THE HOT QUENCHING OF MOLYBDENUM-TUNGSTEN HIGH SPEED STEEL

by

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THESIS

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INTRODUCTION

History and Development

High Speed or "Rapid" Steels belong to that class of high alloy tool steels which have the particular property of retaining a relatively high hardness even though operating at elevated temperature. This characteristic is referred to as "hot hardness" and it is a necessity in tools that function at the high surface speeds used in modern metal cutting practice.

The original high speed type of steel was made quite accidently by Robert F. Mushet in Sheffield, England, in 1868. After some experimenting, it was marketed as "R. Mushet's Special Steel," the chemistry of which was approximately:

Carbon	2.0%
Tungsten	5.0
Manganese	2.5
Silicon	1-1/3
Chromium	0.5

Further experiments resulted in a lowering of the carbon and silicon and in replacing most of the manganese with chromium. Mushet's steel could be hardened without the usual quench and was, therefore, called a "self-hardening" steel.

In 1894 Frederick W. Taylor began experimenting with Mushet's and other self-hardening tool steels in an effort to improve the cutting efficiency of his tools and thereby promote his program of shop efficiency and scientific shop management.

Taylor and his associates, notably Maunsel White, set about improving upon the then existing self-hardening steels. After much experimenting and some failures Taylor and White in 1898 more or less stumbled upon the "high heat" treatment necessary to develop the maximum cutting ability in their high speed steel. To quote from On The Art of Cutting Metals, paragraph 110: (1,p.24)*

"Thus, the discovery that phenomenal results could be obtained by heating tools close to the melting point, which was so completely revolutionary and directly the opposite of all previous heat treatment of tools, was the indirect result of an accurate scientific effort to investigate as to which brand of tool steel was, on the whole, the best to adopt as a shop standard; neither Mr. White nor the writer having the slightest idea that overheating beyond the bright cherry red would do anything except injure the tool more and more the higher it was heated."

In 1906 Taylor and White discovered "that by adding a small quantity of vanadium to tool steel to be used for making modern high chromium-tungsten tools heated to near the melting point, the hardness and endurance of tools, as well as their cutting speeds, are materially improved." (1,p.11)

The analysis of Taylor's most satisfactory high speed steel (determined by exhaustive and, no doubt, exhausting experimentation) was approximately:

Carbon	0.7%
Tungsten	18.0
Chromium	5.5
Manganese	0.1
Vanadium	0.3

Marked differences between Taylor's high speed steel and Mushet's special steel are clearly evident. The carbon content was reduced markedly while tungsten and chromium were increased and manganese was all but eliminated. (The soundness of the Taylor-White research is borne out by the fact that during the following 25 years over 3/4 of

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*Number of the reference in Bibliography.

the high speed steel manufactured was, except for vanadium, nearly the same analysis as that recommended by Taylor.)

The economic importance of high speed steel lured many tool steel manufacturers into the field. With competing companies conducting hundreds of experiments the development and treatment of high speed steel advanced rapidly.

The chemical composition of modern high speed steels is the result of the years of experience in its manufacture. The alloying elements used and typical quantities are as follows:

Tungsten (W) - 18% combined the best advantages of wearing properties, cutting ability, and toughness.

Chromium (Cr) - 4% gives best balance between toughness and hardening ability.

Vanadium (V) - 1 to 2% definitely increases cutting efficiency and improved toughness.

Molybdenum (Mo) - 5 to 8% with 1½ to 6% W has essentially the same effect as 18% W.

Cobalt (Co) - 4 to 12% in the cobalt high speed steels. Cobalt serves to increase the red hardness and also the brittleness. Cobalt high speed steels exhibit undesirable surface decarburization unless protected.

Manganese (Mn) - Not over approximately 0.3% to avoid grain coarsening at the high quenching temperature.

Silicon (Si) - 0.3% or less is satisfactory.

Prior to the present war the great number of commercial high speed steels were usually grouped into three general classifications:

1) Tungsten high speed steels which are applicable to all classes of cutting tools to be used on most all materials. This type accounted for over 75% of the high speed steel used in 1940.

   a) 18% W; 4% Cr; 1% V.) Commonly known as 18-4-1,
   b) 18% W; 4% Cr; 2% V.) 18-4-2, and
   c) 14% W; 4% Cr; 2% V.) 14-4-2, respectively.

