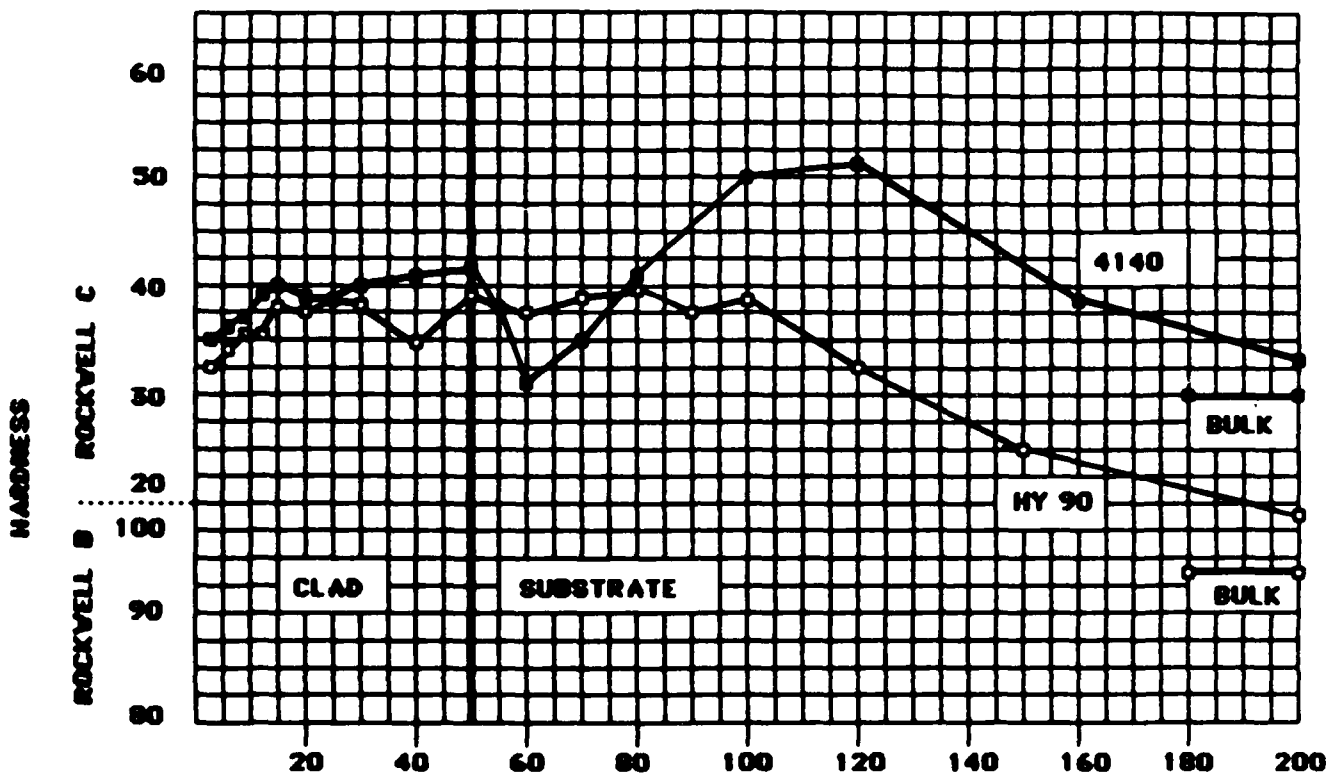


FIGURE 22.

DELORO 22. LASER CLADDED AT 4.65 Kw/cm^2
AND 0.339 cm/sec PROCESSING SPEED.

