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THE USE OF LASERS FOR THE

PRODUCTION OF SURFACE ALLOYS

by

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Submitted in Partial Fulfillment

of the Requirements for the

Degree of Master of Science

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June, 1964

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Department of Mechanical Engineering, May 22, 1964

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Table of Symbols

A   area

C   capacity

c   specific heat

k   thermal conductivity

R   laser spot radius

r   effective distance into material

Q   laser beam power

T   temperature

t   time

V   voltage

α thermal diffusivity

λ wave length

ρ density

Subscripts

b   boiling

f   final

i   initial

m   melting

ABSTRACT

This thesis attempts to explore some aspects of the use of lasers in material forming. The object of a number of experiments was to demonstrate the feasibility of the use of lasers in the production of surface alloys with unusual properties. Two basic techniques were employed. The first was to coat a metal with an alloying element and then using the laser beam to fuse them together. The second method was to alloy two metals and then try to form a metastable phase with the laser beam. It was found possible to alter the carbon content of steel, to fuse a thin layer of tungsten, tungsten carbide, and titanium carbide to a steel surface, and to form titanium carbide on a titanium surface. The results of an experiment to form a metastable solid solution in a copper-silver alloy were not conclusive. In order to better understand the physics involved some theoretical discussion and background material is included.

A thermal analysis establishes the controls required to produce various effects. Extremely rapid heating and cooling rates may be achieved. A surface may be heated at a rate of 10^{10} degrees /second, and any opaque material may be vaporized.

Introduction and

Thermal Analysis

The recent development of the laser has opened
the door to many new areas of research. This device, as
well as being a field of study itself, has certain
unusual properties which make it a potentially useful
tool in many other areas of scientific endeavor. One
area of interest for the mechanical engineer is the
production of new materials or finding easier methods
of producing known materials with unusual properties.
A laser may be most easily adapted to the production
of special alloys on the surface of some more common
materials.

Some consideration should be given to the phe-
nomena involved when the laser beam strikes a metallic
surface and the equations governing the temperature
history within the metal.

From classical electrodynamic theory the electro-
magnetic energy is absorbed exponentially with a dis-
tance constant on the order of 100 $\overset{\circ}{A}$ for conductors.
The energy is first absorbed by the conduction elec-
trons and then after some delay the electrons give up
their energy to the lattice structure. It is believed
that in simple metallic conductors the dominant decay
mode is through acoustic phonons, the relaxation times
being on the order of 10^{-13} seconds. Since the energies
of the acoustic phonons that result are on the order of
10^{-2} to 10^{-3} ev and the energy required to break a metallic
bond is around 1 ev, it would take on the order of

seconds
10^{-10} to 10^{-11} to break a metallic bond. With dielectrics and transition elements this is not necessarily the case. Here it is possible for the electrons to remain in an excited state for some period of time— on the order of 10^{-6} to 10^{-7} seconds. During this time the energy moves with almost zero velocity. Since a single laser spike may be on the order of 10^{-8} seconds, there may be a considerable difference in behavior at the surface of different metals under certain conditions.

At distances into the material large compared to the absorption depth and relatively long laser pulses, the temperature history would be governed by the standard conduction heat flow equations. However, since phase changes may take place, the thermal diffusivity is not constant, the heat source is not constant, etc, an exact calculation becomes hopeless. The pertinent generalized heat flow equations are briefly developed in Appendix A.

If all properties remain constant, the temperature distribution would be described by

$$T - T_i = \frac{Q}{8\pi k (R+r)} \, erfc\left[\frac{r}{2\sqrt{\alpha t}}\right]$$

or
$$T - T_i = \frac{T_0 R}{R+r} \, erfc\left[\frac{r}{2\sqrt{\alpha t}}\right] \quad if \quad \frac{Q}{8\pi k R} > T_0$$

The most interesting result of these equations
is that for a given metal, the condition for vapor-
ization is specfied by the ratio of Q/R and not by
the power density. In other words the quantity
$T_b kR/Q$ must be less than a constant. This constant
may be derived exactly for an ideal laser beam and
would be around .04. Since the laser beams are not
exactly ideal,but are fairly similar, a reasonable
value could be established experimentally. With a
particular laser, if the critical value is found for
one material, the effect on all other materials may be
found.

The value of k varies by more than a factor of
10 between metals. This means that if a given laser
can just melt the surface of silver, it will have
no trouble in melting tungsten, be just able to
reach the boiling temperature of aluminum, and with
out difficulty reach the boiling temperature of steel.
It is assumed that boiling occurs at one atmosphere
pressure.

As far as the effect of vaporization is concerned,
the evaporization rate is the most important factor.
This would be

$$B \simeq \frac{(Q/A - k \frac{dT}{dx})}{h_{lv}}$$

therefore, boiling cannot begin until $k\frac{dt}{dx}$ equals Q/A.

In the range of concern, erf (w) is nearly equal to w. This means that that the time to evaporization is nearly

$$\frac{(T_b kA)^2}{\alpha Q^2}$$

and the depth at which material is melted in this time is approximately

$$\frac{(T_b - T_m)Ak}{2Q}$$

or more exactly for large depths

$$\frac{-2C_1 + 1\sqrt{1-4C_1}}{2C_1}$$

where

$$C_1 = \frac{A(T_b - T_m)}{2Q}$$

To illustrate the significance of all this, consider four metals; aluminum, brass, steel, and silver. The steel would vaporize after 10 microseconds and be melted to a depth of 2.5 microns. The brass would vaporize after 25 microseconds and be melted to a depth of 10 microns. The aluminum would vaporize after 25 microseconds and be melted to a depth of 13 microns. The silver would vaporize after 50 microseconds and be melted to a depth of 25 microns. The temperature distribution at the surface of the four metals is shown in figure 1.

These figures illustrate qualitatively rather than quantatively the behavior of various metals. With a real laser beam both Q and R vary considerably during a pulse. The output power roughly proportional to the input power once laser action begins; however, the spot radius is a function of the degree of coherence between various parts of the ruby, and can vary considerably during a pulse. This would account for the large variation in results obtained when Q/R is near its critical value.

For efficient material removal it is desired to to use a high quality ruby (to reduce the variation in R) run at a Q/R just below critical and a increase in Q/R at the very end of the pulse. A circuit for doing this is shown in figure 1-c.

There are several limitations on the above analysis. The first is that it does not necessairly apply to a giant laser pulse, although some correlation may be obtained for simple conductors by correcting the boiling temperature to the increased light pressure. The second is that it does not apply to materials that have a very long absorption depth. The third is that it does not apply if the material thickness is not much greater than the melting depth.

The analysis may be extended to thin materials by assuming T_b at the surface and using the standard solutions for thin slabs.

Probably the easiest method of finding the temperature distribution after the laser pulse has ended would be to adapt the equation for a unit heat source.

$$T = c_1 (t+T)^{-3/2} e^{-\frac{r^2+c_2}{4\alpha(t+T)}}$$

where the constants c_1, c_2, and T are chosen to most closely fit the distribution at the end of the pulse.

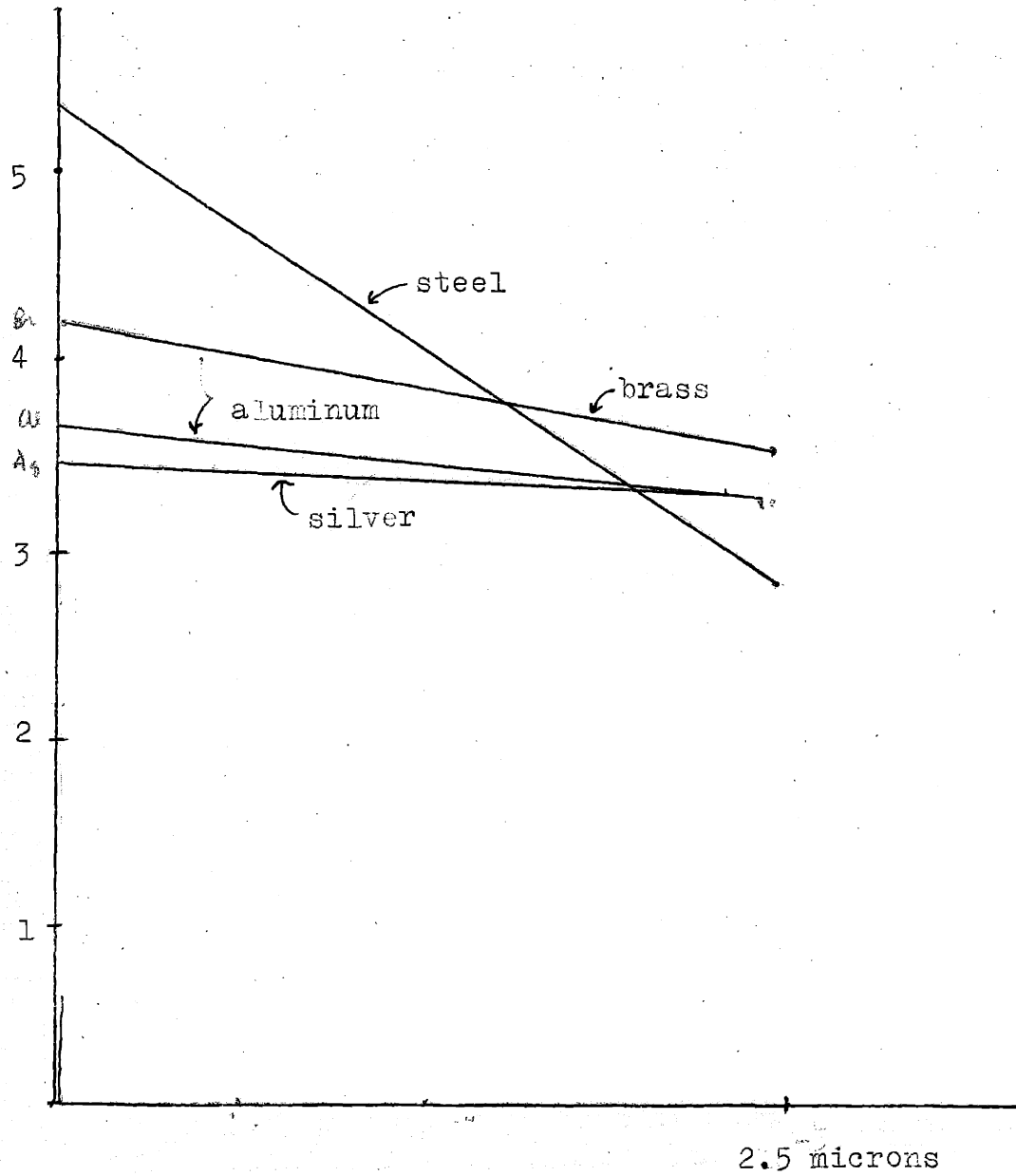In the following experiments the ability of a laser to generate almost any temperature necessary to melt materials will be used as a tool to form surface alloys.

