THE INFLUENCE OF THE GRINDING PROCESS ON THE STRUCTURE OF HARDENED STEEL

by

Walter Edward Littmann

S.B., University of Cincinnati

(1950)

M.S., Massachusetts Institute of Technology

(1952)

SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE

DEGREE OF DOCTOR OF

SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

November 1953

Signature of Author..................................................

Dept. of Metallurgy, November 1953

Certified by..........................................................

Thesis Supervisor

Accepted by ......................................................

Chairman, Departmental Committee on Graduate Students
THE INFLUENCE OF THE GRINDING PROCESS ON THE STRUCTURE OF HARDENED STEEL

By

Walter Edward Littmann

Submitted to the Department of Metallurgy on November 3, 1953 in partial fulfillment of the requirements for the degree of Doctor of Science.

ABSTRACT

The temperature distribution for plunge type surface grinding was measured in the interior of hardened S.A.E. 52100 steel using a thermocouple formed by welding a small constantan wire to the bottom of a hole extending nearly to the ground surface. The extremely rapid heating and cooling rates approaching $5 \times 10^5 \, ^\circ F$ per second were measured by recording the output of the thermocouple with a cathode ray oscillograph. The temperature distributions measured were related to the structural changes which occurred in the steel as a result of the grinding heat.

The heating conditions of grinding were simulated by passage of electric current through thin hardened steel strips to establish the temperature required to form austenite for such rapid heating rates. It was found that rehardening of the steel by grinding heat requires that a peak temperature of about $1500^\circ F$ be reached for moderate work speeds. Peak
temperatures above 600°F were found to be necessary for grinding to produce additional tempering in a prior structure tempered one hour at 300°F. These facts indicated that the temperature drop in the first .0001 inch from the ground surface is of the order of 1500°F.

The peak temperature distribution appears to be uniquely related to the energy input per unit area of work surface ground. This observation permits an estimation of the temperature distribution to be made from the measurement of the power consumed in grinding.

The factors found to decrease the temperature at any point in plunge grinding are decreased feed per pass, increased work speed, lubrication of the rubbing area between the abrasive and work, and the sharpest possible wheel condition consistent with surface finish requirements.

The behavior of retained austenite in the prior structure and in the rehardened zone formed by grinding were studied in 52100 quenched from 1900°F. Some of the retained austenite in the prior structure was transformed to untempered martensite by grinding. The quantity of retained austenite in the rehardened layer formed by grinding was found to be abnormally high for any prior structure.

Thesis Supervisor: John Wulff
Title: Professor of Metallurgy
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>1</td>
</tr>
<tr>
<td>List of Figures</td>
<td>iv</td>
</tr>
<tr>
<td>List of Tables</td>
<td>vi</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>vii</td>
</tr>
<tr>
<td>I Introduction</td>
<td>1</td>
</tr>
<tr>
<td>II Experimental Work</td>
<td>11</td>
</tr>
<tr>
<td>III Discussion of Results</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>60</td>
</tr>
<tr>
<td>IV Conclusions</td>
<td>66</td>
</tr>
<tr>
<td>V Suggestions for Future Work</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>73</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE OF CONTENTS
<table>
<thead>
<tr>
<th>Figure number</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Chip Formation in Grinding</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>A Typical Thermocouple</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>Typical Samples for Temperature Measurement in Grinding</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>Schematic Electrical Circuit for Temperature Measurement</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>Typical oscilloscope traces</td>
<td>17</td>
</tr>
<tr>
<td>6</td>
<td>Taper Section of Sample M-1</td>
<td>25</td>
</tr>
<tr>
<td>7</td>
<td>Apparatus for Electrical Heating</td>
<td>27</td>
</tr>
<tr>
<td>8</td>
<td>Schematic Electrical Circuit for Strip Heating</td>
<td>28</td>
</tr>
<tr>
<td>9</td>
<td>Typical oscilloscope Trace for Strip Heating</td>
<td>29</td>
</tr>
<tr>
<td>10</td>
<td>Section through Hole which Contained Thermocouple</td>
<td>33</td>
</tr>
<tr>
<td>11</td>
<td>Summary of Results from Sample G-19</td>
<td>35</td>
</tr>
<tr>
<td>12</td>
<td>Hardness Changes in Tempering</td>
<td>36</td>
</tr>
<tr>
<td>13</td>
<td>Longitudinal temperature Distribution</td>
<td>39</td>
</tr>
<tr>
<td>14</td>
<td>Taper Section of Sample M-1 at Low</td>
<td>41</td>
</tr>
<tr>
<td>15</td>
<td>Taper Section of Sample G-19</td>
<td>42</td>
</tr>
<tr>
<td>16</td>
<td>Peak Temperature Distributions</td>
<td>51</td>
</tr>
<tr>
<td>Figure number</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------------</td>
<td>--------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>17</td>
<td>Peak Temperature versus $Q_A$</td>
<td>53</td>
</tr>
<tr>
<td>18</td>
<td>Grinding Chips and Abrasive Grains</td>
<td>56</td>
</tr>
<tr>
<td>19</td>
<td>Retained Austenite in Rehardened Layer</td>
<td>61</td>
</tr>
<tr>
<td>20</td>
<td>Structure in Transition Region</td>
<td>62</td>
</tr>
<tr>
<td>21</td>
<td>Transformation Around a Hardness</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Impression</td>
<td>63</td>
</tr>
<tr>
<td>22</td>
<td>Martensite Formed in Retained Austenite</td>
<td>65</td>
</tr>
<tr>
<td>Table No.</td>
<td>Title</td>
<td>Page No.</td>
</tr>
<tr>
<td>---------</td>
<td>---------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>1</td>
<td>Grinding Conditions Used</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>Results from Electrical Heating</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>Grinding Energies</td>
<td>55</td>
</tr>
</tbody>
</table>
ACKNOWLEDGEMENTS

The author takes this opportunity to express his appreciation to Prof. John Wulff for his advice and guidance as thesis supervisor, to the Timken Roller Bearing Company for support of the research, to Dr. E. S. Rowland and Dr. D. J. Girardi of that organization for helpful criticism, and to Prof. M. Shaw and the personnel of the Metal Cutting Laboratory of M.I.T. for use of equipment and help in obtaining force data. The use of the equipment developed by Huggins, Roll and Udin and the personal assistance of Mr. Huggins is acknowledged with sincere thanks.
I \ INTRODUCTION

The effect of the heat which is generated in the grinding operation has long been the object of concern for those who must make machine parts of hardened steel. The process of grinding hardened steel parts with abrasive wheels is of necessity the most widely used method for bringing such parts to their final size and shape. A part is made of hardened and tempered steel because it has maximum strength and resists wear best at a given level of ductility. The heat produced by the grinding operation may reduce the strength and lower the wear resistance of the work being ground besides having a deleterious influence on fatigue properties. Because of its high potential for damage to the work, the grinding process has often been suspect when ground parts fail prematurely. For the same reason the effects of grinding on the structure and properties of ground hardened steel parts should be the object of intensive study, yet the literature concerning the subject is limited. When one begins research in this field, at least one reason for the relative dearth of information becomes clear. The grinding process does not lend itself well to systematic investigation because of the complex interaction of the many variables at play. For this reason most of the information in the literature is of an empirical nature.
The criterion for what constitutes grinding damage is necessarily a function of the application. Some parts are usable though visible burning or cracking is produced by grinding, but most parts must be as nearly free of visible damage as possible. Until very recently there have been few quantitative measurements of grinding damage where visible burn is absent.

Tarasov and Lundberg\textsuperscript{1,2,3,4}, have studied many of the effects of grinding on hardened steel and have summarized methods for detecting and evaluating the degree of damage. They have described how rehardened and overtempering beneath ground surfaces may be detected metallographically; they have also measured the micro-hardness changes accompanying such changes for relatively severe grinding conditions and used an etch crack method for evaluating residual stresses qualitatively.