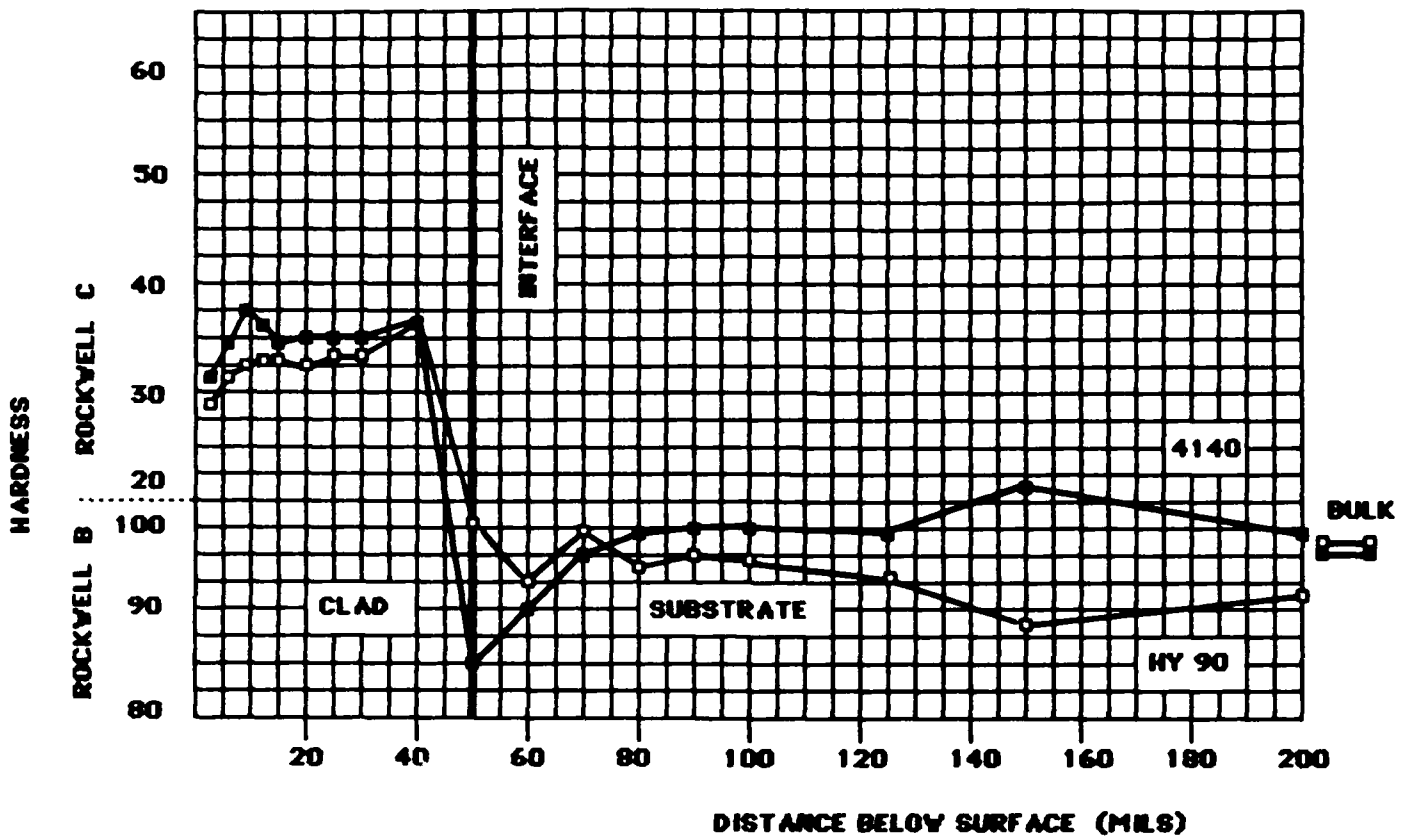


FIGURE 23

STELLITE 6 E + 40% STAINLESS STEEL, LASER CLADDED
 AT 4.65 K ν /cm² AND 0.423 cm/sec PROCESSING SPEED.