2) Cobalt type which is essentially of the tungsten type but with 4 to 12% Cobalt added. These steels are exceptionally well suited to cutting hard, gritty, or scaly metals, such as sand castings,heat treated steels, and cast iron.

3) Molybdenum type usually containing 8% Mo. with 1½ W in addition to the usual chromium, vanadium, and carbon. The hardness and toughness of this type compare favorably with the tungsten type.

In the years preceding 1941, the high speed steel industry annually consumed about 3/4 of the tungsten used in the United States. With the advent of hostilities in the Far East, one of our principal sources of imported tungsten was cut off. In order to conserve the stock of tungsten and make domestic and hemispherical supplies meet the demand, it became imperative that we introduce new or alternate high speed steels or use those of an existing type which required less tungsten and more domestically produced molybdenum. (Since as the WPB has recently stated, the U.S. produces 85% of the world's output of molybdenum.)[2]

In June 1941, the Office of Production Management issued General Preference M-14 to conserve the supply and direct the distribution and use of tungsten in high speed steel.

According to the provisions of Order M-14, users of high speed steel were required to use as much molybdenum high speed steel, by weight, as the tungsten type. Incidentally, the government now (April 1943) requires that three times as much molybdenum steel be used as the high-tungsten type.

It is, therefore, evident that molybdenum high speed steels are of vast current importance and a brief resume of their development is herewith presented.

Taylor, White, and others,during their early researches, found that molybdenum was more effective than tungsten in its alloying effect.

Indeed, around 1900 it was thought that molybdenum would become the major alloying element in high speed steel. There was, however, one serious objection to molybdenum steels--notably, the proneness to decarburization at elevated temperatures and resultant soft spots on the hardened tool.

In 1917 an attempt to utilize molybdenum was made because of the scarcity of tungsten. However, the molybdenum high speed steels produced were not seriously regarded by industry, and nothing more was done until 1930 when the Ordnance Department of the U.S. Army carried out investigations at Watertown Arsenal and concluded that molybdenum could replace tungsten in high speed steels if the necessity arose.

In 1933 a patent was issued to J. V. Emmons and assigned to Cleveland Twist Drill Company on a molybdenum tungsten high speed steel containing 8% Mo, and 1½% W, later known to the industry as "Momax." Decarburization was still a problem, however, and during the period from 1933 to 1938, much research was conducted in an attempt to overcome decarburization. Boron additions were tried but brought on rolling difficulties. Boron and Cobalt used together proved satisfactory.

During this period protective atmosphere furnaces and salt baths for the hardening of high speed steel were developed and did much to alleviate the decarburization problem.

A recently developed high speed steel, the one used in this investigation, contains about 5% Mo, 5½% W, and 1½% V, in addition to the usual chromium. The decarburization tendency of this steel is not serious, being no more pronounced than in the high tungsten type.

Heat Treating Practice for High Speed Steel

Temperature ranges given are general - the actual temperature used depends upon the chemistry of the steel, the size and shape of the section, and the use to which the tool is to be put.

1. Preheat

   Because of the low thermal conductivity of high speed steel, preheating is desirable to prevent undue distortion or even cracking. Also, preheating decreases the time necessary at the high hardening temperature and thereby reduces grain coarsening and brittleness. During preheating simple carbides are dissolved in the austenitic matrix. The usual preheat range is 1450 to 1600 F. In large or irregular sections, a double preheat at 1100 to 1250 F followed by 1450-1600 F is advantageous.

2. High Heat

   Immediately after preheating, the tool is transferred to the high heat furnace and brought rapidly to temperature. The object is to hold the tool for sufficient time to get proper solution of the complex carbides, without excessive grain coarsening or surface damage. Under proper conditions, most of the complex carbides are dissolved in the austenite, only the larger(or primary) carbides being undissolved. The usual temperature range is 2150 to 2450 F, and the time at temperature is measured in minutes and seconds.

3. Quenching

   Since the austenite contains large amounts of alloy carbides it is quite sluggish, and the tool may be hardened by quenching in oil, molten baths at 1000-1150 F, or in air if the section is small.

The most common quenching medium has been, and still is, oil. The practice of quenching in molten baths (lead at 1150 F) was advocated by Taylor and White (1) in 1906, but such hot quenching procedure has come into general use only recently.