Tarasov and Grover\textsuperscript{5} investigating the effect of grinding on fatigue properties reported a 20 to 25\% reduction of the endurance limit for severely ground flat bars of 52100 type steel hardened and tempered to Rockwell C59 compared with gently ground samples. The grinding damage for these samples was confined to overtempering to a depth of 0.001 to 0.004 inch, the maximum softening as measured by Tukon micro-hardness measurements was said to be equivalent to 4 points Rockwell C. Local rehardening under a few grinding scratches was noted as well. Gentle
grinding gave the same endurance limit as gentle grinding followed by hand polishing to remove grinding scratches, no detectible metallographic burn being visible in either case. Scatter of results appeared to increase with polishing after grinding. The data presented were limited to a few samples and the conclusions were admittedly speculative.

Boyer\textsuperscript{6} performed rotating bending fatigue tests on 52100 type steel hardened and tempered, ground to various depths and then polished. His conclusion that even the most gentle grinding reduced the endurance limit was disputed in discussion by Tarasov who said that undetected damage was present. A conspicuous aspect of these investigations is the absence of a quantitative criterion of grinding damage especially when the severity of grinding is reduced to the level of good industrial practice.

The development of X-ray\textsuperscript{7,8} and optical interference\textsuperscript{9} methods for measurement of residual stresses in hardened steel has produced valuable tools to provide quantitative information on the effects of grinding. Such measurements should ultimately be of value in relating the overall effect on the residual stress distribution produced by the grinding operation to the factors which cause the changes.

The most likely origins of changes produced by grinding are the heat generated by grinding and the plastic deformation of the surface by the abrasive grains in the grinding
wheel. Because the chips removed by the grits in a grinding wheel are very small, the depth to which plastic deformation is produced is likewise small. The effects of such plastic deformation are usually obliterated by the heat effects, but Tarasov\textsuperscript{2,4} has reported an increase in the micro-hardness of the surface of gently ground steel (Rockwell C59 oil hardened and tempered) which he attributes to work hardening from plastic deformation. The effects appear to be confined to material within a distance from the surface corresponding approximately to the peak to valley roughness of that surface, usually less than 50 micro-inches for high hardness materials (Rockwell C59). The effect was more pronounced for steel tempered to Rockwell C45.

Wulff\textsuperscript{10} made use of the structural changes in 18-8 stainless steel observed by electron diffraction for very small intervals of depth to deduce the extent of penetration of heat and plastic deformation for various finishing processes. Having found that plastic deformation could produce ferrite only below 390°F by rolling experiments with the steel used he established that the depth at which the first ferrite appeared in the deformed austenite had not exceeded a temperature of 390°F. For fine dry grinding 390°F was reached at a depth of 2.5 × 10^{-4} inch. Wet multi-motion grinding showed 390°F at 1 × 10^{-4} inch and evidence of cold work was found to 3 × 10^{-4} inches. Honing and hand polishing showed no evidence of temperatures above 390°F.
to the surface but cold work was evident to $1.4 \times 10^{-4}$ to $1 \times 10^{-4}$ inch.

Marshall\textsuperscript{12} found that the effects of cold work in annealed 52100 steel detected by line broadening of the X-ray diffraction lines (310 doublet resolution) penetrated to a depth about one half the wheel depth of cut (up to .001 inch downfeed per pass) for dry grinding at a work speed of 4 feet per minute with a 46 grit aluminum oxide wheel. Because the plastic deformation is so localized with hardened steels and its effect on the work appears to be in a beneficial direction it is perhaps more important to first concentrate on the source and effects of the heat generated by grinding.

The heat generated in grinding which can enter the work stems from two sources designated a and b in Figure 1 which shows schematically the formation of a single chip by an abrasive grain in a grinding wheel. In zone (a) most of the deformation energy expended in the formation of a highly strained chip is dissipated as heat along the shear plane. Part of this heat flows into the chip, part into the abrasive grain and the remainder into the work. Because of the vast difference in thermal conductivity of abrasive and steel almost all of the heat flows into the chip and work, the division being estimated at about 65% to chip and 35% to work for grinding.\textsuperscript{10} The specific energy required to remove metal by grinding is
Figure 1

Schematic View of Chip Formation in Grinding
extremely high so that even though the rate of metal
removal is low, the rate of heat input per unit area of
the work is high compared to other metal cutting operations.

The other area (b) where heat is generated is the
region of rubbing contact between the bottom of the abrasive
grain and the freshly cut metal surface. Practically all
of the heat generated in this area enters the work because
of its high conductivity. This contact area is difficult
to lubricate and the friction is of such high order that
considerable attritious wear takes place in such areas,
probably by reaction between the abrasive and the freshly
cut steel. When grinding is continued for comparatively
long periods between wheel dressings, the frictional force
in area (b) builds up to the point where fracture takes
place within the grit or the vitreous bond between the
abrasive grains is broken and new cutting points come into
play. Selection of the proper wheel specification governs
such behavior and has been extensively treated in the
literature of grinding wheel manufacturers. When grinding
is done for relatively short periods of time after dressing
of the wheel as, for example, in the case of plunge grinding
(no cross-feed) of cylindrical parts to final size, the
amount of wheel wear by such breakdown which can be
tolerated becomes extremely small if the part is to be
ground accurately to size and the best degree of surface
finish is to be obtained. For such high precision grinding,
the initial condition of the wheel is determined by the dressing operation and the extent of wear during the grind is determined by the mechanical variables such as wheel speed, work speed, in-feed rate and the coolant used, the break-down characteristics of the wheel being such that no grit ejection and little fracture wear takes place. This type of grinding is easiest to study because the wheel condition, which is probably the most elusive variable in grinding, is most closely controlled and the complications of cross-feed are absent. For these reasons and because such grinding is typical of the finish grinding of many steel parts of high hardness, e.g., rolling contact bearing components, this thesis will be concerned with such plunge type finish grinding.

If the heat from grinding is introduced rapidly enough the surface temperature of the work may rise to the point where tempering can occur beyond the degree imposed by prior heat treatment. The higher the hardness of the part being ground, the more important this type of damage becomes. If more heat is produced, the steel near the surface may be heated to a high enough temperature to be reaustenitized and quenched to untempered martensite and retained austenite as the wheel passes over the work. Such rehardening and overtempering beneath the surface are accompanied by dimensional changes which can alter the distribution of residual stresses as well as changing the
physical properties of the steel undergoing transformation. In addition, the non-uniform thermal expansion of the surface restrained by colder metal beneath, ahead of, and behind the wheel may cause plastic upsetting of the hot metal beneath the wheel leaving a residual tensile stress in the surface as the wheel passes. Finally, the stresses introduced by thermal expansion and structural changes may promote transformation of retained austenite to untempered martensite in the zone beneath the rehardened surface. It has been shown recently that the first detectible plastic deformation in a tensile or bend test is accompanied by transformation of retained austenite.13

The consequences of such possible changes are almost all in a direction such that one would say the work was damaged by the grinding. For example, any of the effects which produce tensile residual stresses near the surface will reduce the fatigue properties of the part being ground. Any tempering which takes place reduces the yield strength and wear resistance of the steel near the surface provided, of course, that the prior tempering has brought hardness to the optimum level. The contraction produced by the tempering reaction will produce residual tension in the material so affected. Any untempered martensite, whether from transformation of retained austenite in the prior structure or whether present at the surface because of
rehardening, provides brittle volume elements which are likely sites for nucleation of fatigue cracks. If the ground surface is to be subjected to alternating stresses, as for example, in ball or roller bearings, it is clear that all of these changes constitute damage because they decrease the load capacity of the metal near the surface which is most severely stressed in the assembled bearing. Because much of the finish grinding of hardened steel is done in the manufacture of rolling contact bearings, this application will be the principle one considered in determining what constitutes grinding damage. This does not impose much limitation since damage relative to bearing applications may just as well be damage if the hardened steel part is a punch, die, gear or shaft, for in all these applications, the properties of the steel near the surface are the most critical.