Figure 1 (a) Temperature distribution
near the surface of 4 different metals at
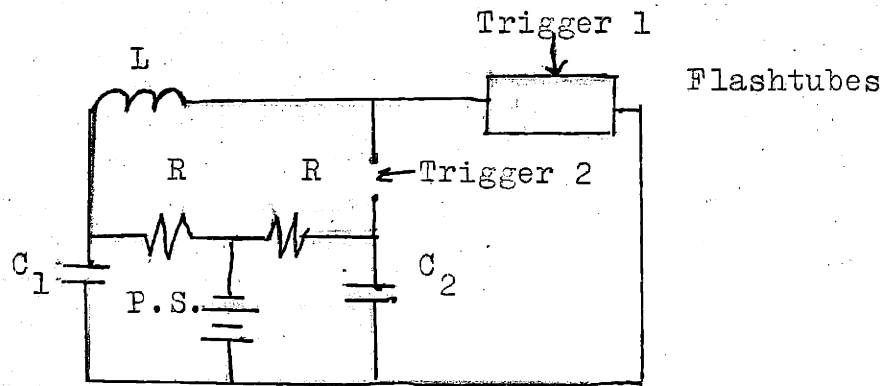the time evaporation begins.
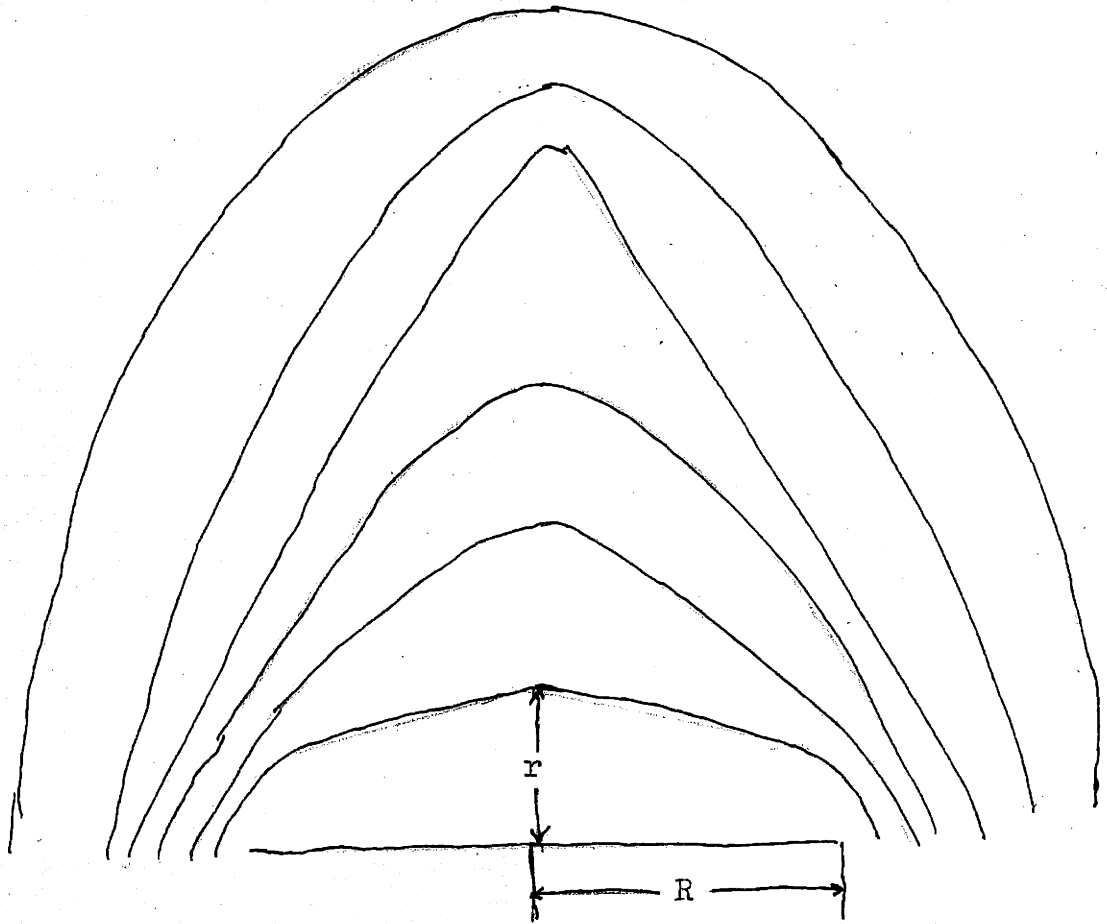
Figure 1 (b) A rough approximation of lines
of constant r. These were made from ob-
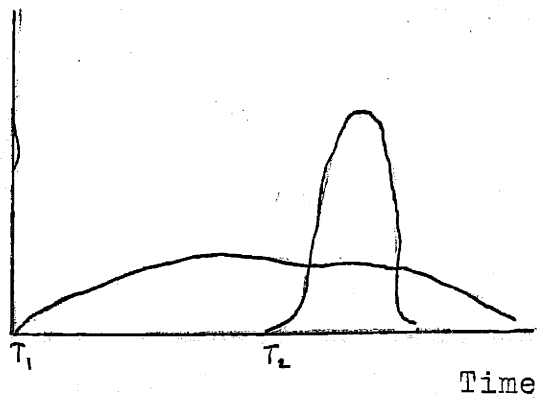servations of holes produced.

Figure 1 (c) Circuit for producing deep holes
   with a laser. Trigger 2 is fired with the
   necessary time delay with respect to trigger 1.
   It is desired to keep the output power just
   below critical for as long as possible.

EQUIPMENT

The laser used was a $2\frac{1}{2}"X\frac{1}{2}"$ .04% chromium 60 growth angle ruby rod with uncorrected flat ends. The ends were coated with 99% and 80% reflective dielectric monolayers. Six series connected EG&G FX 100 flash lamps were used as a pump source. The power supply consisted of a 5 kv source, a 90 mfd storage capacitor, and a limiting inductor. The inductor was 100 turns of number 16 wire at 2 inches in diameter. The flash tubes are triggered with a 30 kv pulse. The laser, power supply, and schematic are shown in figures 3, 4, and 5.

The laser beam was focused with a 1 inch focal length microscope objective. It was necessary to remove the bottom lens of the objective in order to avoid its being damaged.* This was found by experience. The focus was adjusted by focusing the light from a flashlight through the center tube with the ruby removed.

The ruby was mounted on the end of a brass rod by means of an aluminum collar in order to facilitate handling. When the ruby is placed in the center tube care should be taken not to scratch the reflective coating.

The flash energy may be calculated from the formula

$$E \quad \tfrac{1}{2}CV^2$$

and should not go much over 800 joules, since there is a rapid decrease in flashtube life with increased power.

* The power density is sufficient to blacken the cement between the lens sections.

It should be noted that the flashtubes are polarized
and the end with the red dot is positive. The flash-
tubes may sometimes fire spontaneously, usually when a
charge is left on the reflector. The ruby should be
cooled as much as possible between firings. This may be
done by washing it with alcohol.

The laser was mounted on a milling machine so that
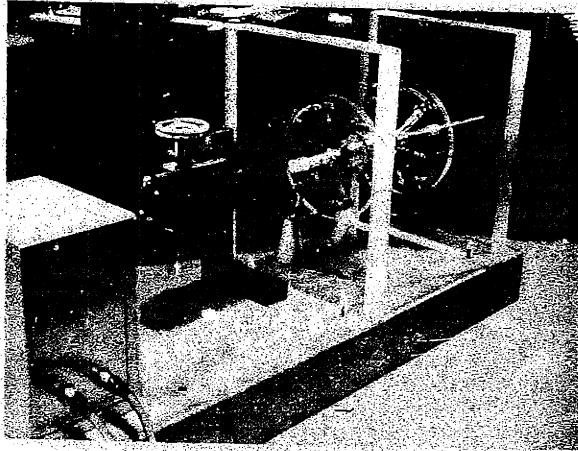some fine control could be obtained in the positioning
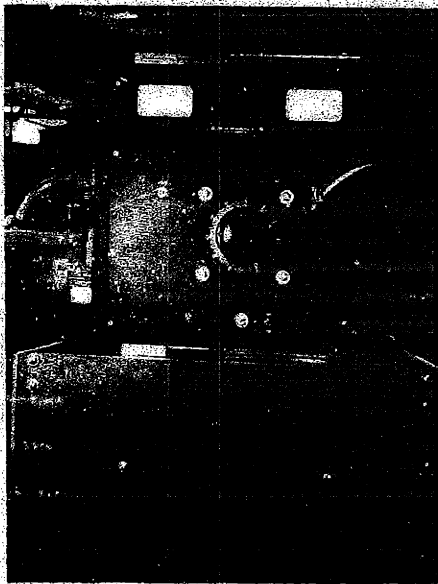of the work,

Figure 2   The laser
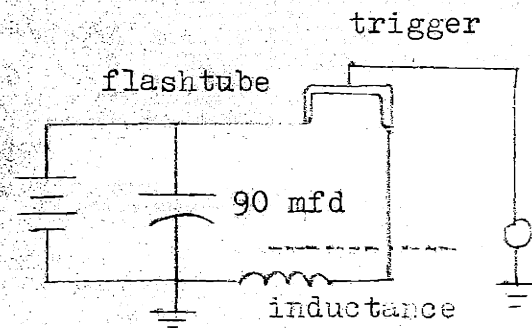

Figure 3   Power supply

Figure 4   Schematic

Experiments

A number of experiments were performed in line
with the overall objective of demonstrating the use of
the laser as a research tool in material processing.
These experiments related to the technique for altering
the surface composition and the formation of metastable
alloys.