Hot quenching is important for several reasons among which are:

(a) Long tools such as broaches, drills, punches, etc. may be straightened as they cool in air from 1100± to 400 F, thus reducing the necessary grinding;

(b) The stresses due to quenching are less severe than during oil hardening; and

(c) Less cleaning is necessary than in oil hardening.

Regardless of the quenching medium used, high speed steel should cool to about 100 F before tempering.

4. Tempering

Quenched high speed steels contain considerable amounts of retained austenite along with the high alloy martensite and undissolved complex carbides. Under such conditions rather severe stresses are present and the toughness is low.

In order to develop maximum cutting efficiency and improved toughness the quenched high speed steels are tempered at 1000 to 1100 F for 2 to 4 hours. The tempering process has been thoroughly investigated by Cohen and Koh, (3)(8) who used X-ray, dilatometric and electrical tests. According to them, tempering normally proceeds as follows:

(a) As the quenched specimen is reheated up to about 600 F, the martensite is tempered and softens somewhat.

(b) From 600 ± to 1100± fine alloy carbides precipitate from the retained austenite so that:

(c) This austenite will transform to martensite on subsequent cooling to room temperature.

The effect of factors (b) and (c) is to increase the hardness whereas (a) causes some softening. As a result, the tempered hardness of a properly quenched high speed steel is usually higher than the hardness "as quenched." This phenomena is known as "secondary hardening." Since the austenite retained in the quench is not transformed until the cooling phase of the tempering operation, it is evident that quenched tools given a single temper may still have considerable "internal" stress due to the untempered martensite present (formed from the retained austenite). Therefore, multiple tempering is commonly practiced and is desirable from the standpoint of tool life and toughness.

TOPICS FOR INVESTIGATION

1. The literature on the treatment of high speed steel contains very little information concerning the effect of holding time at the quenching temperature when hot quenching practice is used. It is felt that such information would be helpful in determining the most suitable hot quenching procedure.

2. A comparison of hot quenching with oil quenching may shed light on the most satisfactory practice to be used for specific applications.

3. An investigation of hot quenching would have enhanced value if the steel used were one available for wide application at the present time. Such a steel, the author believes, is the recently developed molybdenum tungsten type. A comparison of the cutting efficiency of this new tool steel with the well known high tungsten (18-4-1) type would be of value.

SCOPE AND PURPOSE

The purpose of this investigation is:

(1) to determine the effect of time in the hot quench upon the physical properties of hardened molybdenum-tungsten high speed steel and to compare hot quenching with oil quenching.

(2) to evaluate hot quenching and oil quenching by means of lathe breakdown tests on hardened tool bits.

PROCEDURE

Physical Test Selected

In arriving at the proper type of test to evaluate the different heat treatments tension and impact tests were discarded as being subject to extreme variations due to uncontrollable factors. Torsion impact has been proposed as a means of measuring the toughness of tool steels, but equipment was not available for such tests.

The test chosen was the transverse bending of hardened beam specimens. The transverse test is well adapted to duplication of test conditions and gives an index of toughness as well as the transverse bending strength and maximum deflection under load.

Preparation and Heat Treatment of Test Beams

The test pieces employed were of the molybdenum-tungsten type high speed steel of the following chemical analysis:

Carbon	0.82%
Manganese	0.30%
Silicon	0.33%
Chromium	4.01%
Tungsten	5.65%
Molybdenum	4.99%
Vanadium	1.56%

Samples approximately 4½ inches long were cut from commercial ½ inch square annealed stock. These specimens were then shaped equally on all sides to 0.4 inch square and surface ground to 0.385 inch square preparatory to heat treatment. The heat treating procedure follows:

Preheat - Held 20 minutes at 1025 ± F and then 15 minutes at 1500 F.

High Heat - Following the double preheat the specimens were transferred to an electric furnace of the "globar" type, equipped with a carbonaceous block for protective atmosphere, operating at 2230 ± 5 F and held for 4 minutes.

<u>Quench</u> - Five different methods of cooling to room temperature were used:

1) Quench in still oil at 70 F.
2) Quench in lead at 1025 F for 2 minutes; cool in still air.
3) Quench in lead at 1025 F for 2 minutes; hold at 1025 F for 15 minutes; cool in the "holding" furnace.
4) & 5) Quench in lead at 1025 F for 2 minutes, hold at 1025 F for 1 and 2 hours respectively; cool in the "holding" furnace.