Since the principal damage produced by grinding has as its origin in the heat generated by the grinding process it seemed logical to determine what sort of time-temperature history is required to produce measurable changes in the structure of hardened steel. The principal objective of this investigation was to appraise with quantitative measurements the temperature distribution produced in the grinding of hardened steel and to relate such measurements to observable changes in structure.
II EXPERIMENTAL WORK

Since the extent of structural change in a ground piece of hardened steel is dependent on the thermal history experienced, an effort was made to measure directly the temperature distribution in time and space in samples as they were being ground.

To measure the temperature distribution a thermocouple was formed by welding a constantan wire .010 inch in diameter to the bottom of a hole of small diameter. A section of a typical sample is shown in Figure 2. A 30 gage constantan thermocouple wire with fiberglass insulation or with asbestos insulation could be inserted freely into holes .021 inch or .026 inch respectively in diameter, so the last 3/16 inch of each hole was made .021 inch or .026 in diameter to minimize the change in heat flow conditions imposed by the presence of the hole. The weld was made by clamping leads from a spot welder to the sample and to the bare constantan wire as close as possible to the entrance to the hole. Using the electronic controller attached to the welder, a single cycle of 60 c.p.s. alternating current at an adequate voltage was required to make a sound spot weld between the pointed end of the constantan wire and the flat area generated at the bottom of the hole by the chisel edge at the end of the twist drill used to drill the hole.
Figure 2: Section through a typical weld of a pointed constantan wire at the bottom of a .026 inch diameter hole. The actual weld was broken in mounting for polishing, but the position of the wire relative to the hole is typical. 95X
When the wire was ground to a point and the point rounded somewhat before welding, the resultant weld area was about .001 to .004 inch in diameter and roughly circular measured on sections through welds and fractures resulting when good welds were broken in tension. A weld was considered sound if it was capable of supporting the weight of the sample in tension.

The technique described above was successfully applied to make samples for temperature measurements in hardened SAE 52100 steel. For measurements in steel ground intermittently on a reciprocating table surface grinder, samples 1/2 x 1/2 inch square of various lengths were machined from 3/4 inch square bars of spheroidized S.A.E. 52100 steel of the following composition: C - 1.00, Cr - 1.44, Ni - .20, Mn - 0.35, Si - .28, P - .016, S - .013%. Holes were drilled from one side perpendicular to the surface and extending almost all the way through the sample so that the bottom of the longest hole was about .050 inch from the surface. The other holes were successively shorter in about .050 inch steps so that after the first thermocouple was ground through the next was used etc. A photograph of a typical sample for intermittent grinding appears in Figure 3a.

The thermocouple circuit was completed by spot welding an iron wire on the side of the sample farthest from the
Figure 3a: A typical sample for intermittent grinding.

Figure 3b: A partly used cylindrical sample for continuous grinding. The small permanent magnet is shown attached to the sample near the magnetic pick-up used to trigger the sweep on the oscilloscope.
surface to be ground. Copper leads were run from this iron wire and from the constantan wire to a cathode ray oscillograph where the output of the thermocouple could be observed and recorded by photographing the trace using a 35 mm camera loaded with a very high speed panchromatic film. A schematic diagram of the electrical circuit is shown in Figure 4. Typical records made in this fashion appear in Figure 5.

The circuit was arranged so that the horizontal movement of the spot on the oscilloscope was begun a moment before the arc of contact between wheel and work approached a position directly above the thermocouple. On the reciprocating table surface grinder this was accomplished by using a microswitch activated by a cam attached to the table of the grinder to close a circuit momentarily feeding sufficient voltage to trigger the sweep. On the rotary grinder at higher work speeds it was more convenient to use a magnetic pick-up to trigger the sweep. A small permanent magnet was attached to the sample so that with each revolution it barely missed the poles of an earphone on which the steel diaphragm was replaced by a thin sheet of plastic as shown in Figure 3b. Each time the magnet passed the phone, a pulse of voltage was generated which was sufficient to trigger the sweep. This synchronization
Figure 4: A schematic diagram of the electrical circuit used to measure the time temperature history beneath a ground surface.
**Figure 5a:** A typical record of emf versus time for two successive passes on a sample ground intermittently. 1 division horizontally is 0.005 second; 1 division vertically is 5 millivolts.

**Figure 5b:** A typical photograph of the oscilloscope trace for a continuously ground sample. 1 division horizontally is 0.00083 second; 1 division vertically is 0.45 millivolts.
of the sweep permitted the superposition of the emf versus
time records at all depths for a given sample to give the
distribution of temperature in time and space.

The samples to be ground were drilled and then hardened
by austenitizing for one hour at 1550°F, quenching into
oil at room temperature and tempering for one hour at 300°F
to give a hardness of 64 Rockwell C. This heat treatment
is typical of high hardness application of 52100 steel.
Decarburization was prevented by sealing the samples into
evacuated Pyrex tubes before hardening. At 1550°F the glass
flowed and conformed to the shape of the sample. Penetration
of the glass into the holes was prevented by spot welding
thin strips of steel over the openings. The oil quench was
sufficiently rapid to permit thorough hardening despite
the coating of glass, which was cracked off during the
quench.

An alternative method of preventing decarburization
was required for the samples to be ground continuously on a
rotary grinder. These samples consisted of short cylinders
machined from 52100 tubing. The cylinders were 1 1/4 inches
high, 4.75 inches outside diameter with a wall thickness of
3/8 inch. A partly used cylindrical sample is shown in
Figure 3b. Holes were drilled to successively different
depths and copper wires peened into them to prevent penetra-
tion of lead since these cylinders were austenitized in
lead at 1550°F, then quenched and tempered to the same specifications as the samples for intermittent grinding. Excessive solution of the copper in the lead heating bath was prevented by coating the sample with an adherent layer of carbon soot from a smoky gas flame. After hardening and tempering the copper was drilled out. The most effective method of preparing the bottoms of the holes in the hardened samples for welding was to rotate a high speed steel drill just small enough to fit freely in the hole, the friction between the drill and the hardened flat at the bottom of the hole produced a clean enough surface to permit spot welding of the constantan wire. The debris from drilling and cleaning was removed with a magnetized steel needle.

Before welding, the distance between the bottom of the hole and the surface was measured within .0005 inch using a micrometer. When the sample was ground, a measurement of the thickness of the sample at any given time thus revealed the distance of any of the thermocouples from the surface.

The samples were ground under a variety of grinding conditions listed in Table 1. Before a given temperature distribution measurement was made, the wheel was always dressed using a diamond pyramid of the type described by Marshall.\textsuperscript{12} The wheel was fed down .001 inch between each dressing crossfeed and dressing was completed as soon as
<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Wheel</th>
<th>$V_{ft./min}$</th>
<th>$V_{ft./min}$</th>
<th>$d_{in./pass}$</th>
<th>Coolant</th>
</tr>
</thead>
<tbody>
<tr>
<td>G 12</td>
<td>38A60H8VG</td>
<td>6500</td>
<td>60</td>
<td>.001</td>
<td>soluble oil</td>
</tr>
<tr>
<td>G 13</td>
<td>&quot;</td>
<td>6000</td>
<td>60</td>
<td>.001</td>
<td>&quot;</td>
</tr>
<tr>
<td>G 15</td>
<td>&quot;</td>
<td>6000</td>
<td>30</td>
<td>.001</td>
<td>&quot;</td>
</tr>
<tr>
<td>G 17</td>
<td>&quot;</td>
<td>6000</td>
<td>60</td>
<td>.0005</td>
<td>&quot;</td>
</tr>
<tr>
<td>G 18</td>
<td>&quot;</td>
<td>6000</td>
<td>60</td>
<td>.0005</td>
<td>&quot;</td>
</tr>
<tr>
<td>M-1</td>
<td>&quot;</td>
<td>6000</td>
<td>60</td>
<td>.0005</td>
<td>&quot;</td>
</tr>
<tr>
<td>G 19</td>
<td>37C60P5V</td>
<td>5700</td>
<td>20</td>
<td>.0005</td>
<td>&quot;</td>
</tr>
<tr>
<td>G 20</td>
<td>37C60P5V</td>
<td>5600</td>
<td>20</td>
<td>.0005</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

Y-1 37C36JV  6000  15 .001 none for 10 cuts in rapid succession
Y-11 37C36JV  6000  15 .0023 (one pass) none

Rotary grinder

R-1

R-5

.000011 soluble oil
all traces of previous grinding were removed. The dressing
crossfeed was maintained constant for all the samples which
were ground on the reciprocating table surface grinder. A
somewhat lower speed of crossfeed was used on the rotary
grinder, but all runs made on that grinder had the wheel
dressed at the same rate.