The small areas involved were a severe handicap in
making quantitative measurements. The only easily meas-
ured quantity was hardness; however, some very rough
surfaces prevented even hardness measurements. In some
cases it was possible to measure composition with an
electron probe microanalyzer. A good deal of work was
confined to visual observation of the result.

The first experiments were with plating gold onto
a steel surface. This experiment was to determine the
feasibility of several methods of bonding such metals
together in the simplest manner possible. It was also
hoped that a sufficient area could be covered without
excessive surface roughness in order to make coefficient
of friction and wear tests.

The first method tried was to simply place some
gold foil against the steel and hit it with a laser
beam. A hole could easily be melted in the foil, how-
ever, no trace of gold could be found on the steel.
Since the gold was being scattered, it was felt that
sandwiching it between the steel and a coverglass would
contain it. This resulted in a few specks being deposited

on the steel. The steel was then given a 5 micron thick gold plate. The laser beam removed all traces of gold where it hit. Finally, gold foil was sandwiched between gold plated steel and a coverglass. In this case it was possible to melt the steel and yet leave some gold where it was melted. Suitable specimens could not be produced.

A number of experiments were run on altering the carbon content of steel. The rapid cooling that occurs after a laser pulse ends will bring steel to a fully hard condition. Since the maximum hardness is a function of carbon content, it is possible to measure changes over some range of carbon content with a small hardness tester. Unfortunately it is impossible to measure the carbon content of steel with an electron microanalyzer.

Several common types of steel were tried under different conditions. It was found that mild steels could be fully hardened when coated with a carbon containing fluid, such as mineral oil or rubber cement. The carbon penetrated up to 20 microns into the steel. No change in carbon content could be obtained by coating the surface with a thin film of powdered carbon. When a colloidial graphite suspension was used, the steel appeared to have a large amount of carbon deposited at the grain boundaries. With a high carbon alloy steel the maximum hardness could be achieved with no carbon addition, and the addition of carbon also produced carbon at the grain boundaries.

The steel hardness that was measured with a 50

gram load on a Durimet small hardness tester went as
high as 1500 HV. However, this could not be consis-
tantly duplicated and measurements of 1000 HV to
1200 HV appeared to be more typical. The maximum hard-
ness seemed to occur several microns below the surface,
but this was somewhat difficult to judge as the sur-
face was not very smooth. Figure 5 shows the change in
hardness.

The structures produced were a fine grain (ASTM
size 14 to 15) martensite over most of the area. There
was a band about 25 microns wide around the periphery
in which the carbide and ferrite portions of the pear-
lite grains recombined,and yet the grain boundary with
the ferrite matrix was unchanged. In some cases a series
of concentric rings were observed. This is believed to
be the result of the light pattern from the laser. At
a depth of around 25 microns the structure appeared
to be a tempered martensite as shown in figure 6.

At first some difficulty was encountered in trying
to see the grain structure of the martensite. It was
found that a long etch with 5% picric acid, a high
magnification, and a relatively low level of illum-
ination in the microscope is required for seeing the
microstructure. It may also be seen by a slight anneal-
ing which will allow some carbide to precipitate at the
grain boundaries. Before the grains were seen, a back

Laue pattern was made of the affected area of an oil hardenable steel. Since the x ray beam was .05 inches in diameter, it was necessary to prepare the area by repeated shots. The Laue pattern is shown in figure .

Another experiment was run to determine if larger atoms could be diffused into the steel in order to alter its properties. Tungsten was chosen, because it was thought that its high melting point and high strength might impart some unique surface properties. The first method tried was to coat the surface with potassium tungstate and cover it with a coverglass. There was no appearant effect on the steel, possibly because the powder was not fine enough as well as there being too much energy required to break the chemical bonds. The second method tried was the use of pure powdered tungsten. This was held against mild steel with a coverglass. The result is shown in figure 8 . It was thought originally that the black area was powdered tungsten fused to the steel and the white islands were plain steel. However, this area was analyzed with the electron microanalyzer, and it was found that there was no tungsten in the black area and that sections of the white area were almost pure tungsten with various intermediate compositions in the rest of the area. The x-ray intensity from the tungsten along the line in figure 8 is shown in figure 9 . Careful examination shows that the pure tungsten may be

distinguished from the surrounding matrix, because it is lighter in color. Unfortuately this difference did not photograph well. The layer was too thin for the hardness measurements to have any meaning.

Several experiments were run on methods of forming surfaces with carbides of tungsten and titanium, since they are quite hard. It was found that with the sandwich method mentioned above, carbides could be fused to a mild steel surface. The titanium carbide formed a continuous solid more readily than the tungsten carbide. Photographs of some of these attemps are shown in figures 10 and 11, and the electron probe outputs for tungsten taken along the lines indicated are shown in figures 12 and 13 .

Titanium carbide was also formed directly on titanium by coating the metal with a colloidial graphite suspension. The layer of carbide appeared to be covered with a layer of carbon.

It was found that with 2024 T3 aluminum, it is po possible to determine where the laser beam struck by etching with 1% NaOH or .5% HF. The area affected will turn darker. The material also exhibited shrinkage cracks; see figure 14.

The experiments in forming metastable compounds were with an alloy of copper and silver. From the theoretical standpoint copper and silver should form a continuous solid solution,* however, in practice they
* That is the Hume-Rothery criteria are satisfied.

have a eutectic. In recent years the solid solution
has been reported by Duwez et al. It was formed by
shooting a small drop of molten metal against a large
heat sink forming a film 1 to 50 microns thick. Cooling
rates have been estimated at two million degrees per
second[2].

The first attempt was to plate silver with copper
and hope for some intermediate alloy being formed.
This method did not appear to be satisfactory when
inspected with a microscope; therefore, it was not ana-
lyzed with the electron probe.

The second attempt used a copper-silver alloy. At
one point it was cooled to nitrogen temperature, but
this caused more problems than detectable improvement
and was abandonned.

The effect of the laser beam was to produce a
tinted circle 300 microns in diameter with a small
very irregular area of dark craters and a few scattered
craters around 10 microns in diameter, see figure 15.
The electron probe was run across three of these areas
and the results are shown in figures 16 and 17 . The
relative composition may be very roughly calculated by
taking the ratio of copper intensity (bottom trace) to
the total intensity of both traces. This may be done,
because the standard intensity of the two metals is about
the same and the characteristic lines are far apart. This
indicates a composition of 25 to 35 weight percent copper
which is 35 to 50 atomic percent.

Discussion

Although these experiments did not deal directly
with temperature measurements, the observations made
concerning relative effects on different metals were
in close agreement with what the theory perdicts.
The importance of the temperature theory in these
experiments is that almost any temperature necessary
for melting a material may be generated by means of a
laser beam. The only experiment in which the power was
less than adaquate was the attempt to form a metastable
copper silver alloy. A considerable improvement could
be made with a more versital laser and power supply.

Another problem was the difficulty in analysis of
the specimens; espebially when only a very thin surface
layer was involved. The small hardness measurements
are meaningless for small layers. The electron micro-
analyzer requies the material to be uniform 1 micron
in diameter and several microns deep, depending on the
material, for the measurements to have any meaning.

If the desired specimen could be produced on a
thin film, a transmission Kossel pattern may be made
the electron microanalyzer. Reflected Kossel patterns
could be made with a special adapter, however, one was
not available. It

X-rays may be used to distinguish amorphous from
crystaline materials by means of a reflected Laue
pattern. With a single crystal a Laue pattern is a

achieve the desired effect. For these reasons a cover-
glass is always necessary for tungsten, tungsten carbide,
and titanium carbide on steel; however, in theory it
is not necessary for gold on steel.

The bonding of gold to steel experiments could be
very much improved with more control of the laser output.
The thermal analysis shows that the focal length of the
lens should be about 10 times as long and the laser
output pulse around 400 microseconds to melt to 2 microns
the steel. These numbers are only intended to indicate
the right ballpark. The exact requirements depend on
a number of variables, such as pulse shape, and should
be determined by experiment. In this case the area
covered in one shot would be 100 times as great and a
surface suitable for friction and wear measurements
could easily be produced.

It was noted that the titanium carbide fused into
a more continuous lump than the tungsten carbide. This
may have been the result of a higher thermal diffusivity
of the titanium carbide. The melting temperatures are
almost the same. The tungsten carbide in one case did
distribute itself in a reasonably flat surface. It is
believed that this was a combination of coverglass
pressure and beam pattern.

The electron microanalysis of the copper-silver alloy indicated that the sample had less copper than intended. It seems that the β phase formed only a thin film at the α grain boundaries. Visual observations had been somewhat confusing. This would make it impossible to get a pure β phase indication and would account for the small spikes in copper concentration which go above the amount expected in the α phase.

When the laser beam hit, some of the α grains were melted from the surface, thus the β phase was exposed and melted. This would account for the cellular pattern in the affected area as well as the increased copper concentration.