<u>Temper</u> - When cool any adhering lead was removed from the quenched specimens, and they were subjected to a double tempering operation for the purpose of removing quenching stresses and improving the hardness and strength. The cold specimens were placed in an unheated electric furnace and heated to 1025 F for 1 hour followed by cooling in still air. When cold they were again placed in an unheated electric furnace heated to 1025 F for 1 hour and furnace cooled.

The tempered specimens were carefully ground to approximately 0.375 inch square, and small mild steel pads 1/16 inch thick were cemented to the middle of the specimen to provide for the locating of the deflection bar on the neutral axis of the test beam. The specimens were then coated with layout dye, and their midpoint located and center punched lightly. From this point, the loading and supporting center lines were located and scribed.

<u>Transverse Testing Procedure</u>

The beams were tested on a Tinius Olsen hand operated testing machine capable of applying a maximum load of 12,800 pounds. The testing device was designed to apply the loads at the quarter points, thus subjecting the test beam to a constant bending moment between the loading points. The setup is shown in Figure 1, page 15. The method used in observing the deflection of the neutral axis is shown in

Figure 2, page 16. The actual testing procedure consisted of locating the beams in the testing device by the use of scribed center lines and applying an initial load of 100 pounds after which the two Ames dial gages were set on zero. Deflection readings were taken at load increments of either 500 or 1000 pounds until (and if) failure occurred.

Rockwell C hardness tests were made on the broken beam, the reported values representing the average of at least 20 tests.

<u>Lathe Breakdown Tests</u>

The test bits were prepared from ½ inch square by 3½ inches long stock of the same analysis as that used in the transverse bending tests.

Four bits were double preheated at 1025 and 1500 F for ½ hour at each temperature and "high" heated at 2235 for five minutes after which two were oil quenched and the other two hot quenched at 1025 F, held for 2 hours, then furnace cooled. All bits were double tempered at 1025 F, for 1 hour air cooled, followed by 1 hour, and furnace cooled.

These bits and two commerically hardened high tungsten (18-4-1) type tool bits of the same size were surface ground on a Norton grinder to remove all decarburized skin, then carefully ground to the desired shape (as specified on the lathe test summary, page 32) on an Oesterlein Tool Grinder. The nose radius was ground off hand. After grinding all cutting surfaces were hand honed, and the nose radius honed to fit a templet of the desired radius.

The test bits were rigidly supported in a heavy duty tool post and holder.