The cylindrical samples were ground continuously on a
6 inch Taft Pierce rotating table surface grinder especially
constructed to permit continuous variation of work rpm,
wheel speeds and feed rates.

The maximum amplification within the oscilloscope was
sufficient to give a sensitivity of 5 millivolts per division
vertically. For temperatures less than 300°F a preamplifier
was used so that a sensitivity of .5 or .05 millivolts per
division could be obtained. To convert the emf versus time
to temperature versus time, a calibration of the hardened
52100 steel-constantan thermocouple was made.

The calibration curve for Type I.C. constantan versus
hardened 52100 (1550°F, 1 hour oil quench, no temper) is
parallel to that for the standard (Type I.C.). Iron-constantan
thermocouple, the temperature at a given emf being about
40°F higher for the 52100-constantan thermocouple. As the
calibration was done at temperatures above 600°F the curve
was observed to approach the iron-constantan until above
1100°F the curves coincided. On cooling the points fell
somewhat to the left of those for heating. Apparently as tempering progressed during heating, the emf versus temperature relation underwent an irreversible change. Since the heating rates were so rapid and time at temperature so short for the measurements in grinding, the calibration curve used consisted of the portion up to 600°F parallel to the I.C. curve plus the extrapolation of that curve to higher temperatures parallel to the I.C. curve. The maximum possible error because of the effect of tempering during grinding on the thermoelectric characteristics of the junction was estimated to be about 20°F, i.e. the observed temperature using the extrapolated curve could be no more than about 20°F higher than if a curve corrected for tempering were used.

The question logically arises as to how much the presence of the hole and constantan wire altered the heat flow conditions in the area where the temperature was being measured. The answer to this question is so intimately connected with the results obtained that it will be discussed with those results.

The structural changes which occurred in ground samples were observed by several techniques. Metallographic examination of taper sections using the optical microscope was used to the limit of its ability to reveal resolvable detail. Because of the fineness of the structure in
52100 hardened according to commercial practice, the limitation of optical resolution was a genuine obstacle. To bypass this difficulty, in some cases some samples were hardened by heating in evacuated Vycor tubing at 1900°F 1 hour and quenching in oil. The resulting structure was coarse enough and contained sufficient retained austenite to permit some observations on its behavior in the heat affected zone. Several such samples were ground severely to develop rehardened zones of appreciable depths. The structure within such rehardened layers was coarse enough to permit analysis by optical metallography.

X-ray measurements\textsuperscript{14} were made of the retained austenite contents of the rehardened layers. The retained austenite in samples ground severely enough to produce rehardening to any depth was always greater than that of the structure prior to grinding. For samples quenched from 1550°F and tempered at 300°F, the rehardened layer contained as much as 25 to 35%. For samples quenched from 1900°F and ground severely the retained austenite in the rehardened zone was sometimes as high as 70% from the X-ray measurement. Metallographic examination of such samples after tempering 7 seconds at 700°F to darken the martensite revealed that the amount of retained austenite at the extreme surface was even higher.
The other principal tool used to evaluate the changes occurring as a result of grinding was microhardness testing. Because of the extremely localized nature of all hardness changes in the heat affected zone, the load used was 20 grams. This was found to be the lightest load giving results of sufficient reproducibility to be useful. The impressions were made using a Reichert Microhardness Tester. The impressions were measured using a 140:1 oil immersion objective (1.30 N.A.) with a special measuring eyepiece which permitted individual readings to be reproduced within about 0.2 micron. An example of a tapersection showing microhardness impressions is shown in Figure 6.

To check the accuracy of the temperature measurements and to establish the temperature required to reaustenitize the surface for heating rates approaching those experienced beneath a ground surface, an attempt was made to reproduce such heating rates by electrical heating. Apparatus capable of producing such heating rates and equipment to follow the temperatures were fortunately available in the Welding Laboratory of the Massachusetts Institute of Technology. This equipment has been described in the literature by Huggins, Roll and Udin. Thin strips of steel were clamped between the electrodes of a 40 KVA spot welder and a very high current was passed for a short time which was regulated electronically by the welding controller. The sample was
Figure 6: Taper section (1/50) of sample M-1 showing the chromium plate at the top used to preserve the ground surface contour, the light etching zone of rehardened steel at the bottom of the gauge made by a single grit, and typical microhardness impressions made using a 20 gram load. 1200X optical magnification. Magnification of distances in the vertical direction is 60,000 because of the taper section. Etch: 4% Nital with Zephirum Chloride.
enclosed in an evacuated chamber into which hydrogen was allowed to leak to minimize oxidation. The quench was hydrogen gas turned on by the welder controller. A lead sulfide cell sighted on the strip changed its resistance in proportion to the temperature of the strip. This change of resistance was calibrated to permit conversion to temperature when recorded on a cathode ray oscillograph. A sketch of the apparatus on the welder and a schematic electrical diagram appear in Figures 7 and 8.

Strips of 52100 were prepared .007 inch thick, 3/8 inch wide, and about 1\(\frac{1}{2}\) inch long. These were hardened by sealing them off in evacuated Pyrex tubes in pairs. The glass collapsed and helped keep the strips flat when they were quenched into water from 1550\(^\circ\)F after 1 hour. These strips were heated in the apparatus described by passing 7 cycles of 60 cps alternating current. The power was varied to give peak temperatures from 1350 to 1650\(^\circ\)F. A photograph of the oscilloscope screen for the heating and cooling of one of these samples is shown in Figure 9. The trace shown is similar to the shape of the heating and cooling curve which is obtained from the trace with the calibration data. The results obtained from the welder are summarized in Table 2.*

* It should be emphasized here that the apparatus described was designated and built by Huggins, Roll and Udin. The author cooperated with Mr. R. A. Huggins, instructor at M.I.T. in obtaining the results from electrical heating.
Figure 7: A sketch of the apparatus attached to a spot welder to produce rapid heating by passage of electric current through a thin strip of steel.
Figure 8

A schematic diagram of the electrical circuit used to measure the time temperature history of thin strips heated electrically in a spot welder.
Figure 9: A typical photograph of the oscilloscope trace obtained with the thin strips heated rapidly by electric current. The horizontal sweep represents about 1/2 second. The trace shown is not of temperature versus time but the actual temperature versus time curve obtained from such a trace is of similar shape. The rapid heating at the left, the sharp peak temperature and the rapid cooling to the right are all evident.
<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Peak Temp °F</th>
<th>Heating Rate °F/sec.</th>
<th>Hardness Kg/mm² (20 g load)</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-14</td>
<td>1650</td>
<td>10,700</td>
<td>1150 - 1200</td>
<td>Rehardened</td>
</tr>
<tr>
<td>S-15</td>
<td>1560</td>
<td>11,000</td>
<td>1150 - 1200</td>
<td>Rehardened</td>
</tr>
<tr>
<td>S-16</td>
<td>1350</td>
<td>9,300</td>
<td>605 - 635</td>
<td>Tempered</td>
</tr>
<tr>
<td>S-17</td>
<td>1470</td>
<td>9,570</td>
<td>540 - 580</td>
<td>Tempered</td>
</tr>
<tr>
<td>S-18</td>
<td>1508</td>
<td>10,100</td>
<td>505 - 550</td>
<td>Tempered</td>
</tr>
<tr>
<td>S-20</td>
<td>1540</td>
<td>10,500</td>
<td>--</td>
<td>Partly re-hardened</td>
</tr>
</tbody>
</table>
Force measurements were made using a grinding
dynamometer designed and built by the personnel of the
Metal Cutting Laboratory of the Massachusetts Institute
of Technology to permit comparison of the total energy
input in grinding with the observed temperature distribution.
III DISCUSSION OF RESULTS