It is suggested that if the experiment were repeated, a fine grain eutectic composition be used to start with. In order to increase the cooling rate, a shorter focal length lens should be used and the laser should be operated at lower power. This would reduce the area, and reduce the error caused by vertical segregation.

The pressence of a metastable solid solution could be verified with a reflected Kossel pattern or by examination of the microstructure with an electron microscope. The expected grain size is less than 1 micron. Once the grains are observed, the specimen could be annealed slightly to see if the specimen reverts to a normal eutectic structure.

In the present case it is possible that there was a thin layer of β phase over α phase, which would also produce the intensity pattern observed. The layer did not appear as red as β phase would have been expected; however, looks in this case could be very misleading.

A number of other metastable alloys have been reported by Duwez. Some of these are easier to form than the copper- silver solid solution. Once the techniques for producing and analyzing the alloys is developed, there should be little trouble in testing a large number of possibilities. Also reported are amorphous structures in such materials as Au-Si, and very fine grain sizes (ASTM 21 in copper).

Another line of research could be directed to the changes in aluminum alloys such as 2024 T3 when hit with a laser beam. These changes were evidenced by the reaction of the area to 1% NaOH or .5% HF. The effect penetrated at least .005" into tho the metal. This effect would be useful in determining the critical value of Q/R for aluminum, as well as lines of constant r.

There are many other applications for the employment of lasers. For instance they could be used for the removal of the surface layer of cesium from tungsten in thermionic emmission experiments. At the present time a good deal of work has to be done on establishing the relationship of various parameters on the control of the laser beam
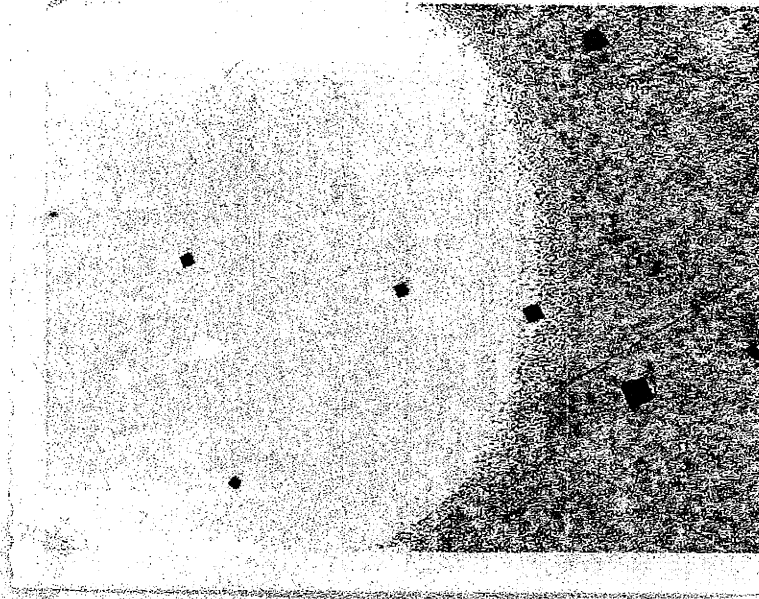
Figure 5   Hardness change in alloy steel. The
    diagonals of the small indentations are about
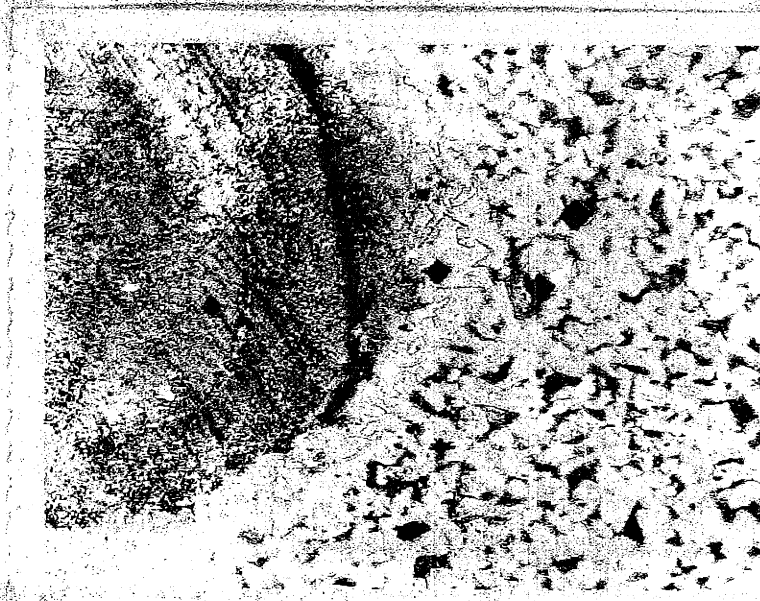   10 microns

Figure 6   Changes in 1018 steel 50 microns below
    surface. Tempered martensite surrounded with
    partially transformed pearlite.
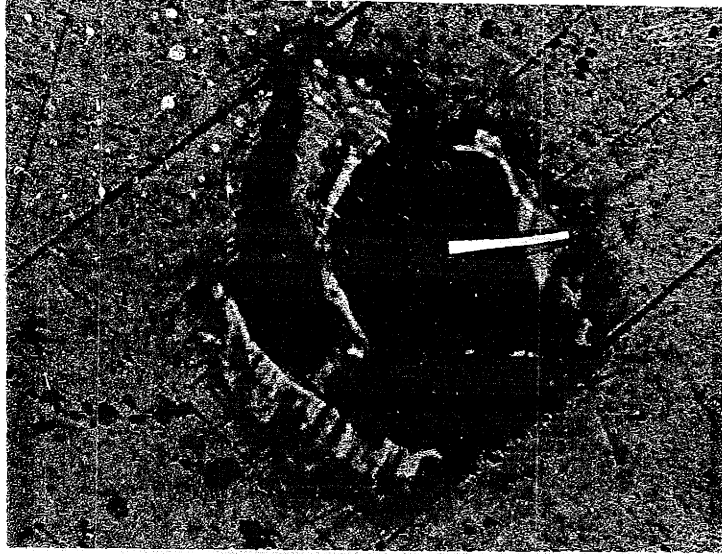
Figure 8   Tungsten fused to steel surface. The
      lighter sections of the islands in the dark
      area are pure tungsten. The white line indicates
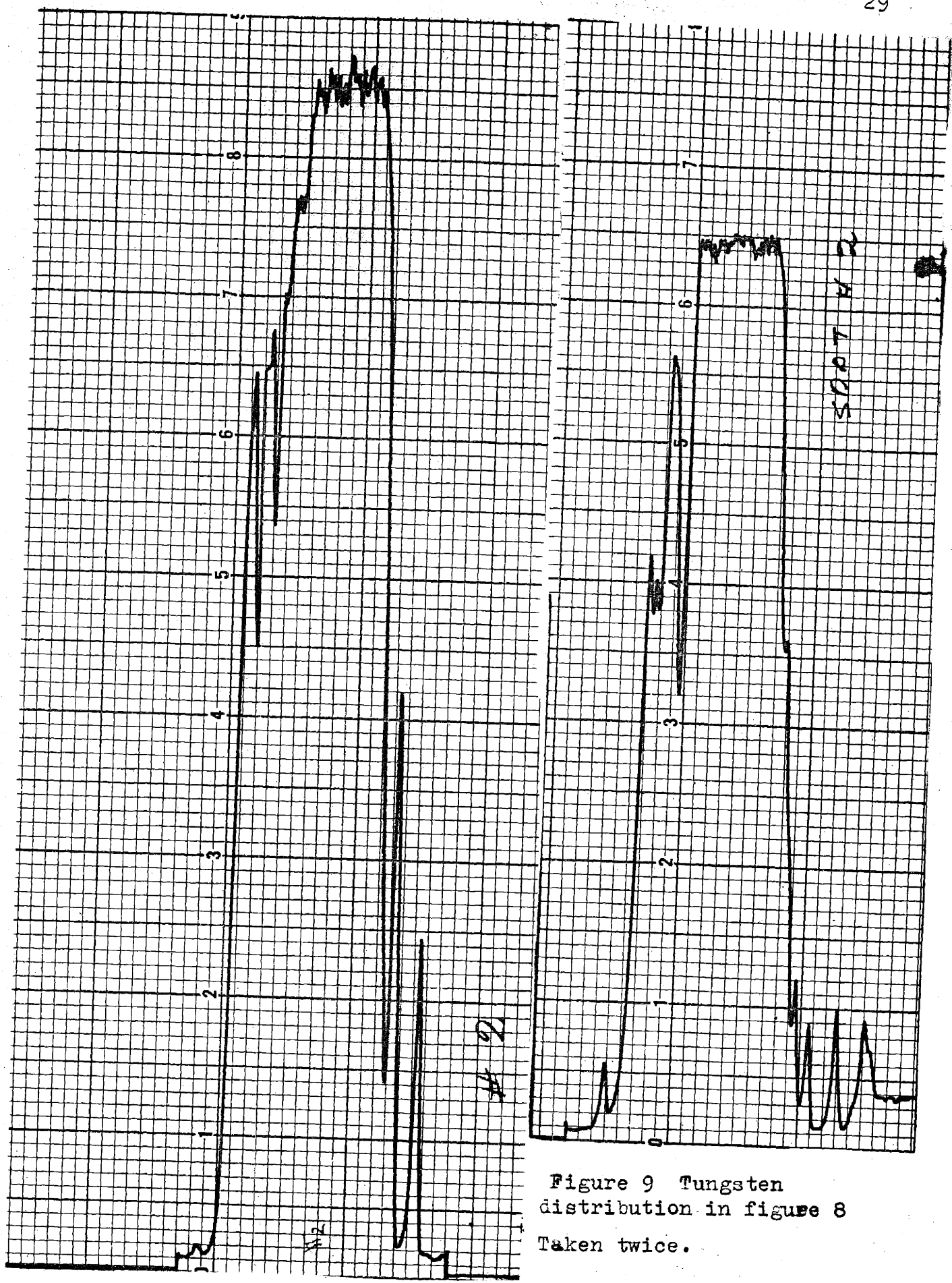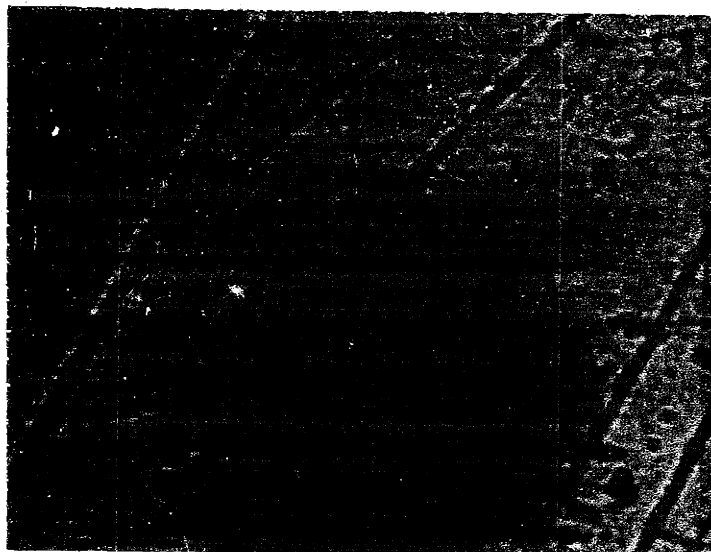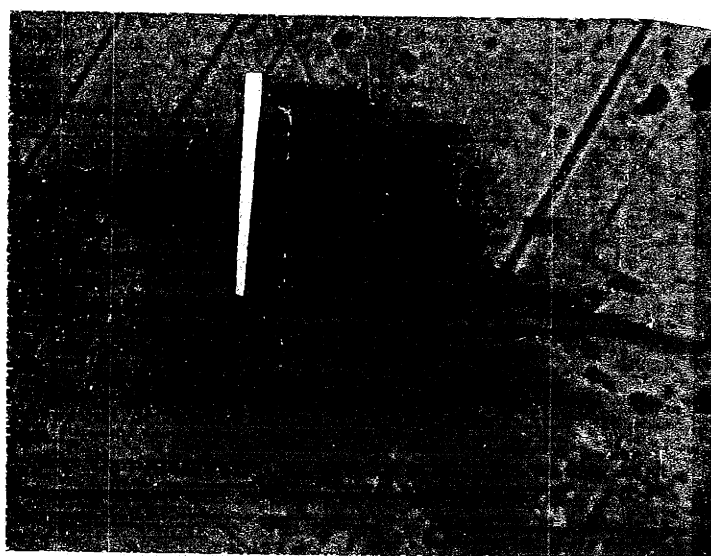   the path taken with the electron probe.