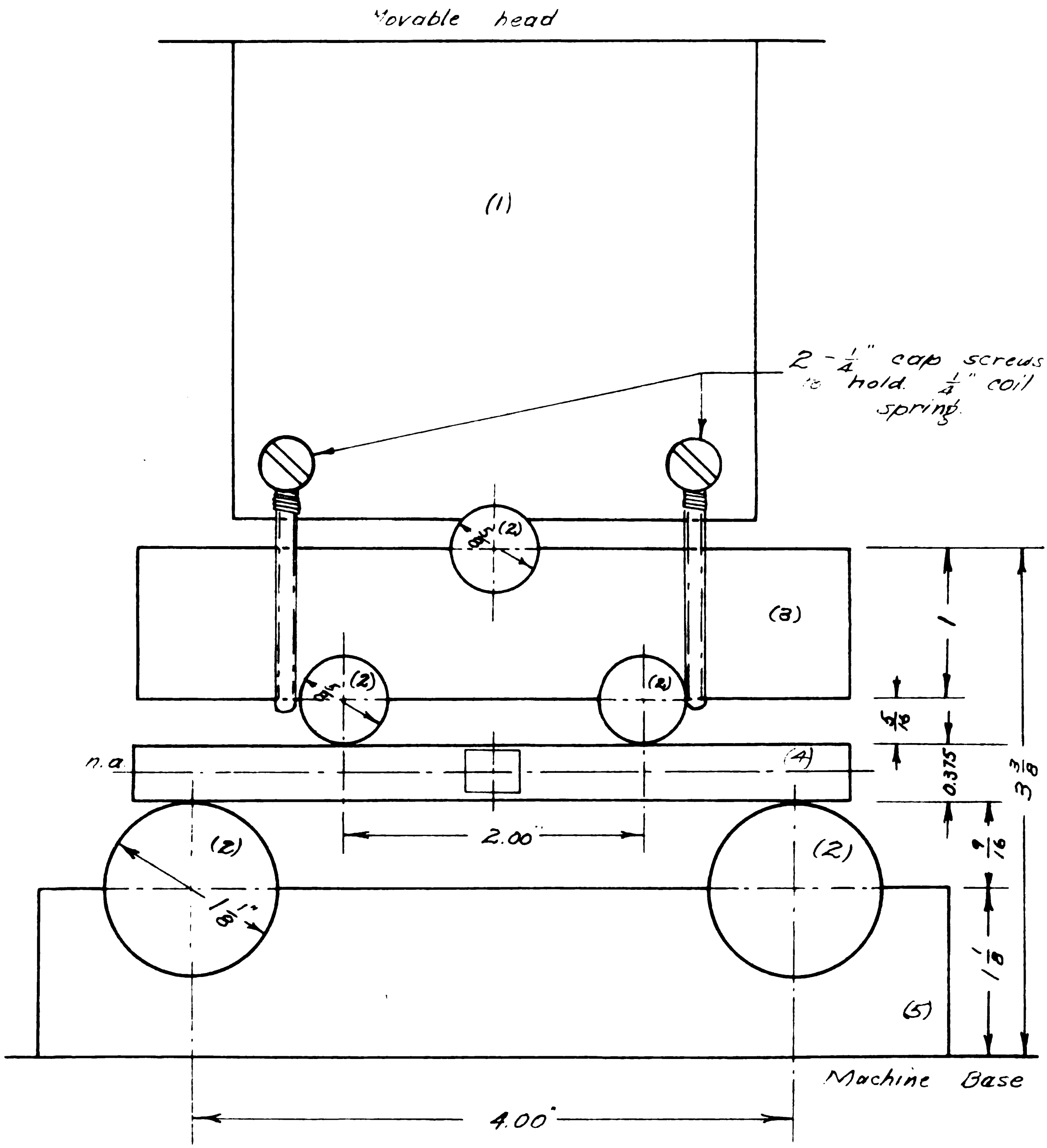
The work piece was a length of railway car axle (the specifications and physical properties of which appear on the lathe test summary, page 32), which was mounted in a 19" x 6' LeBlond Heavy Duty Geared Head Engine Lathe, equipped with a $7\frac{1}{2}$ hp motor and having 12 driving speeds and 36 feeds. Surface speed of the workpiece was measured by a Schurchardt & Schutte speed indicator which had been previously calibrated and found accurate.

The tool life under cut was measured by a stop watch, a check being made by measuring the length of cut. The tool was considered as having failed when worn to the extent that the diameter of the work piece increased 0.002" to 0.003".

LOADING DEVICE — FIG. 1

Showing means of applying bending moment to specimens. Dials and deflection harness not shown for greater clarity.