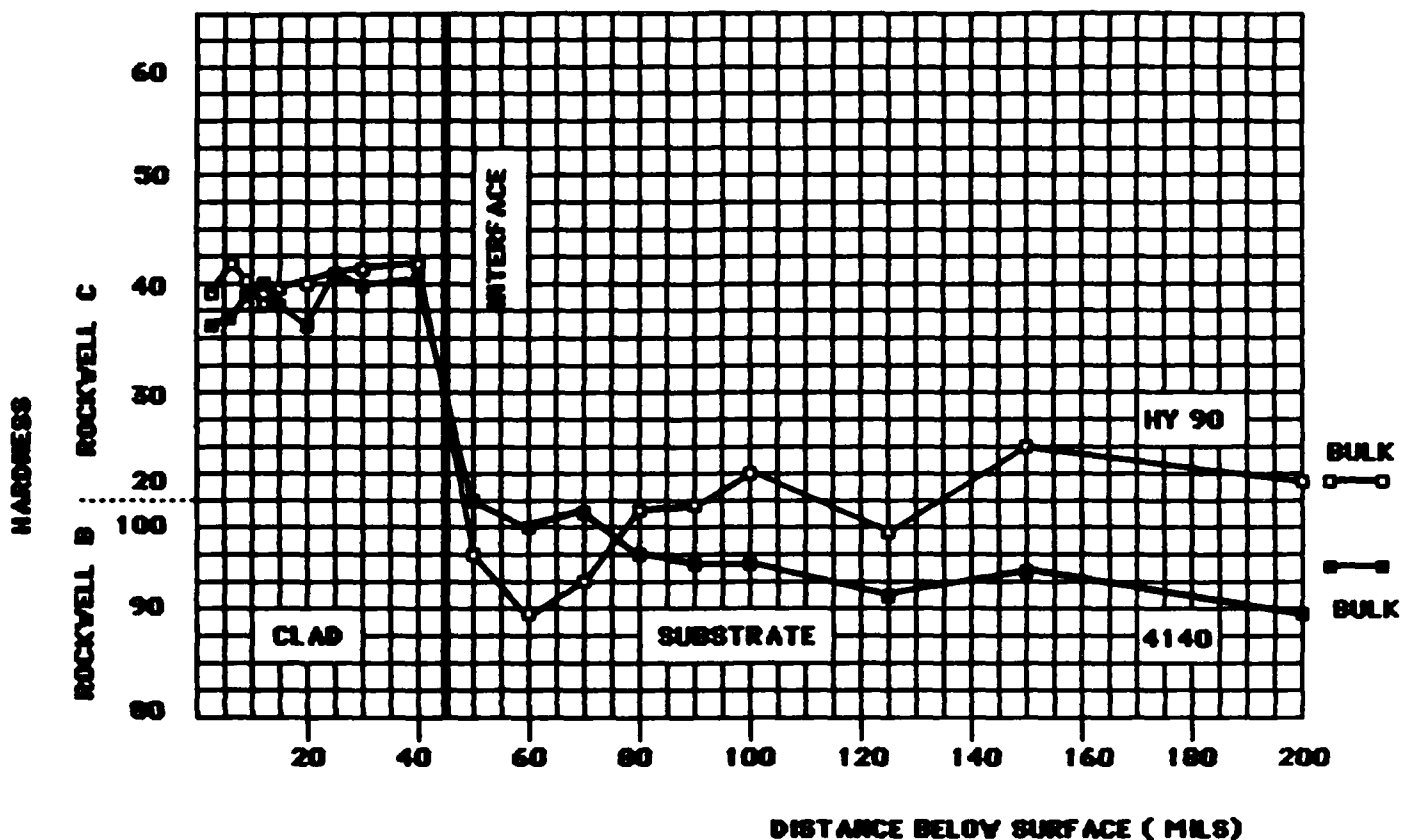


FIGURE 24.

DELORO 35. LASER CLADDED AT 4.65 KV/cm²
AND 0.423 cm/sec PROCESSING SPEED.

LIST OF REFERENCES

- 1) Rose, A., and Strassburg, V. (1956). Stahl and Eisen, 76, No. 15. 976-983.
- 2) Sandven, O.A. (1981). Laser Surface Heat Treatment With Profiled Beams. Proc. International Laser Conf., Anaheim, CA.
- 3) Carslaw, H.S. and Jaeger, J.C. (1959). Conduction of Heat in Solids. Oxford Press, 2nd ed. 75.
- 4) *ibid.* 270.
- 5) Sandven, O.A. (1983). Three-Dimensional Heat Flow Model for Prediction of Case Depth in Laser Surface Transformation Hardening. ICALEO Conf., Los Angeles, CA.
- 6) ASM METALS HANDBOOK, 9th Ed. (1978). Vol. 1: 145-151.

APPENDIX I

The program listed on the following pages is based on the one-dimensional heat flow model and should not be used for low processing speed.

The program is written for use on a Texas Instrument TI 59 programmable calculator with a PC-100C printer.

User Instructions

1. Partition the calculator to mode 714:29 by entering 3 and push 2th op. 17.
2. Enter power density in A (w/cm^2).
3. Enter speed in B (cm/sec).
4. Enter spot length in C (cm).
5. Enter thermal conductivity and press R/S (w/cmC°).
6. Enter thermal diffusivity and press R/S (cm^2/sec).
7. Enter room temperature in D (C°).
8. Enter transition temperature and press R/S (c°).
9. Execute program by pressing A¹.

The calculator will print dwelltime, surface temperature and case depth. If the heat input is insufficient to form any case, "NO CASE" is printed. If the processing speed is too low for this model, "USE 3-D" will be printed.

If cooling rates behind the laser spot are desired, enter the total time (dwelltime + cooling time combined) and press B¹. This must be done after the case depth has been calculated. The calculator will print surface temperature at the entered time, the rate of cooling (in c°/sec), the temperature at the bottom of the case and the rate of cooling at this point. The procedure can be repeated for any desired total time.

PROGRAM FOR PREDICTION OF CASE DEPTH
(One-Dimensional)

000	76	LBL	051	43	RCL	101	01	01
001	11	A	052	01	01	102	00	0
002	53	(	053	95	=	103	04	4
003	42	STD	054	42	STD	104	02	2
004	00	00	055	07	07	105	00	0
005	65	X	056	25	CLR	106	01	1
006	00	0	057	69	DP	107	06	6
007	93	.	058	00	00	108	69	DP
008	08	8	059	01	1	109	02	02
009	05	5	060	06	6	110	69	DP
010	95	=	061	04	4	111	05	05
011	42	STD	062	03	3	112	92	RTN
012	10	10	063	01	1	113	02	2
013	54	)	064	07	7	114	65	X
014	92	RTN	065	02	2	115	43	RCL
015	76	LBL	066	07	7	116	10	10
016	12	B	067	02	2	117	55	+
017	53	(	068	07	7	118	43	RCL
018	42	STD	069	69	DP	119	03	03
019	01	01	070	01	01	120	65	X
020	54	)	071	69	DP	121	53	(
021	92	RTN	072	05	05	122	43	RCL
022	76	LBL	073	43	RCL	123	04	04
023	13	C	074	07	07	124	65	X
024	53	(	075	99	PRT	125	43	RCL
025	42	STD	076	01	1	126	07	07
026	02	02	077	06	6	127	55	+
027	91	R/S	078	65	X	128	89	+
028	42	STD	079	43	RCL	129	54)
029	03	03	080	04	04	130	34	TX
030	91	R/S	081	55	+	131	85	+
031	42	STD	082	43	RCL	132	43	RCL
032	04	04	083	01	01	133	05	05
033	54	)	084	95	=	134	95	=
034	92	RTN	085	32	X:T	135	42	STD
035	76	LBL	086	43	RCL	136	08	08
036	14	D	087	02	02	137	43	RCL
037	53	(	088	77	GE	138	06	06
038	42	STD	089	01	01	139	32	X:T
039	05	05	090	13	13	140	43	RCL
040	91	R/S	091	25	CLR	141	08	08
041	42	STD	092	69	DP	142	77	GE
042	06	06	093	00	00	143	01	01
043	54	)	094	04	4	144	68	68
044	92	RTN	095	01	1	145	25	CLR
045	76	LBL	096	03	3	146	69	DP
046	15	H'	097	06	6	147	00	00
047	53	(	098	01	1	148	08	8
048	43	RCL	099	07	7	149	01	1
049	02	02	100	69	DP	150	01	0
050	55	+						