Accuracy of Temperature Measurements

The results of temperature measurements made by welding a small diameter constantan wire to the bottom of a hole in hardened samples of 52100 steel showed that such a thermoelectric junction was capable of following the extremely rapid temperature changes at a given point within a sample being ground on a surface grinder. Metallographic examination of the boundary between the rehardened zone and overtempered bulk material in Figure 10 showed that as the surface being ground approached the measuring junction the presence of the hole did not alter the heat flow conditions sufficiently to cause a perceptible added penetration of the rehardened zone at the surface.

The microhardness measurements in Figure 6 showed that some additional tempering was present in the steel just above the measuring junction when a sample was ground to within about .003 inch of the junction. The measurements nearer the surface do not show the same drop in hardness above the hole which tends to indicate that the additional tempering may have been produced by the welding of the thermocouple. In any case, the magnitude of the effect is small, corresponding to about a 50 degree Fahrenheit difference in peak temperature between the softer material above the hole and the steel at the same depth to either side from the hole.
Figure 10: A section through the hole which contained a thermocouple weld until the ground surface was about .003 inch from the bottom of the hole. The heavy layer is nickel, plated to preserve the edge of the sample in polishing. The first .001 inch of nickel plate is porous. The thin rehardened zone is barely visible at the surface of the steel. Magnification, 80X. Etch: 4% Nital with Zephiran Chloride.
The heat transfer conditions for the area shown in Figure 10 were somewhat worse than for all the temperature measurements made because the weld in that sample (G-20) broke during the run at a depth of about .007 inch. Eight successive passes were made with very poor contact between the constantan and steel before the grinding was stopped and the sample sectioned. Thus the effect observed here is certainly more than would occur in a sample with a sound weld. The presence of a broken weld was always immediately evident in the oscilloscope traces and the sample discarded whenever the weld was defective.

Further evidence supporting the accuracy of the temperature measurements may be seen in Figures 11 and 12. The degree of tempering which takes place for the extremely rapid heating and cooling rates in grinding is expected to be a function of the peak temperature reached so long as the shape of the time-temperature history is not radically altered. The agreement of the points obtained from the synthetic reproduction of grinding conditions by electrical heating with those from grinding measurements tend to confirm this expectation. The peak temperature corresponding to a given hardness appears to be 40 to 60°F higher for the electrically heated samples. There are 3 factors which may act in a direction which would explain this difference. First, the electrically heated strips were in the "as quenched"
Figure 11: Summary of results obtained from sample G-19, severely ground. The peak temperature distribution is compared with the corresponding microhardness distribution made on a taper section of the sample after grinding.
Figure 12: Hardness changes during tempering from transient grinding heat compared with that for normal tempering times and temperatures. The curve for grinding was obtained from Figure 11.
Hardness vs Peak Temperature in Grinding

Hardness vs Temperature for One Hour at Temperature

Data from Electrical Heating
condition whereas the ground samples were tempered 1 hour
at 300°F so that the first stage of tempering was sub-
stantially complete in the structure prior to grinding.
This should have little influence, however, since the
degree of tempering corresponding to the hardness range
in the area of comparison is well into the third stage
of tempering. The third stage is essentially complete
after tempering one hour at 750 to 850°F.¹⁶ The assumption
has been made that a given hardness in the ground sample
corresponds to a given degree of tempering. The validity
of this assumption is open to question, but unless there
is a gross change in the mechanism and sequence of events
in tempering it is probably the best available quantitative
criterion of extent of tempering for studying the localized
structural changes occurring in grinding.

The presence of a very high compressive stress in
the heated region beneath the grinding contact may accelerate
the rate of tempering since the dimensional change ac-
companying the tempering is a contraction.

The third and the most likely reason for the fact
that the hardness corresponding to a given peak temperature
is low for the ground sample is the repeated heating of a
given element of volume to successively higher and higher
temperatures. Thus the prior structure of any given volume
element before the last grinding pass of .0005 inch is the
structure only .0005 inch below it. In view of these observations, the agreement observed for the two methods of heating is acceptable.

The area of the measuring junction was usually .001 to .0014 inch in diameter, roughly circular. The area over which the junction measured an average temperature was thus small compared to the extent of temperature variation in a plane parallel to the surface being ground. The longitudinal variation of temperature at a given time is indicated in Figure 13 compared to the diameter of a typical weld area. As the length of the arc of contact between wheel and work decreases, the extent of longitudinal temperature variation becomes more important. For the lightest feed rate investigated, the length of the arc of contact was about $7.8 \times 10^{-3}$ inches. This was the shortest contact length for any of the grinding conditions used. Figure $5b$ shows the extent of longitudinal temperature variation for these conditions. One division horizontally corresponds to .00083 second during which the work moved .0417 inch. Thus the time for the arc of contact to pass the thermocouple was about .00015 second, represented by .18 division horizontally. If the area of the measuring junction were large compared with the extent of longitudinal temperature variation, the time temperature curve would show a sharp peak for a maximum whereas the trace shows a perceptibly
Figure 13: Isotherms under the arc of contact shown in a longitudinal section of a sample being ground. The extent of longitudinal temperature variation is compared with the length of the arc of contact and the diameter of the thermocouple weld area. The grinding conditions are those of Sample G-12.
rounded region with a very small variation in temperature near the peak during the time required for the measuring junction to pass the arc of contact. For very small values of $D^*$, then, the lateral temperature variation is the principal source of error in the observed temperature. The lateral temperature variation is reflected in the resulting structural gradient in Figure 14. The average temperature measured by the junction is always lower than the peak temperature beneath individual grit paths. By values of $D$ over a few times the maximum peak to valley distance in surface contour, lateral heat flow has smoothed the lateral temperature distribution as shown by Figure 15, which shows that the boundary of the rehardened region is somewhat smoother than the surface contour at $D = .0001$ inch.

The temperature distributions measured with the steel constantan thermocouple under the conditions described, therefore, appear to be representative of the temperature distribution in the absence of the hole within about $50^\circ F$ for distances from the measuring junction to the ground surface exceeding about .0005 inch.

* $D$ will be used to indicate the depth of a point beneath the ground surface.
Figure 14: Taper section of sample M-1. (The area of Figure 6 is included at the left side of the area shown here at a lower magnification.) Optical magnification 250X, vertical magnification of distance is 12,500X because of the 1/50 taper section. Etch: 4% Nital with Zephiran Chloride.
Figure 15: Taper section of sample 19 showing irregularity of the lower boundary of the rehardened zone. Optical magnification is 500X, vertical magnification of distance is 2100X because of taper section. Etch: 4% Nital with Zephiran Chloride.
Relation of Temperature Measurements to Structural Changes

The results summarized in Figures 11 and 12 for extremely severe grinding reveal the peak temperatures which must be reached for a given degree of tempering to occur for the grinding conditions used. It should be noted that the curve of hardness versus peak temperature in grinding would probably be higher for a single grinding pass because the degree of tempering at a given depth has resulted from repeated cycles of heating and cooling with a small increase in the peak temperature for each successive cycle.