Figure 9   Tungsten
distribution in figure 8

Taken twice.

a

b

Figure 10 (a) Tungsten carbide distributed
fairly evenly in dark area. Electron probe trace
is figure 12. (b) Tungsten carbide fused into a
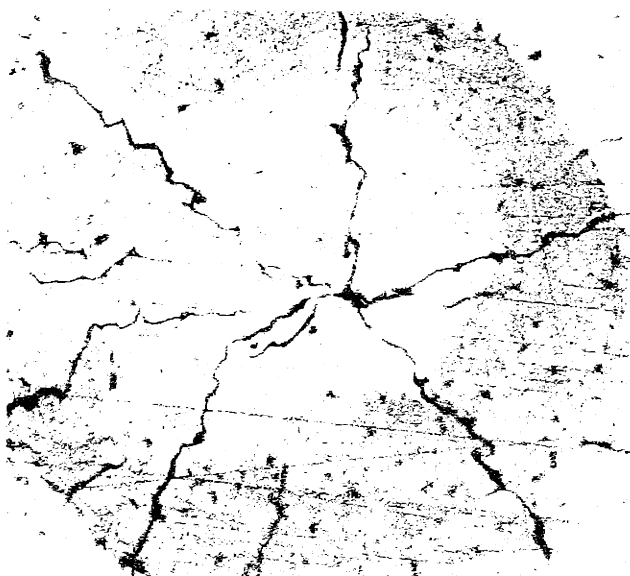lump. Electron probe trace is figure 13.
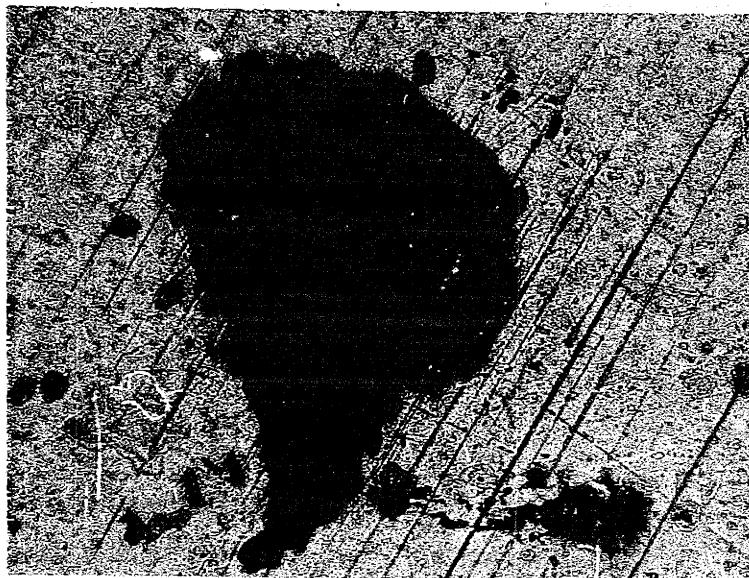
Figure 11 Titanium carbide fused to a steel surface.

Figure 14 Aluminum area hit with a laser beam and etched with 1% NaOH. Cracks are about 100 microns deep.
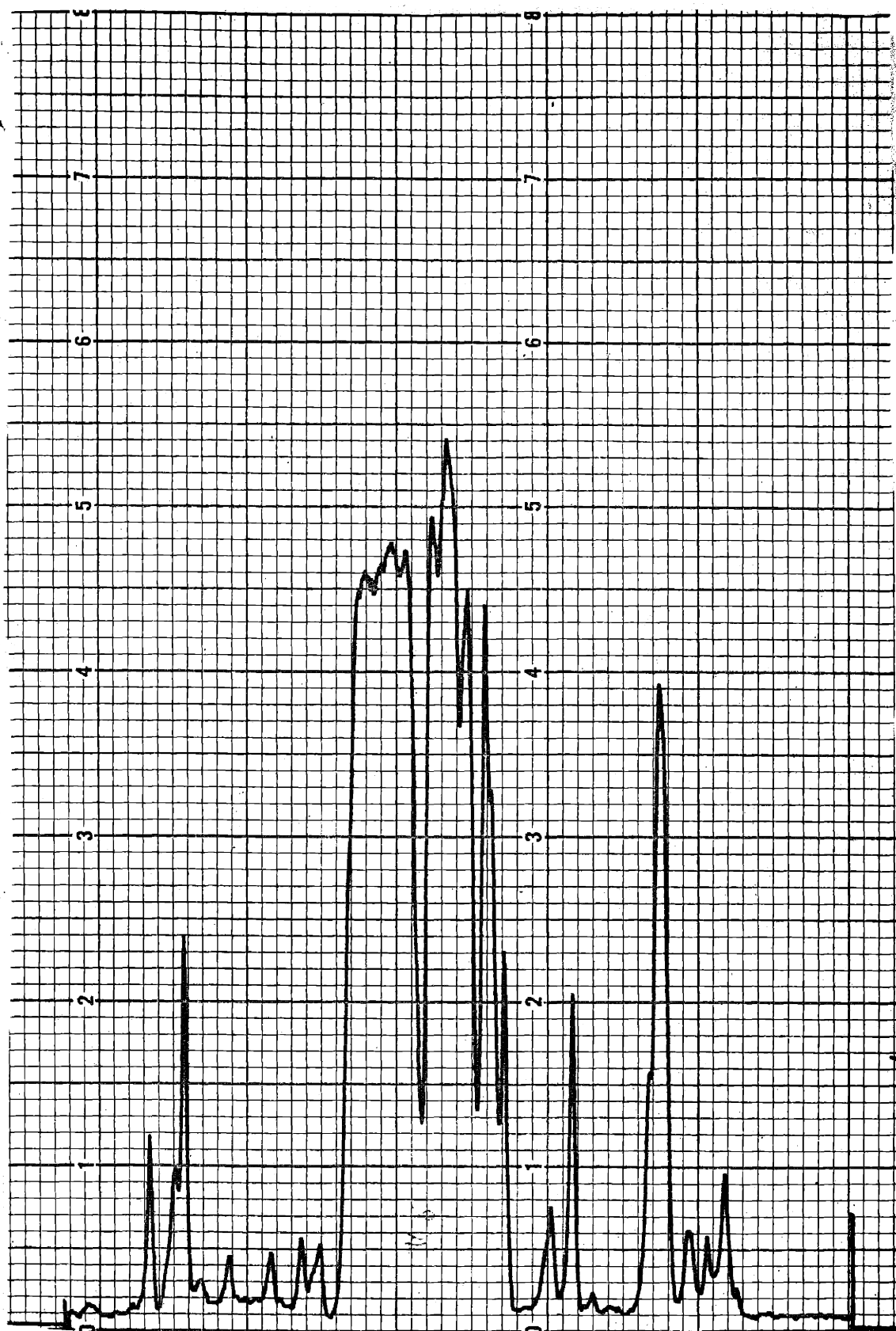
Figure 12   Tungsten trace in figure 10 a.
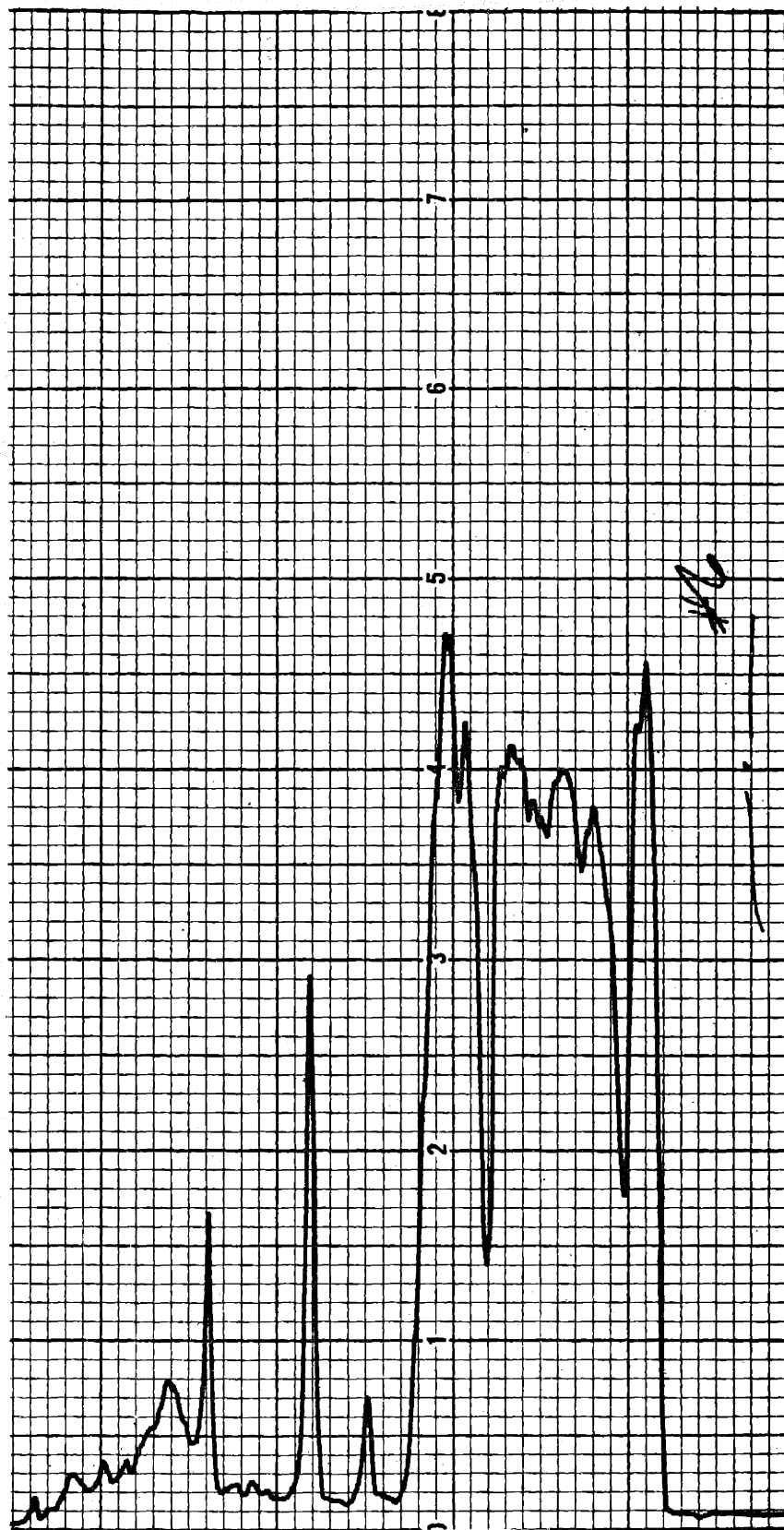
Figure 13 (a)