PROGRAM FOR PREDICTION OF CASE DEPTH
(One-Dimensional)

```

151 02 2
152 69 DP
153 01 01
154 01 1
155 05 5
156 01 1
157 03 3
158 03 3
159 06 6
160 01 1
161 07 7
162 69 DP
163 02 02
164 69 DP
165 05 05
166 54 )
167 92 RTN
168 25 CLR
169 69 DP
170 00 00
171 03 3
172 06 6
173 04 4
174 01 1
175 03 3
176 05 5
177 02 2
178 01 1
179 69 DP
180 01 01
181 03 3
182 07 7
183 01 1
184 07 7
185 03 3
186 00 0
187 03 3
188 03 3
189 69 DP
190 02 02
191 69 DP
192 05 05
193 43 RCL
194 08 08
195 59 INT
196 99 PRT
197 02 2
198 65 X
199 43 RCL
200 10 10

```

```

201 55 +
202 43 RCL
203 03 03
204 65 X
205 53 (
206 43 RCL
207 04 04
208 65 X
209 43 RCL
210 07 07
211 54 )
212 34 FX
213 95 =
214 42 STD
215 11 11
216 02 2
217 65 X
218 53 (
219 43 RCL
220 04 04
221 65 X
222 43 RCL
223 07 07
224 54 )
225 34 FX
226 95 =
227 42 STD
228 12 12
229 00 0
230 42 STD
231 13 13
232 00 0
233 93 .
234 00 0
235 05 5
236 42 STD
237 14 14
238 43 RCL
239 13 13
240 65 +
241 43 RCL
242 14 14
243 95 =
244 42 STD
245 13 13
246 55 +
247 43 RCL
248 12 12
249 95 =
250 10 E'

```

```

251 65 X
252 43 RCL
253 11 11
254 85 +
255 43 RCL
256 05 05
257 95 =
258 42 STD
259 15 15
260 43 RCL
261 15 15
262 75 -
263 43 RCL
264 06 06
265 95 =
266 50 IxI
267 32 X:T
268 01 1
269 77 GE
270 03 03
271 31 31
272 43 RCL
273 06 06
274 32 X:T
275 43 RCL
276 15 15
277 77 GE
278 03 03
279 14 14
280 86 STF
281 01 01
282 43 RCL
283 14 14
284 55 +
285 02 2
286 95 =
287 42 STD
288 14 14
289 43 RCL
290 13 13
291 75 -
292 43 RCL
293 14 14
294 95 =
295 42 STD
296 13 13
297 55 -
298 43 RCL
299 13 13
300 95 -

```

PROGRAM FOR PREDICTION OF CASE DEPTH
(One-Dimensional)

301	10	E'	351	86	STF	401	34	FX
302	65	x	352	01	01	402	95	=
303	43	RCL	353	54	)	403	42	STD
304	11	11	354	92	RTN	404	19	19
305	85	+	355	76	LBL	405	43	RCL
306	43	RCL	356	17	B'	406	18	18
307	05	05	357	53	(	407	75	-
308	95	=	358	42	STD	408	43	RCL
309	42	STD	359	16	16	409	19	19
310	15	15	360	02	2	410	85	+
311	61	GTD	361	65	x	411	43	RCL
312	02	02	362	43	RCL	412	05	05
313	60	60	363	10	10	413	95	=
314	87	IFF	364	55	+	414	42	STD
315	01	01	365	43	RCL	415	20	20
316	03	03	366	03	03	416	59	INT
317	21	21	367	65	x	417	99	PRT
318	61	GTD	368	43	RCL	418	53	(
319	02	02	369	04	04	419	43	RCL
320	38	38	370	34	FX	420	08	08
321	43	RCL	371	95	=	421	75	-
322	14	14	372	42	STD	422	43	RCL
323	55	+	373	17	17	423	20	20
324	02	2	374	43	RCL	424	54)
325	95	=	375	17	17	425	55	+
326	42	STD	376	65	x	426	53	(
327	14	14	377	53	(	427	43	RCL
328	61	GTD	378	43	RCL	428	16	16
329	02	02	379	16	16	429	75	-
330	38	38	380	55	+	430	43	RCL
331	25	CLR	381	89	#	431	07	07
332	69	DP	382	54	)	432	54)
333	00	00	383	34	FX	433	95	=
334	01	1	384	95	=	434	59	INT
335	05	5	385	42	STD	435	99	PRT
336	01	1	386	18	18	436	43	RCL
337	03	3	387	43	RCL	437	13	13
338	03	3	388	17	17	438	55	+
339	06	6	389	65	x	439	02	2
340	01	1	390	53	(	440	55	+
341	07	7	391	53	(	441	53	(
342	69	DP	392	43	RCL	442	43	RCL
343	01	01	393	16	16	443	04	04
344	69	DP	394	75	-	444	65	x
345	05	05	395	43	RCL	445	43	RCL
346	43	RCL	396	07	07	446	16	16
347	13	13	397	54	)	447	54)
348	99	PRT	398	55	+	448	34	FX
349	99	ADV	399	89	#	449	95	=
350	21	INV	400	54	)	450	10	E'