In Figure 12 the shape of the curve of hardness versus peak temperature reached in grinding is similar to the curve for one hour at each tempering temperature. The displacement to higher temperatures at the same hardness is the effect of the much shorter times in the vicinity of the maximum temperature. The softening proceeds slowly at first, a peak temperature of about 600°F being required to produce a decrease in hardness from Rockwell C64 to Rockwell C63. It should be noted here that the microhardness measurements plotted are reliable for distances exceeding .001 inch from the surface. Sample G-19 was severely ground at low work speed so that the penetration of heat would yield a hardness gradient permitting accurate microhardness measurements over a wide range of peak
temperatures. For values of D less than .001 inch the steepness of the actual temperature gradient must result in a very steep hardness gradient so that the measured microhardness is somewhat higher than the actual hardness because of the effect of the underlying material.

If one attempts to evaluate the softening beneath the surface of a sample ground under normal conditions, the use of microhardness measurements does not yield accurate quantitative information because of the steepness of the hardness gradient. Such microhardness measurements always underestimate the degree of softening. An example of this is shown in Figure 11. Some of the actual hardness measurements are plotted as individual points to show the experimental scatter of the microhardness measurements. The minimum hardness measured was about 600 kg/mm² in the ground sample whereas in the samples heated electrically, it was observed that the minimum hardness due to overtempering was 505 kg/mm².

Near the ends of the thin strips numbered S-14 and S-15 which were rehardened in the heated sections, the cooling effect of the copper clamps imposed a steep temperature gradient with a resultant gradient in degree of tempering extending from the cold end toward the center section which was heated to a constant temperature for about one-half inch. The important feature of these
Gradients in peak temperature and structure were that they became less steep toward the rehardened zones in contrast to the gradient near the surface of sample G-19. Microhardness measurements along longitudinal sections of S-14 and S-15 therefore gave results which could not have been affected by the underlying material or by a very steep gradient in structure. That the hardness of the material which just failed to be reaustenitized must be lower than the 595 Kg/mm² measured in Sample G-19 is further demonstrated by the extrapolation of the curve of hardness versus peak temperature in Figure 11. The hardness predicted by this extrapolation for a peak temperature of 1500°F is about 500 Kg/mm². Thus the actual curve of hardness must follow the path indicated by the broken line in Figure 11 with a peaked minimum at about 500 Kg/mm².

For higher work speeds than 20 feet per minute the curve of peak hardness versus peak temperature will be displaced to the right, i.e., a somewhat higher peak temperature will be required for a given degree of tempering to occur because the effective time in the vicinity of the peak temperature will be less. However, since temperature is so much more powerful than time in the kinetics of tempering, the shift in the curve with work speed is expected to be small. (A 400°F increase
in temperature is equivalent to an estimated factor of $10^6$ in time in producing a hardness equivalent to Rockwell C60.)

The grinding severity encountered in normal commercial finish grinding is such that the extent of structural change is usually confined to values of $D$ less than a few thousandths of an inch. The lateral variation in temperature is appreciable. However, from the data of Figure 14, for example, and the knowledge of the temperature range corresponding to the boundary of the rehardened zone, the nature of the temperature gradient can be inferred from the observed structural changes.

The heating rate for the steel near the surface which is rehardened was measured to be about $500,000^\circ F$ per second for a work speed of 20 feet per minute. This heating rate decreases as the peak temperature is approached but the fact that commercial grinding work speeds may be in excess of 200 feet per minute indicates that $5 \times 10^5$ $^\circ F$ per second is a typical heating rate for material near the surface in surface grinding. The effect of heating rate on the critical temperature for several steels has recently been reported for heating rates up to $2400^\circ F$ per second by Feuerstein and Smith. The data obtained for hardened 52100 in this investigation have been compared with their data for 4130 steel hardened and tempered at $400^\circ F$. 
Extrapolation shows that for $5 \times 10^5 \, ^\circ\text{F}$ heating rate, the temperature required to form austenite in hardened 52100 is about $1600^\circ\text{F}$. Because of the compressive stress generated near the surface by the non-uniform heating in grinding the actual temperature required to form austenite in grinding may be somewhat lower. Feuerstein and Smith reported a $50^\circ\text{F}$ rise in $\text{Ac}_1$ and $\text{Ac}_3$ when tensile stress of 4500 psi was applied to annealed 1080 steel. This shift is in accordance with that predicted by the Clapeyron equation \[ \frac{dT}{dP} = T_e \frac{\Delta V}{\Delta H} \] where $T_e$ is the equilibrium temperature, $\Delta V$ is the volume change for the transformation (negative for $\alpha \to \gamma$) and $\Delta H$ is the enthalpy change in the transformation (positive for $\alpha \to \gamma$). The same relation would predict a depression of the transformation temperature for a given heating rate by a compressive stress. Thus it is reasonable to conclude that the temperature required to form a rehardened structure in hardened 52100 is between 1500 and $1600^\circ\text{F}$ for a moderate grinding work speed. Increasing degrees of prior tempering will move the temperature required to form austenite toward the high side of this range as will increased work speeds which give higher heating rates. The stress effect is in the opposite direction so that $1500^\circ\text{F}$ to $1550^\circ\text{F}$ is the most likely range for austenite formation by the heat produced in surface grinding.
The knowledge of the peak temperature required to produce perceptible tempering and that required to produce rehardening can be used to infer the steepness of the temperature gradient near the surface from the metallographic examination of a taper section of a ground sample. In Figure 14, for example, the distance between the boundary of the rehardened zone and the last perceptible tempering is .8 inch on the photomicrograph. The effective vertical magnification is 12,500X because of the taper section, so point a and b represent a difference in depth of $64 \times 10^{-6}$ inches. Since point a experienced a peak temperature near 1500°F and point b a peak temperature of about 700°F, the average temperature gradient between a and b was $12.5 \times 10^6 \, ^\circ F$ per inch. Extrapolating linearly to the surface gives an estimated surface temperature of 1900°F. The actual surface temperature was probably somewhat higher since the temperature gradient may be expected to become even greater nearer the surface.

A striking example of the errors of microhardness measurements made in such a sample is shown in Figure 14. The indicated hardness just under the rehardened zone was about 850 Kg/mm² whereas the foregoing discussion indicates that a more likely actual value would be at least 200 to 300 Kg/mm² less.
It was noted that the steel in the gross asperities was usually overtempered whereas most of the rehardened zones were at the bottom of the scratches made by individual grits, these latter being the zones immediately beneath the rapidly moving grits. The "spears" of rehardened material appearing in the taper section are seen to have a very narrow zone of overtempering beneath and to either side of them. The narrow zone of overtempering reflects the very steep temperature gradients which were present. If yielding took place because of the non-uniform thermal expansion, the steep temperature gradient produced a correspondingly steep residual tensile stress gradient. In addition, the overtempered material just beneath the rehardened zone has undergone contraction proportional to the degree of tempering, generating additional residual tensile stress.

If one obtains the value of compressive strain resulting from the non-uniform heating near the surface by simply multiplying the thermal expansion coefficient by the temperature rise and estimates the compressive stress by multiplying the strain by the elastic modulus, the stress generated is found to be about 23,000 psi per 100 degrees Fahrenheit rise in temperature. This estimate assumes that thermal expansion takes place freely normal to the ground surface and laterally, but is completely restrained in the direction of work travel.
It is pure speculation to estimate the temperature at which yielding would occur under these conditions for hardened steel, but a stress of 207,000 psi for a temperature rise of 900°F beneath a ground surface could conceivably cause yielding in 52100 steel tempered an hour at 450°F without any metallographically detectible burn or overtempering. This is important because the absence of metallographically detectible burning does not then constitute evidence of no grinding damage with respect to residual stresses. Furthermore the relation of structural changes to temperature history in grinding will be useful in analyzing the effects of grinding on residual stresses in hardened and tempered steel.