Figure 13 (b) Tungsten distribution in figure 10 (b)

Figure 15 Area of copper-silver alloy treated
with a laser beam. The area affected is in
the lower half of the photograph. The high
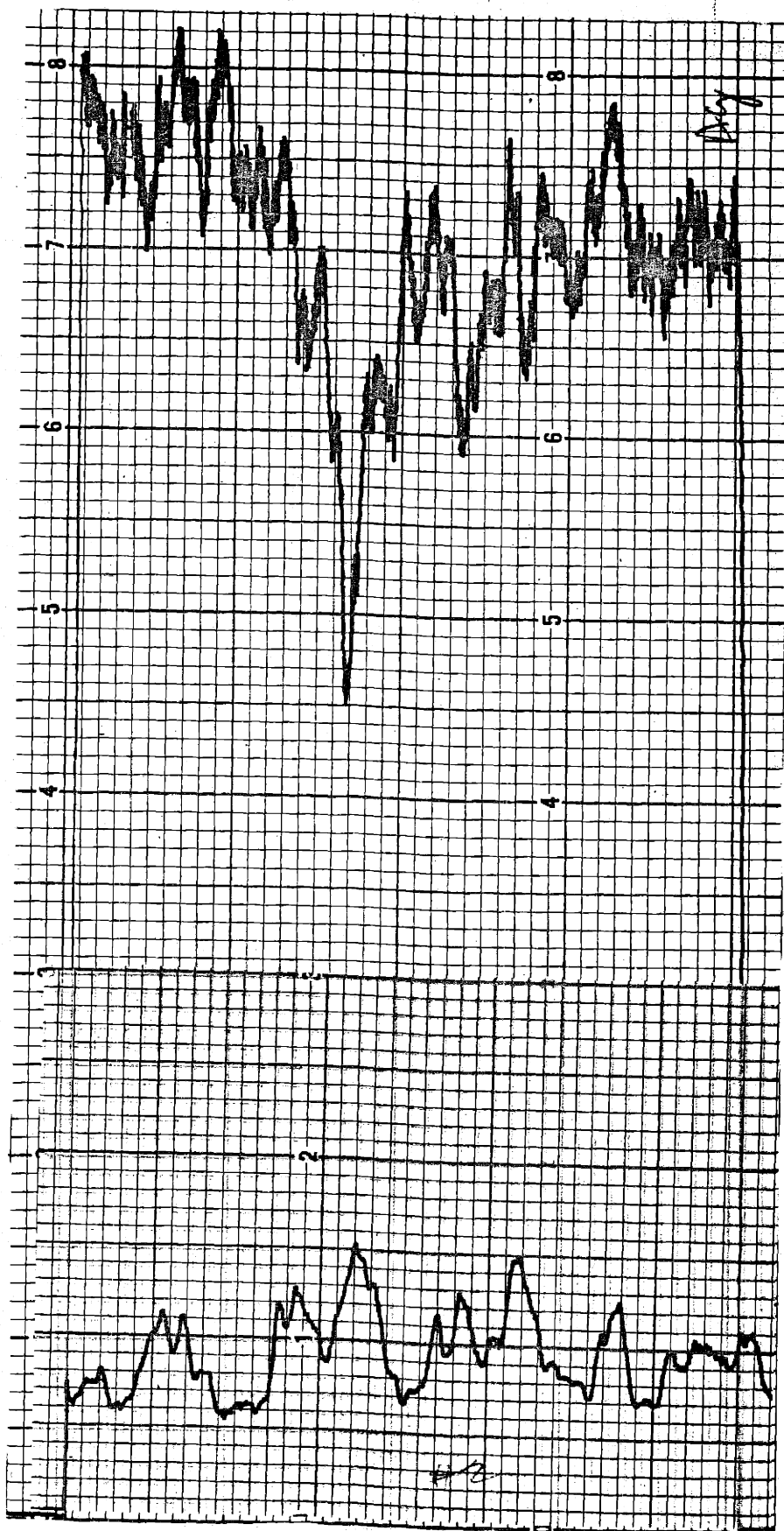copper concentration is in the black areas
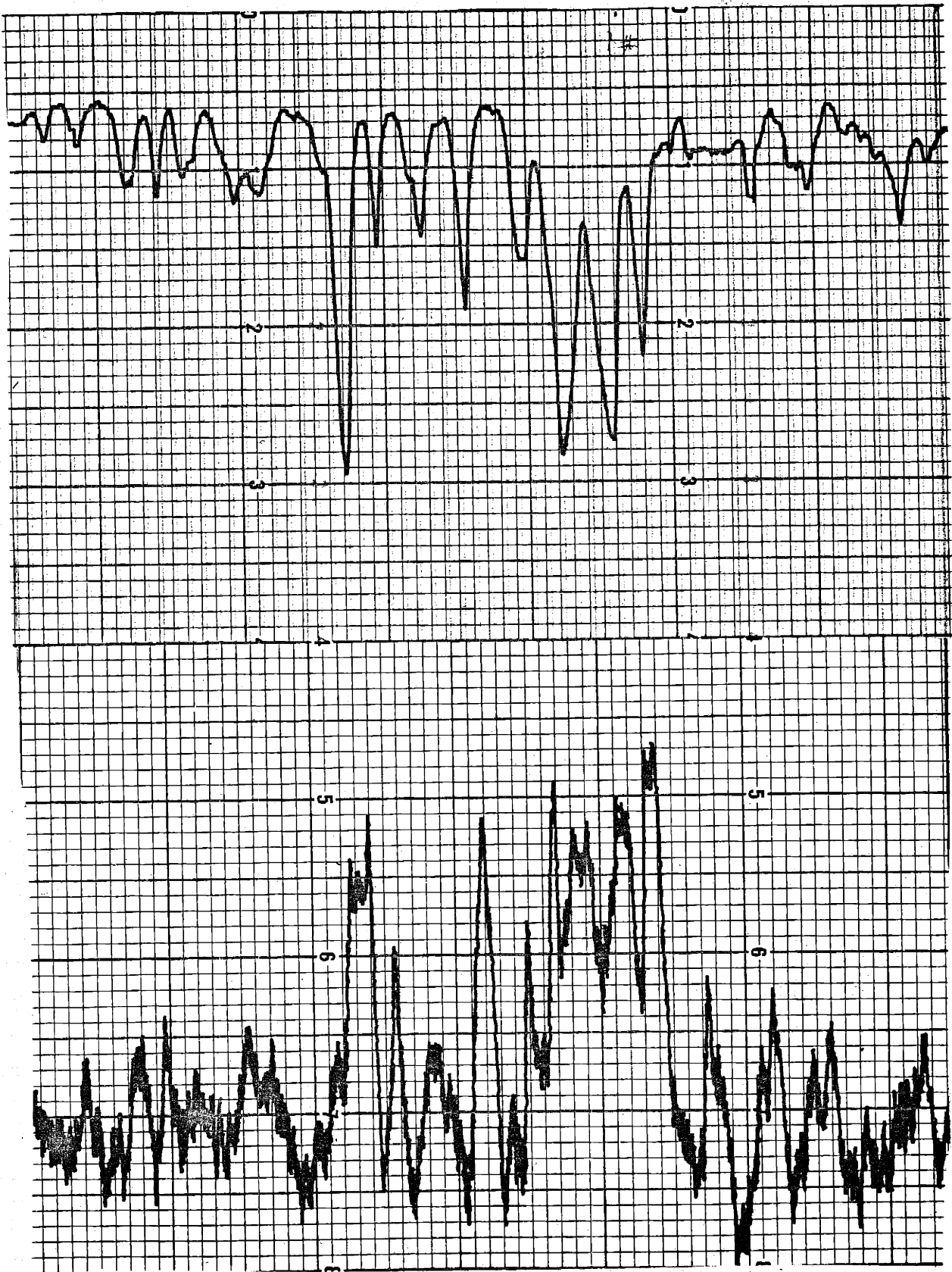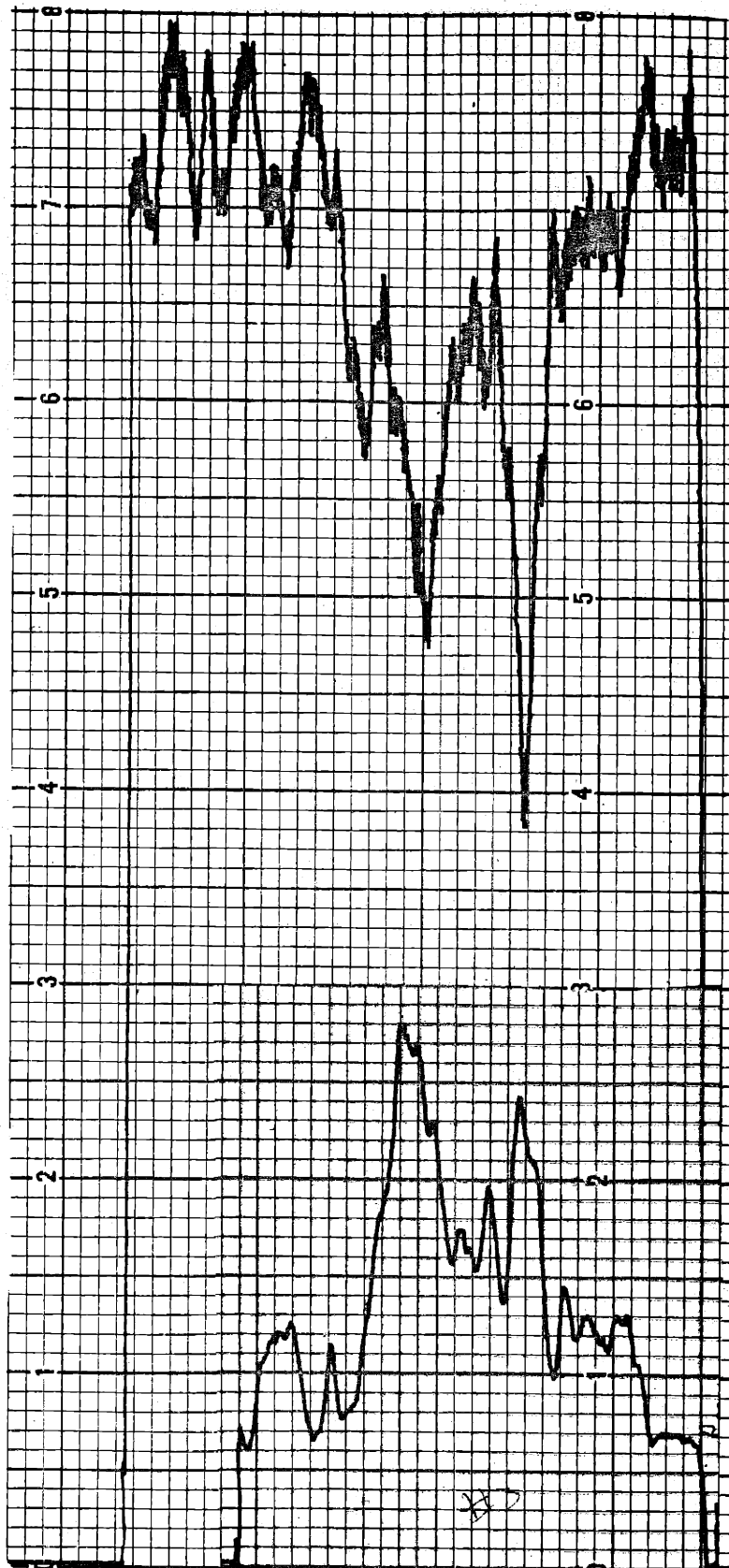within the light area.