PROGRAM FOR PREDICTION OF CASE DEPTH
(One-Dimensional)

```

451 65 X
452 43 RCL
453 17 17
454 65 X
455 43 RCL
456 16 16
457 34 FX
458 95 =
459 42 STD
460 21 21
461 43 RCL
462 13 13
463 55 +
464 02 2
465 55 +
466 53 (
467 43 RCL
468 04 04
469 65 X
470 53 (
471 43 RCL
472 16 16
473 75 -
474 43 RCL
475 07 07
476 54 )
477 54 )
478 34 FX
479 95 =
480 10 E*
481 65 X
482 43 RCL
483 17 17
484 65 X
485 53 (
486 43 RCL
487 16 16
488 75 -
489 43 RCL
490 07 07
491 54 )
492 34 FX
493 95 =
494 42 STD
495 22 22
496 43 RCL
497 21 21
498 75 -
499 43 RCL
500 22 22

```

```

501 85 +
502 43 RCL
503 05 05
504 95 =
505 42 STD
506 23 23
507 59 INT
508 99 PRT
509 53 (
510 43 RCL
511 15 15
512 75 -
513 43 RCL
514 23 23
515 54 )
516 55 +
517 53 (
518 43 RCL
519 16 16
520 75 -
521 43 RCL
522 07 07
523 54 )
524 95 =
525 59 INT
526 99 PRT
527 54 )
528 92 RTN
529 76 LBL
530 10 E*
531 53 (
532 42 STD
533 24 24
534 04 4
535 32 X: T
536 43 RCL
537 24 24
538 77 GE
539 06 06
540 73 73
541 43 RCL
542 24 24
543 65 X
544 00 0
545 93 .
546 03 3
547 02 2
548 07 7
549 05 5
550 09 9

```

```

551 01 1
552 01 1
553 85 +
554 01 1
555 95 =
556 35 1/X
557 43 STD
558 25 25
559 53 (
560 00 0
561 93 .
562 02 2
563 05 5
564 04 4
565 08 8
566 02 2
567 02 2
568 09 9
569 05 5
570 09 9
571 02 2
572 65 X
573 43 RCL
574 25 25
575 75 -
576 00 0
577 93 .
578 02 2
579 08 8
580 04 4
581 04 4
582 09 9
583 06 6
584 07 7
585 03 3
586 06 6
587 65 X
588 43 RCL
589 25 25
590 33 X: T
591 85 +
592 01 1
593 93 .
594 04 4
595 02 2
596 01 1
597 04 4
598 01 1
599 03 3
600 07 7

```

PROGRAM FOR PREDICTION OF CASE DEPTH
(One-Dimensional)

601	04	4		639	25	25
602	01	1		640	45	YX
603	65	X		641	05	5
604	43	RCL		642	54)
605	25	25		643	65	X
606	45	YX		644	01	1
607	03	3		645	22	INV
608	75	-		646	23	LNx
609	01	1		647	45	YX
610	93	.		648	43	RCL
611	04	4		649	24	24
612	05	5		650	33	X ²
613	03	3		651	94	+/-
614	01	1		652	95	=
615	05	5		653	42	STD
616	02	2		654	26	26
617	00	0		655	01	1
618	02	2		656	22	INV
619	07	7		657	23	LNx
620	65	X		658	45	YX
621	43	RCL		659	43	RCL
622	25	25		660	24	24
623	45	YX		661	33	X ²
624	04	4		662	94	+/-
625	85	+		663	55	+
626	01	1		664	89	#
627	93	.		665	34	IX
628	00	0		666	75	-
629	06	6		667	43	RCL
630	01	1		668	24	24
631	04	4		669	65	X
632	00	0		670	43	RCL
633	05	5		671	26	26
634	04	4		672	85	+
635	02	2		673	00	0
636	09	9		674	95	=
637	65	X		675	54)
638	43	RCL		676	92	RTN

APPENDIX II

The program listed on the following pages utilizes a one-dimensional heat flow model for the high speed range, and a three-dimensional model for the low speed ranges.