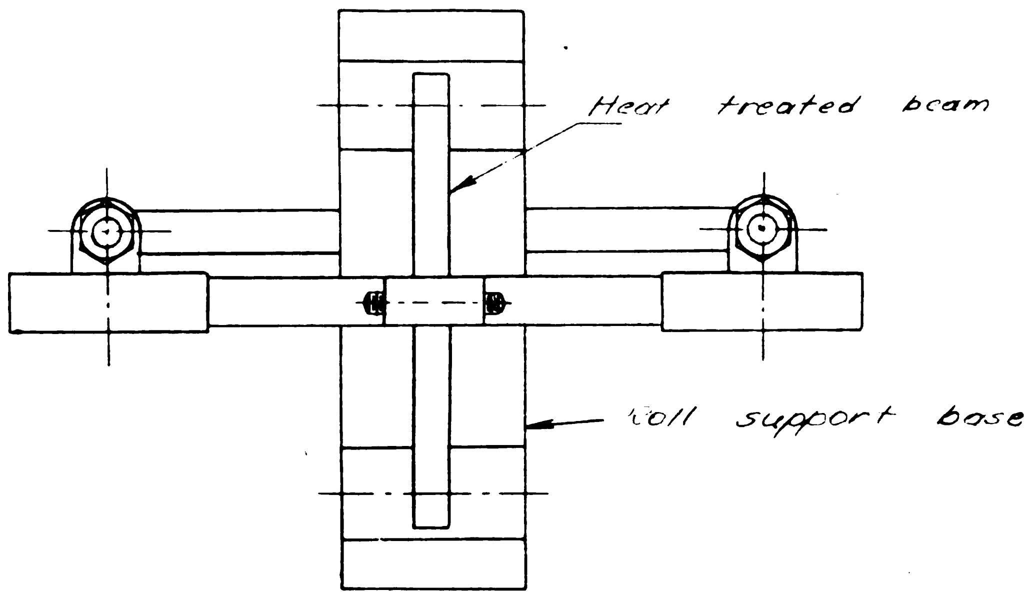
Full Scale

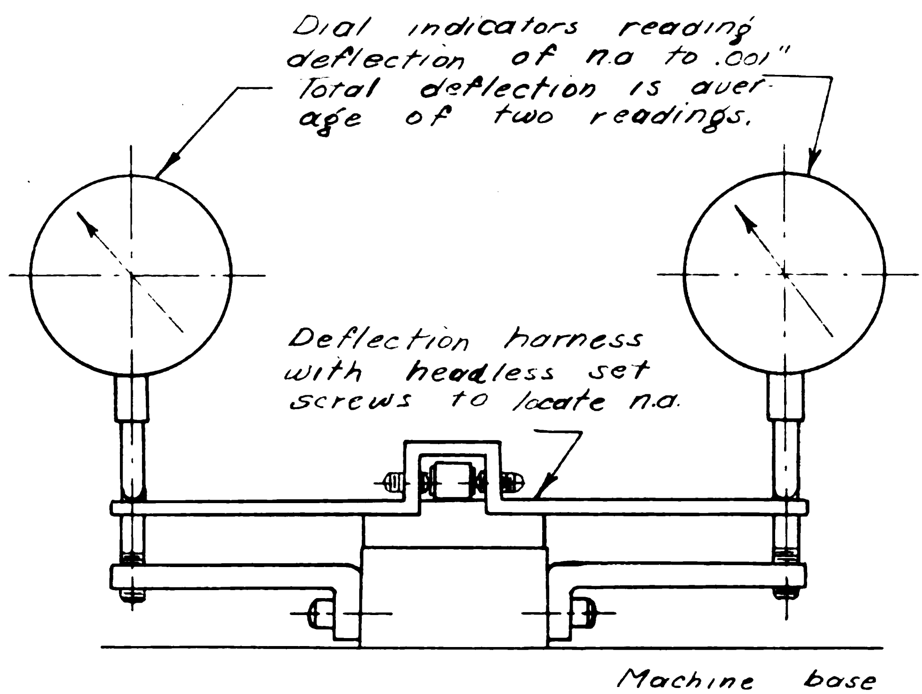


(1) Mild steel stock
(2) Carbon tool steel - quenched and tempered to 65 R_c.
(3) SAE 3250 - quenched and tempered to 500 BHN
(4) Test specimen 0.375 ins. square with 0.25' ins. sq. pads at midspan.
(5) SAE 1045 base quenched and tempered

DEFLECTION READING – FIG. 2

Showing position of deflection harness and use of dial indicators to obtain deflection of the midspan n.a. under equal increments of load. Loading head not shown here.
Half Scale





CALCULATIONS - DATA AND RESULTS

Transverse Bending Tests

Figure 3, page 19, shows the appearance of a test beam before and after application of the load. It is apparent that corrections were necessary in the beam span, the load moment arm, and deflection because of roll on the supports and under the loading head as the load was applied.

These corrections were established by both graphical and analytical means. The beam was assumed to take the shape of an arc of a circle between the supporting rolls. The corrections were determined for an indicated deflection of 0.140 inch and are linear functions of the indicated deflection. The deflection due to roll, span correction, and moment arm correction are plotted as functions of the indicated deflection on Figures 4, 5, and 6, pages 20, 21, and 22.

Calculations of the modulus of rupture and toughness were based on corrected values of moment arm, beam span, and deflection at the midpoint of the beam. The friction couple produced by the action of the loading and supporting rolls was neglected. The modulus of elasticity was determined for each test as a check on the testing procedure.