With some knowledge of the relation of temperature distribution to structural changes occurring in grinding, the effect of some of the mechanical variables in grinding on the temperature distribution is the next logical item of interest.

Effect of Mechanical Variables on Temperature Distribution

The temperature distribution from Sample G-19 was included for comparison with several temperature distribution curves for more normal grinding conditions in Figure 16. The shape of the curves is similar even though the grinding conditions vary widely. As the severity of grinding is decreased, the temperature at any value of D decreases.
Figure 16

Peak Temperature Distribution for Various Grinding Conditions

<table>
<thead>
<tr>
<th>Curve</th>
<th>d inches</th>
<th>V ft./min.</th>
<th>Wheel Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.0005</td>
<td>20</td>
<td>37C60P5v (sic)</td>
</tr>
<tr>
<td>b</td>
<td>0.0001</td>
<td>30</td>
<td>38A60H8VG (Al₂O₃)</td>
</tr>
<tr>
<td>c</td>
<td>0.0001</td>
<td>60</td>
<td>&quot;</td>
</tr>
<tr>
<td>d</td>
<td>0.0005</td>
<td>60</td>
<td>&quot;</td>
</tr>
<tr>
<td>e</td>
<td>0.000011</td>
<td>250</td>
<td>&quot;</td>
</tr>
<tr>
<td>f</td>
<td>0.000011</td>
<td>250</td>
<td>&quot;</td>
</tr>
<tr>
<td>g</td>
<td>0.000011</td>
<td>250</td>
<td>&quot;</td>
</tr>
</tbody>
</table>
Since the temperature at any point should be related to the quantity of energy being introduced, the temperatures at various values of D were compared with the total energy input to the surface in Figure 17. The energy input was obtained from force measurements made under the same conditions as the temperature measurements. The total energy input per unit area was obtained as follows:

\[ Q_A = \frac{F_H (V + v)}{12bv} \]

where:  
- \( F_H \) = horizontal force component in lbs.,
- \( V \) = surface speed of grinding grits (\( \frac{\pi D' N}{12} \)) in feet per minute,
- \( D' \) = wheel diameter in inches,
- \( v \) = work speed in feet per minute,
- \( b \) = width of contact between wheel and work in inches,
- \( Q_A \) = total grinding energy per square inch of work area ground in a plunge cut.

From \( Q_A \) and Figure 17, an approximate idea of the temperature distribution in the work being ground may be obtained for plunge grinding. It is not implied that all the grinding energy enters the work as heat, but that the fraction of the total grinding energy which actually enters the work as heat does not vary widely. To test the validity of this
Figure 17: Peak temperature plotted against $Q_A$ for various values of D. Obtained from force measurements and curves of Figure 18.
assumption it is worthwhile to examine how the grinding energy may be distributed. The heat generated by the chip formation will flow into the chip being formed and into the work. As mentioned in the introduction, an estimated 35% of this shear energy flows into the work. Nearly all of the energy used to overcome friction between the grit and work enters the work. The relative magnitude of the shear energy compared to the total energy is unknown but some simple calculations give some pertinent information. If one assumes the maximum reasonable temperature possible for the chips being ejected by the grinding, the maximum quantity of heat leaving with the chips can be estimated and compared with \( Q_A \). Assuming that the chips leave as solid metal at the melting point, the estimated heat content was approximated by the heat content of pure iron at the melting point and designated \( Q_c \). From the weight of chips removed per square inch of area ground for values of \( d \) and \( V \), the maximum heat carried away by the chips was calculated. The results are summarized in Table 3.

The actual temperature of the chips is certainly well below the melting point for even when grinding is done dry only a small fraction of the chips are hot enough to become molten although they are heated further by oxidation after leaving the work as shown in Figure 18a. Thus the estimated fraction of \( Q_A \) entering the work is larger than the tabulated
<table>
<thead>
<tr>
<th>V ft./min.</th>
<th>d inches</th>
<th>$q_A$ ft lb/sq in.</th>
<th>$q_C/q_A$</th>
<th>$q_S/q_A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>.0001</td>
<td>46</td>
<td>.220</td>
<td>.34</td>
</tr>
<tr>
<td>60</td>
<td>.0002</td>
<td>76.7</td>
<td>.265</td>
<td>.41</td>
</tr>
<tr>
<td>60</td>
<td>.0005</td>
<td>145.8</td>
<td>.358</td>
<td>.55</td>
</tr>
<tr>
<td>30</td>
<td>.0001</td>
<td>45.8</td>
<td>.222</td>
<td>.34</td>
</tr>
<tr>
<td>30</td>
<td>.0002</td>
<td>76.3</td>
<td>.266</td>
<td>.41</td>
</tr>
<tr>
<td>30</td>
<td>.0005</td>
<td>183</td>
<td>.276</td>
<td>.43</td>
</tr>
<tr>
<td>30</td>
<td>.0010</td>
<td>366</td>
<td>.302</td>
<td>.47</td>
</tr>
<tr>
<td>26</td>
<td>.000093</td>
<td>5.08</td>
<td>.185</td>
<td>.29</td>
</tr>
<tr>
<td>26</td>
<td>.000093</td>
<td>48.8</td>
<td>.193</td>
<td>.30</td>
</tr>
</tbody>
</table>
Figure 18a: Typical chips formed by dry grinding of hardened 52100. 120X

Figure 18b: Photograph of some of the grits which generated the chips in a, above. Metal pick-up and chips are evident on the grits which were in contact with the steel. 120X.
values and does not vary widely or abruptly as the severity of grinding is changed over a wide range. Since such a large proportion of the grinding energy enters the work and since the shear energy appears to account for less than half of the total energy input, the factors affecting the friction between grits and work are very important in determining quantity of heat entering the work. This fact is shown clearly by the variation in temperature distribution observed for grinding conditions as nearly identical as possible shown in Figure 16, curves e, f and g.

The grinding conditions used were identical except for the condition of the wheel. For curve e, the wheel had become glazed from grinding at the same feed rate on the rotary grinder for about 10 minutes without dressing. Prolonged grinding at light values of downfeed per revolution caused considerable attritious wear. Unfortunately force measurements were not made simultaneously with the temperature measurements. A significant trend was noted however if the observed temperature distribution was used to deduce the value of $Q_A$ from Figure 13. The value of $Q_A$ changed as the ground surface approached the thermocouple. This progressive change could only be due to a change in the condition of the wheel.

The practical importance of these observations is that a simple measurement of the value of $Q_A$ will provide a
quantitative approximation of the peak temperature distribution near the surface being ground. It would hardly be convenient to measure the forces and obtain $Q_A$ as has been done in this investigation, but the power consumption during grinding may be compared with that when the wheel is idling and an estimate made of $Q_A$ from the following equation:

$$Q_A = \frac{\text{Power input in ft. lb./min.}}{12 \text{ by}}$$

where $b$ and $v$ are the same as in the previous equation, p. 52.

Since the heat penetration is probably the principal source of damage in grinding such estimation of $Q_A$ provides a quantitative criterion of the potential tending to cause damage. In a given grinding operation, for example it might be used as a guide in determining at what point the grinding wheel ought to be redressed.

The condition of the grits in contact with the work after prolonged grinding is shown in Figure 18b.

The mechanical factors which decrease $Q_A$ have been found to be: (1) a decrease in the wheel depth of cut $d$, (2) an increase in work speed $v$, (3) the sharpest possible wheel which will produce an acceptable surface finish. The effect of $d$ and $v$ are shown in Table 3 (p. 55). Changing $d$ by a factor of 10 changes $Q_A$ by a factor of 8. This explains why a "spark out" is so effective in removing the
heat effects of previous passes without producing new heat
affected zones of any appreciable depth. The effect of
increased work speed is most strikingly shown by comparing $Q_A$ for the work speeds of 26 and 260 feet per minute at a
constant feed rate of .0023 inches per minute on a rotary
grinder. The rate of stock removal is constant but $Q_A$ is
5.08 ft. lbs. per square inch for the higher work speed
compared to 48.8 ft. lbs. per square inch for the work speed
slower by a factor of ten.