The program is written for use on a Texas Instrument TI 59. programmable calculator with a PC-100 printer.

User Instructions

1. Partition the calculator to mode 799:19 by entering 2 and push 2th op. 17.
2. Enter laser power (watts) in A.
3. Enter speed (cm/sec) in B.
4. Enter thermal conductivity (w/cmC°) in C.
5. Enter thermal diffusivity (cm²/sec) in D.
6. Enter transformation temperature (C°) in E.
7. Enter size of laser spot (cm) in A¹.
8. Enter room temperature (c°) in B¹.
9. Press C¹. The value of the parameter $B = vb/2\alpha$ will be displayed. Now press R/S. The calculator will print surface temperature, depth of case (in cm and mils), the value of the parameter B and the ratio of the parameters Z and B ($Z = v_2/2\alpha$). The results are valid if:

$$B \geq 0.5$$

$$Z/B \geq 0.5 \text{ for } 1 \geq B \geq 0.5$$

$$Z/B \geq 0.4 \text{ for } 4 \geq B \geq 1$$

$$\text{for all values of } B \geq 4$$

PROGRAM FOR PREDICTION OF CASE
(Three-Dimensional)

000	76	LBL	051	53	(	101	01	1
001	11	A	052	43	RCL	102	42	STD
002	53	(	053	00	00	103	12	12
003	42	STD	054	55	+	104	00	0
004	00	00	055	43	RCL	105	42	STD
005	54	)	056	05	05	106	12	12
006	92	RTN	057	33	X ²	107	42	RCL
007	76	LBL	058	65	X	108	12	12
008	12	B	059	00	0	109	12	B'
009	53	(	060	93	.	110	42	STD
010	42	STD	061	08	8	111	14	14
011	01	01	062	05	5	112	85	+
012	54	)	063	95	=	113	42	RCL
013	92	RTN	064	42	STD	114	06	06
014	76	LBL	065	07	07	115	95	=
015	12	C	066	43	RCL	116	59	INT
016	53	(	067	05	05	117	99	PRT
017	42	STD	068	55	+	118	42	RCL
018	02	02	069	43	RCL	119	14	14
019	54	)	070	01	01	120	75	-
020	92	RTN	071	95	=	121	42	RCL
021	76	LBL	072	42	STD	122	10	10
022	14	D	073	08	08	123	95	=
023	53	(	074	43	RCL	124	32	INT
024	42	STD	075	05	05	125	01	1
025	03	03	076	65	X	126	77	GE
026	54	)	077	43	RCL	127	01	01
027	92	RTN	078	01	01	128	90	90
028	76	LBL	079	55	+	129	42	RCL
029	15	E	080	04	4	130	11	11
030	53	(	081	55	+	131	55	+
031	42	STD	082	43	RCL	132	42	RCL
032	04	04	083	03	03	133	12	12
033	54	)	084	95	=	134	95	=
034	92	RTN	085	42	STD	135	42	STD
035	76	LBL	086	09	09	136	11	11
036	16	A'	087	91	R/S	137	42	RCL
037	53	(	088	43	RCL	138	12	12
038	42	STD	089	04	04	139	95	+
039	05	05	090	75	-	140	42	RCL
040	54	)	091	43	RCL	141	11	11
041	92	RTN	092	06	06	142	95	=
042	76	LBL	093	95	=	143	42	STD
043	17	B'	094	42	STD	144	12	12
044	53	(	095	10	10	145	42	RCL
045	42	STD	096	02	2	146	12	12
046	06	06	097	00	0	147	12	12
047	54	)	098	35	1/X	148	42	STD
048	92	RTN	099	42	STD	149	12	12
049	76	LBL	100	11	11	150	12	12
050	12	C'						

PROGRAM FOR PREDICTION OF CASE
(Three-Dimensional)