Figure 26 a

Figure 16 b

Figure 16 c Copper silver alloy analysis. The upper
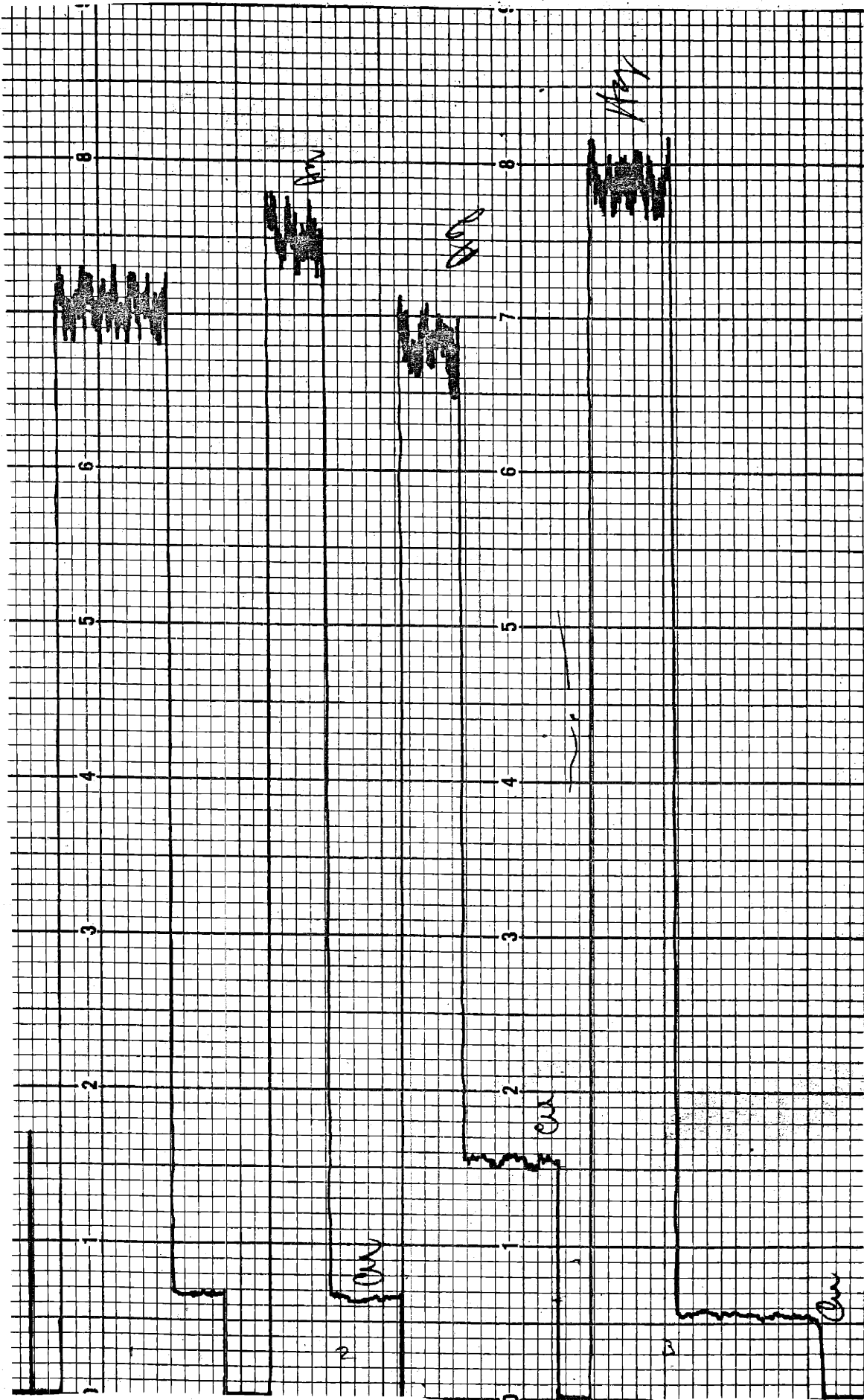trace is the silver intensity.

Figure 17 Copper silver alloy outside of affected area.