One final comment is in order with regard to grinding
coolants. Since the heat generated in grinding can flow by
metallic conduction into the work much more readily than into
the coolant, the coolant actually removes the grinding heat
from the work surface in front of and behind the area of
contact between wheel and work. This is a necessary function
if the work is to be ground to very high dimensional tolerances
because no bulk temperature rise can be permitted which will
cause the part to be ground undersize. The fluid can minimize
the grinding heat generated by exerting a beneficial influence
on lubrication between grits and work and thus reducing $Q_A$.
Mayer has found a reduction of $Q_A$ by 50% for the best of
several grinding coolants compared to grinding dry or with
tap water as a coolant. The logical criterion for evaluation
of grinding coolants on the basis of this investigation is
the effect of the coolant on $Q_A$. 
Transformation of Austenite in Grinding

Austenite formed near the surface by the heat generated by grinding behaves differently from that quenched in a sample homogeneously heated. Evidence of this is the abnormally high retained austenite indicated by X-ray measurements at the surface and confirmed by Figure 19. This abnormally high retained austenite content may be attributed to the high austenitizing temperatures which approach the melting point. The extremely small size of the martensite plates formed in the high austenite areas indicate a subdivision of the structure by plastic flow which limits the size of the martensite plates which can form, another factor tending to limit the extent of martensite formation.

Examination of the zone which just failed to be re-austenitized shows that little if any transformation of retained austenite to bainite takes place in the prior structure as shown in Figure 20. It is interesting to note that the prior austenite grain boundaries were rehardened more readily than the interior of the grains.

Figure 21 shows the transformation which took place in the zone around a microhardness impression made in the re-hardened zone of Sample Y-1 indicating the tendency of the retained austenite in such rehardened zones to transform to martensite when subjected to plastic deformation in compression.
Figure 19: Structure near the surface of sample Y ground repeatedly under extremely severe conditions. Sample taper-sectioned (1/25) and tempered 7 seconds at 700°F to "darken" the martensite present before polishing. 1000X. Etch: 4% Nital with Zephiran Chloride.
Figure 20: Structure in the region between completely rehardened and only overtempered zones. Rehardening is evident in prior austenite grain boundaries. The coarseness of the original structure is contrasted with the fineness of the structure in the rehardened area. 1000X. Etch: 4% Nital with Zephiran Chloride.
Figure 21: Transformation in the zone around a micro-hardness impression (100 gram load) made in the rehardened zone of sample Y. Martensite "darkened" by tempering 7 seconds at 700°F after the microhardness indentation. 1000X Etch: 4% Nital with Zephran Chloride.
It was found that some of the retained austenite in the prior structure did transform to martensite after having reached the peak temperature in the overtempered region. Figure 22 shows lighter etching small martensite in some of the original retained austenite. This transformation probably occurred during the cooling as the work moved past the grinding contact area. It might have taken place as a result of plastic deformation of the retained austenite during cooling because of the non-uniformity of the heating and cooling or because of a change in the micro-stress distribution favoring further transformation.

It is questionable whether the behavior of retained austenite in these samples hardened from 1900°F can be extrapolated to predict the same behavior in 52100 hardened from 1550°F, but it at least suggests that similar effects may be possible.
Figure 22: Martensite formed within retained austenite volumes in overtempered region of sample Y-11. Darkening of martensite in prior structure was due to grinding heat. 2500X. Etch: 4% Nital with Zephiran Chloride.
IV CONCLUSIONS

1. The temperature distribution has been measured as a function of depth below the surface of hardened 52100 steel by welding a constantan wire to the bottom of a hole extending nearly to the surface and observing the output of the thermocouple so formed on a cathode ray oscillograph. The measurements so made represent the actual temperature distribution with a maximum error ± 30°F for distances from the surface exceeding .001 inch.

2. The structural changes which occur under the influence of heat generated by grinding have been shown to be related to the peak temperatures experienced at a given position in the steel being ground. The peak temperature required to produce a hardness change from Rockwell C64 to Rockwell C63 in 52100 steel by tempering reaction was found to be about 600°F. The peak temperature required to reaustenitize hardened and tempered 52100 steel for the type of heating cycles experienced in grinding is between 1500 and 1600°F. Knowledge of the peak temperatures required to produce a given structural change permits estimation of the temperature distribution for heat affected structures so close to the ground surface that direct measurement is impossible. The lower boundary of the rehardened region must have reached 1500 - 1600°F, and the deepest evidence of
overtempering for 52100 tempered to Rockwell C64 must correspond to at least 600°F. For a sample ground with a feed of .0005 inch per pass at 60 ft./min with an abundance of fluid showed a gradient of about 1250°F per .0001 inch close to the surface being ground. The surface temperature extrapolated from such measurements on that sample was in excess of 1900°F.

3. The distribution of peak temperatures versus depth for depths beyond .0005 inch appears to be uniquely related to the energy input per unit area of the surface being ground for work speeds from 30 to 250 ft. per minute and a range of wheel depths of cut from 10 x 10⁻⁶ to 10⁻³ inches per pass. For depths less than .0005 inch, lateral temperature variations become appreciable.

4. Between 65 to 95% of the total grinding energy flows into the work as heat. More than half of the total grinding energy is used to overcome friction between the abrasive grains and the work and does not contribute to chip formation.

5. The mechanical factors which minimize the heat introduced in grinding are decreased wheel depth of cut, increased work speed, lubrication by the coolant, and the sharpest wheel which will produce an acceptable surface finish.

6. In samples of 52100 quenched from 1900°F and ground severely, the rehardened layer contained retained austenite.
up to 70% which was susceptible to transformation when plastic deformation was imposed. Untempered martensite was formed in the retained austenite of the structure prior to grinding as a result of the grinding operation.
V SUGGESTIONS FOR FUTURE WORK

1. An electron microscope study should be made of the structural changes for the short time, high temperature cycles experienced in grinding to see whether the mechanism of tempering is different for the conditions encountered beneath a ground surface. This study could be expected to shed light on the question whether a given hardness change corresponds to the same degree of tempering for the extremely short times at temperature in grinding and whether compressive stresses affect the rate of reaction.

2. The effect of stress and heating rate on the critical temperatures should be extended to include more rapid heating rates for various prior structures.

3. The relationship of $Q_A$ to temperature distribution should be checked for a wider variation of conditions with simultaneous measurement of temperature distribution and forces or energy input.

4. The residual stresses produced by grinding should be compared with the distribution of structural changes and temperature to determine their principal origin.

5. The behavior of retained austenite near the ground surface should be investigated for steel hardened according to normal heat treating practice.
BIBLIOGRAPHY


BIBLIOGRAPHY
con't.


18. Mayer, J., Unpublished research at the Metal Cutting Laboratory of M.I.T.
BIOGRAPHICAL NOTE

The author was born in the home of a Lutheran Minister in Cincinnati, Ohio on November 14, 1926. He received elementary education at a parochial school and graduated from Withrow Public High School in that same city. After two years service in the United States Navy he entered the University of Cincinnati, pursuing a cooperative course in Metallurgical Engineering. His cooperative employment included experience in electroplating, steel manufacture, and foundry practice. After graduation from the University of Cincinnati in June 1950 with the degree of B.S. in Metallurgical Engineering, he entered the graduate school of the Massachusetts Institute of Technology. He received the S.M. in Metallurgy from the Massachusetts Institute of Technology in June 1952.

The author was married to Jane Colley in December 1949 and the marriage blessed with two sons during residence at M.I.T.

The author was honored by the Cincinnati chapter of the American Society for Metals with the Esslinger award for the outstanding student in Metallurgy at the University of Cincinnati in 1950 when he was also elected an associate member of Sigma Xi.