151	43	RCL	201	01	1	251	08	08
152	10	10	202	00	0	252	54)
153	95	=	203	00	0	253	34	FX
154	50	IXI	204	00	0	254	95	=
155	32	X:T	205	95	=	255	42	STD
156	01	1	206	99	PRT	256	15	15
157	77	GE	207	98	ADV	257	02	2
158	01	01	208	22	INV	258	65	X
159	90	90	209	58	FIX	259	43	RCL
160	43	RCL	210	43	RCL	260	13	13
161	10	10	211	09	09	261	55	-
162	32	X:T	212	99	PRT	262	43	RCL
163	43	RCL	213	43	RCL	263	05	05
164	14	14	214	16	16	264	95	=
165	77	GE	215	99	PRT	265	42	STD
166	01	01	216	98	ADV	266	13	13
167	29	29	217	54	)	267	01	1
168	02	2	218	92	RTN	268	42	STD
169	42	STD	219	76	LBL	269	17	17
170	12	12	220	19	D'	270	04	4
171	43	RCL	221	53	(	271	32	X:T
172	11	11	222	42	STD	272	43	RCL
173	55	+	223	13	13	273	09	09
174	43	RCL	224	55	+	274	77	GE
175	12	12	225	02	2	275	06	06
176	95	=	226	55	+	276	37	37
177	42	STD	227	53	(	277	02	2
178	11	11	228	43	RCL	278	32	X:T
179	43	RCL	229	03	03	279	43	RCL
180	13	13	230	65	X	280	09	09
181	75	-	231	43	RCL	281	77	GE
182	43	RCL	232	08	08	282	05	05
183	11	11	233	54	)	283	32	32
184	95	=	234	34	FX	284	01	1
185	42	STD	235	95	=	285	32	X:T
186	13	13	236	10	E'	286	43	RCL
187	61	GTO	237	65	X	287	09	09
188	01	01	238	02	2	288	77	GE
189	45	45	239	65	X	289	04	04
190	58	FIX	240	43	RCL	290	11	11
191	04	04	241	07	07	291	53	(
192	43	RCL	242	55	+	292	00	0
193	13	13	243	43	RCL	293	23	
194	32	FRT	244	02	02	294	00	0
195	55	+	245	65	X	295	01	1
196	02	2	246	53	(	296	02	2
197	93		247	43	RCL	297	01	1
198	05	5	248	03	03	298	04	4
199	04	4	249	65	X	299	06	6
200	65	X	250	43	RCL	300	65	6

PROGRAM FOR PREDICTION OF CASE
(Three-Dimensional)

301 43 RCL
 302 09 09
 303 33 X²
 304 85 +
 305 00 0
 306 93 .
 307 00 0
 308 05 5
 309 06 6
 310 00 0
 311 06 6
 312 05 5
 313 65 X
 314 43 RCL
 315 09 09
 316 85 +
 317 00 0
 318 93 .
 319 00 0
 320 06 6
 321 06 6
 322 06 6
 323 01 1
 324 54)
 325 65 X
 326 43 RCL
 327 16 16
 328 33 X²
 329 85 +
 330 53 (
 331 00 0
 332 93 .
 333 00 0
 334 02 2
 335 01 1
 336 08 8
 337 01 1
 338 04 4
 339 65 X
 340 43 RCL
 341 09 09
 342 33 X²
 343 75 -
 344 00 0
 345 93 .
 346 00 0
 347 01 1
 348 04 4
 349 04 4
 350 02 3

351 05 5
 352 65 X
 353 43 RCL
 354 09 09
 355 75 -
 356 00 0
 357 93 .
 358 02 2
 359 08 8
 360 03 3
 361 01 1
 362 06 6
 363 01 1
 364 54)
 365 65 X
 366 43 RCL
 367 16 16
 368 85 +
 369 53 (
 370 00 0
 371 93 .
 372 00 0
 373 06 6
 374 05 5
 375 05 5
 376 01 1
 377 65 X
 378 43 RCL
 379 09 09
 380 35 1/X
 381 33 X²
 382 75 -
 383 00 0
 384 93 .
 385 03 3
 386 02 2
 387 08 8
 388 07 7
 389 07 7
 390 04 4
 391 65 X
 392 43 RCL
 393 09 09
 394 35 1/X
 395 85 +
 396 00 0
 397 93 .
 398 09 9
 399 07 7
 400 00 0

401 02 2
 402 04 4
 403 07 7
 404 54 =
 405 95 =
 406 42 STO
 407 17 17
 408 61 GTD
 409 06 06
 410 37 37
 411 53 (
 412 00 0
 413 93 .
 414 00 0
 415 04 4
 416 08 8
 417 09 9
 418 02 2
 419 06 6
 420 65 .
 421 43 RCL
 422 09 09
 423 33 X²
 424 75 -
 425 00 0
 426 93 .
 427 00 0
 428 03 3
 429 05 5
 430 08 8
 431 08 8
 432 05 5
 433 65 X
 434 43 RCL
 435 09 09
 436 85 +
 437 00 0
 438 93 .
 439 01 1
 440 02 2
 441 01 1
 442 07 7
 443 08 8
 444 54 X
 445 65 X
 446 43 RCL
 447 16 16
 448 33 X²
 449 75 -
 450 00 0

PROGRAM FOR PREDICTION OF CASE
(Three-Dimensional)

451 00 0
 452 93 . 0
 453 00 0
 454 01 1
 455 02 2
 456 09 9
 457 02 2
 458 02 2
 459 65 X
 460 43 RCL
 461 09 09
 462 33 X²
 463 75 -
 464 00 0
 465 93 . 0
 466 00 0
 467 07 7
 468 02 2
 469 04 4
 470 00 0
 471 05 5
 472 65 X
 473 43 RCL
 474 09 09
 475 85 +
 476 00 0
 477 93 . 3
 478 03 3
 479 03 3
 480 05 5
 481 02 2
 482 06 6
 483 05 5
 484 54)
 485 65 X
 486 43 RCL
 487 16 16
 488 85 +
 489 53 ()
 490 00 0
 491 93 . 1
 492 01 1
 493 03 3
 494 04 4
 495 08 8
 496 03 3
 497 02 2
 498 85 X
 499 53 RCL
 500 09 09