Appendix A

Development of Temperature Equations

Assume that no melting occurs, constant properties, and a point heat source of strength $Q(t)$. It has been shown by others that the temperature at the present time t due to the source at time t_1 is

$$\frac{Q(t_1) \, d\tau_1 \, e^{\frac{-r^2}{4\alpha^{2/2}(t-\tau_1)}}}{\rho c \left[4\pi\alpha^{2/2}(\tau-\tau_1)\right]^{3/2}}$$

where $Q(t_1)$ to the amount of heat emitted by heat source $Q(t)$ in the time interval $(t_1, t_1 + dt_1)$

If the source is a step function starting at t_0

$$T = \frac{1}{\rho c} \int_0^\tau \frac{Q(\tau) \, e^{-\frac{r^2}{4\alpha^2(t-\tau_1)}}}{\left[4\pi\alpha^2(t-\tau_1)\right]^{3/2}} \, d\tau_1$$

This may be evaluated by a change in parameter

$$S^2 = \frac{r^2}{4\alpha \, (\tau-\tau_1)}$$

$$dS = -\frac{1}{2}\frac{r}{2\alpha}(\tau-\tau_1)^{-\frac{3}{2}} \, d\tau_1$$

Since as $r \to 0$ the temperature $\to \infty$, it would be advisable to modify this equation. The first thing would be consider the temperature response of a semi-infinite body exposed to a constant temperature. This would be

$$T - T_i = (T - T_f) \; erfc\left(\frac{x}{2\sqrt{\alpha t}} \right)$$

The maximum T_f could be is the boiling temperature.

Consider that the spot the energy is distributed on is roughly a hemisphere; then use the spot radius in equation to calculate the surface temperature. Only if it is less than T_b should it be used. The result is

$$T = \frac{Q}{8\pi \; k(R + r)} \; erfc\left(\frac{r}{2\sqrt{\alpha t}} \right)$$

or

$$T = \frac{T_b R}{R + r} \; erfc\left(\frac{r}{2\sqrt{\alpha t}} \right)$$

if

$$T_b < \frac{Q}{8\pi \; kR}$$

The distance parameter r is the distance in from the surface for small r and the radius from the center of the laser spot for large r. Lines approximating constant r are shown in figure 1 b.

Appendix B

The Ruby Laser

The ruby laser was the first and is the most explored laser system. The ruby is a single crystal rod of Al_2O_3 doped with about .05% chromium. The crystal is placed in an optical cavity. This cavity may be formed by reflective coatings on the ends or it may use external mirrors. Sometimes one end is a total internal reflection wedge. The output end is around 80% reflective.

There are three energy levels of importance with this system. The pumping light is absorbed by the Cr between 4000 and 5500 A. The electrons decay very rapidly from this upper broad band to an intermediate very narrow metastable level. The average life time in this state is .003 seconds. The radiation emitted by decay to the ground state is 6943 A (see figure 18).

Some of the first photons emitted enteract with other atoms and stimulate emission. If the initial direction of a photon is parallel to the ruby axis, oscillations of the stimulated emissions will be obtained in the the resonant cavity. These oscillations form in filiments with a diameter of around 10^{-4} meters and and lifetime of .1 microseconds. The diameter, number of filiments, and alignment between between filiments depend on the on the quality of crystal and the pumping energy above threshold. A large diameter and low threshold are very desirable.
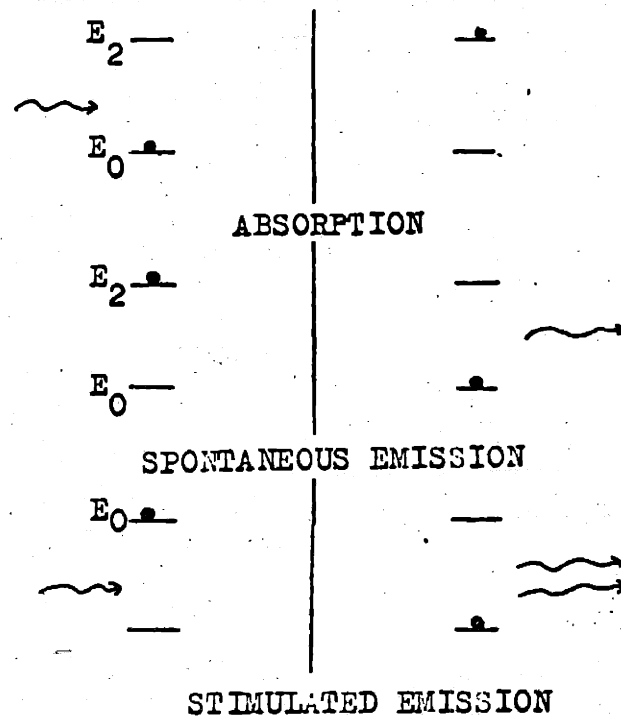
Under ordinary conditions the laser emitts a series
of pulses for a period of several hundred microseconds,
depending on input energy. It is possible, however,
to get a single very high power pulse.(the total
energy in less than a microsecond) by supercharging or
Q spoiling. There are several techniques that may be
used.

1. By rotating a mirror at the non-reflective
end of a crystal. When the mirror is parallel to the
other end of the crystal, resonance is established and
radiation may occur.

2. By placing a mirror, a Kerr cell, and a fixed
polarizer at the non- reflective end of the laser.
resonance is established when the Kerr-cell is ener-
gized so its plane of polarization is the same as that
of the fixed polarizer. If the c axis of the crystal
is parallel to the laser axis, the output is polarized
and the fixed polarizer is not needed.

3. By placing a thin film in the cavity. The
film is suddenly exploded, thus permitting resonance.

The efficiency of a ruby laser is greatly increased
by cooling, and for this reason lasers are frequently
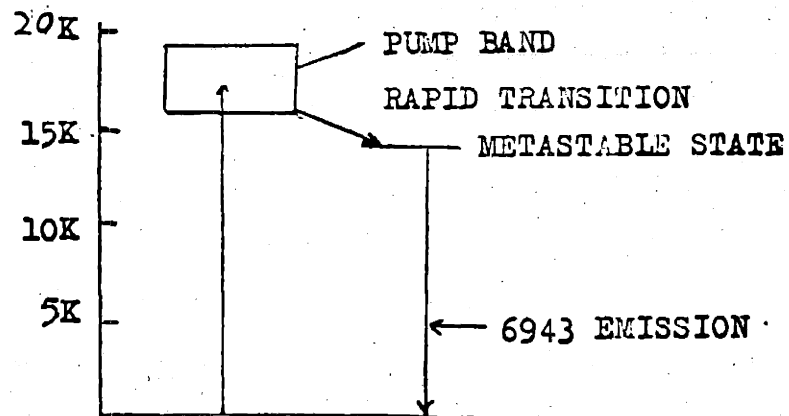cooled to liquid nitrogen temperature.

E_2 —

E_0 —

ABSORPTION

E_2 —

E_0 —

SPONTANEOUS EMISSION

E_0 —

STIMULATED EMISSION

(a)

20K — PUMP BAND

RAPID TRANSITION

15K — METASTABLE STATE

10K —

5K — ← 6943 EMISSION

Figure 18(a) Basic transition processes
(b) Energy levels for ruby.

Appendix C

Optics

The laser beam is frequently assumed to be diffraction limited; however, this is not the case with real lasers. The important consideration for these experiments is just how small an area the beam can be focused onto. One of the main problems in laser research is to approach the ideal case.

Figure 19 shows the radiation pattern from an ideal laser. Nearly all the energy is in the main beam. The angle of divergence α is about λ/D radians. For a quarter inch diameter rod, would equal

$$\frac{6943 \times 10^{-8}}{.7} = 10^{-4} \text{ radians}$$

Practical lasers at best have beam spread angles of .005 radians. This is because the output is from a number of separate filiments of small diameter. The average diameter depends on the quality of the crystal. The beam spread angle of the laser used in this experiment is .01 radians. The laser may be improved by optically correcting the ends rather than leaving them flat.

Figure 20 (a) shows ideal laser beam collimation and figure 20 (b) shows the collimation of the beam from a real laser. In the practical case d equals f In other words the spot diameter is just proportional to focal length.
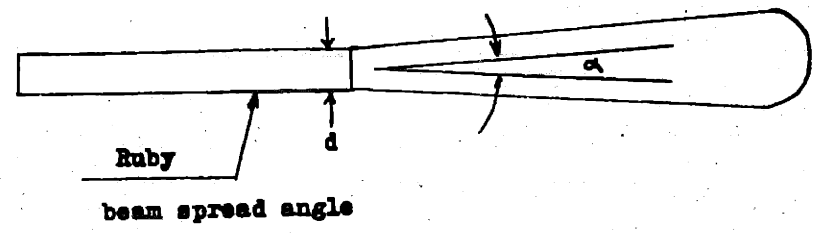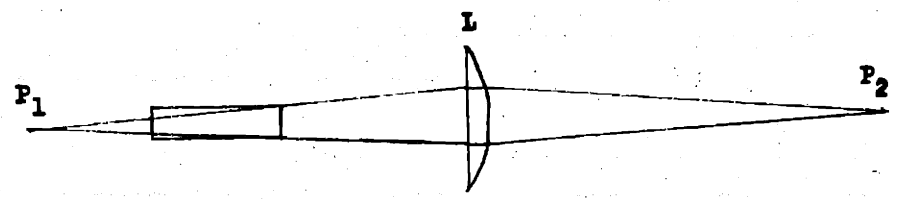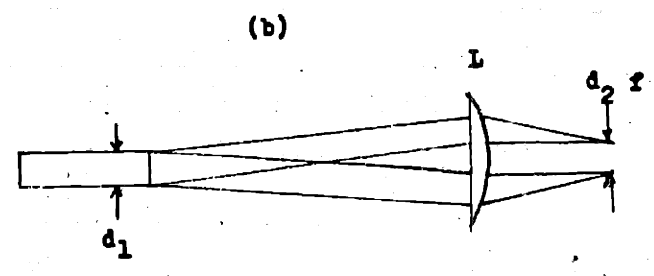
Figure 19   Idealized laser radiation

Ruby

d

beam spread angle

P_1

L

P_2

(a)

(b)

L

d_2 f

d_1

Figure 20 (a) Ideal (b) Practical laser beam
    collimation

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