501 35 1/X
 502 33 X²
 503 75 -
 504 00 0
 505 93 .
 506 04 4
 507 04 4
 508 04 4
 509 02 2
 510 09 9
 511 06 6
 512 65 X
 513 43 RCL
 514 09 09
 515 35 1/X
 516 85 +
 517 01 1
 518 93 .
 519 00 0
 520 01 1
 521 06 6
 522 04 4
 523 06 6
 524 08 8
 525 54)
 526 95 =
 527 42 STD
 528 17 17
 529 61 GTD
 530 06 06
 531 37 37
 532 53 ()
 533 00 0
 534 93 .
 535 00 0
 536 01 1
 537 09 9
 538 09 9
 539 01 1
 540 65 X
 541 43 RCL
 542 09 09
 543 33 X²
 544 85 +
 545 00 0
 546 93 .
 547 00 0
 548 06 6
 549 03 3
 550 01 1

551 08 8
 552 65 X
 553 43 RCL
 554 09 09
 555 85 +
 556 00 0
 557 93 .
 558 00 0
 559 01 1
 560 01 1
 561 54 X
 562 65 X
 563 43 RCL
 564 16 16
 565 33 X²
 566 75 -
 567 53 +
 568 00 0
 569 93 .
 570 00 0
 571 00 0
 572 05 5
 573 06 6
 574 05 5
 575 65 X
 576 43 RCL
 577 09 09
 578 33 X²
 579 75 -
 580 00 0
 581 93 .
 582 00 0
 583 04 4
 584 06 6
 585 04 4
 586 65 X
 587 43 RCL
 588 09 09
 589 85 +
 590 00 0
 591 93 .
 592 00 0
 593 00 0
 594 04 4
 595 01 1
 596 85 X
 597 53 RCL
 598 09 09
 599 09 09
 600 09 09

PROGRAM FOR PREDICTION OF CASE
(Three-Dimensional)

601	53	(	651	00	0	701	02	2
602	00	0	652	93	.	702	01	1
603	93	.	653	03	3	703	04	4
604	01	1	654	02	2	704	01	1
605	01	1	655	07	7	705	03	3
606	02	2	656	05	5	706	07	7
607	03	3	657	09	9	707	04	4
608	03	3	658	01	1	708	01	1
609	65	x	659	01	1	709	65	x
610	43	RCL	660	85	+	710	43	RCL
611	09	09	661	01	1	711	19	19
612	35	1/X	662	95	=	712	45	YX
613	33	X ²	663	35	1/X	713	03	3
614	75	-	664	42	STD	714	75	-
615	00	0	665	19	19	715	01	1
616	93	.	666	53	(	716	93	.
617	04	4	667	00	0	717	04	4
618	04	4	668	93	.	718	05	5
619	04	4	669	02	2	719	03	3
620	01	1	670	05	5	720	01	1
621	65	x	671	04	4	721	05	5
622	43	RCL	672	08	8	722	02	2
623	09	09	673	02	2	723	00	0
624	35	1/X	674	09	9	724	02	2
625	85	+	675	05	5	725	07	7
626	01	1	676	09	9	726	65	x
627	93	.	677	02	2	727	43	RCL
628	00	0	678	65	x	728	19	19
629	02	2	679	43	RCL	729	45	YX
630	01	1	680	19	19	730	04	4
631	06	6	681	75	-	731	85	+
632	03	3	682	00	0	732	01	1
633	54	)	683	93	.	733	93	.
634	95	=	684	02	2	734	00	0
635	42	STD	685	08	8	735	06	6
636	17	17	686	04	4	736	01	1
637	43	RCL	687	04	4	737	04	4
638	15	15	688	09	9	738	00	0
639	65	x	689	06	6	739	05	5
640	43	RCL	690	07	7	740	04	4
641	17	17	691	03	3	741	02	2
642	95	=	692	06	6	742	09	9
643	54	)	693	65	x	743	65	x
644	93	RTN	694	43	RCL	744	43	RCL
645	75	LBL	695	19	19	745	19	19
646	10	F'	696	33	X ²	746	45	YX
647	53	(	697	85	+	747	05	5
648	42	STD	698	01	1	748	54	Y
649	18	18	699	93	.	749	65	x
650	65	x	700	01	1	750	01	1

PROGRAM FOR PREDICTION OF CASE
(Three-Dimensional)

```
751 22 INV
752 23 LNX
753 45 YX
754 43 RCL
755 18 18
756 33 X2
757 94 +/-
758 95 =
759 42 STD
760 19 19
761 01 1
762 22 INV
763 23 LNX
764 45 YX
765 43 RCL
766 18 18
767 33 X2
768 94 +/-
769 55 +
770 89 #
771 34 FX
772 75 -
773 43 RCL
774 18 18
775 65 x
776 43 RCL
777 19 19
778 95 =
779 54 )
780 92 RTN
```