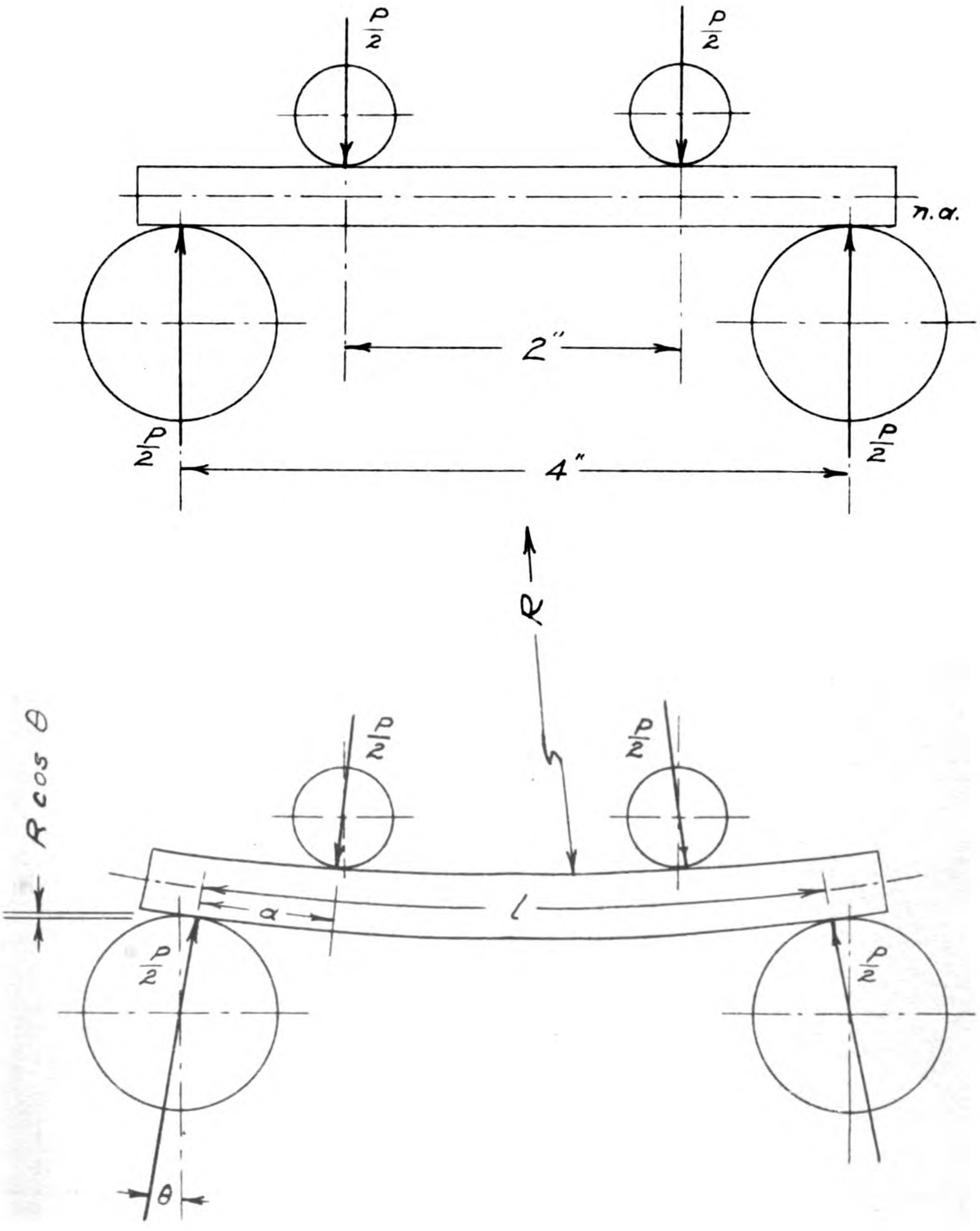
Toughness of the specimens was determined by the expression $T = \frac{1}{2}S^2/E$ which is strictly true only if the stress is proportional to the strain. In some tests this was not the case since the proportional limit had been exceeded. However, the method used places the toughness on the basis of the material and its treatment and does not depend upon the size or type of loading of the specimen. Since in most tests the deviation from a straight line relationship of stress to strain was slight, the value of toughness may be considered a very close

approximation. Figure 7, page 24, represents a typical load deflection curve.

The value of E (modulus of elasticity) used in the toughness calculations was 30,000,000 psi since the average of all experimental values was found to be 30,021,300.

FREE BODY DIAGRAM — FIG. 3

Showing action line of forces acting on beams before and after application of loads by machine.



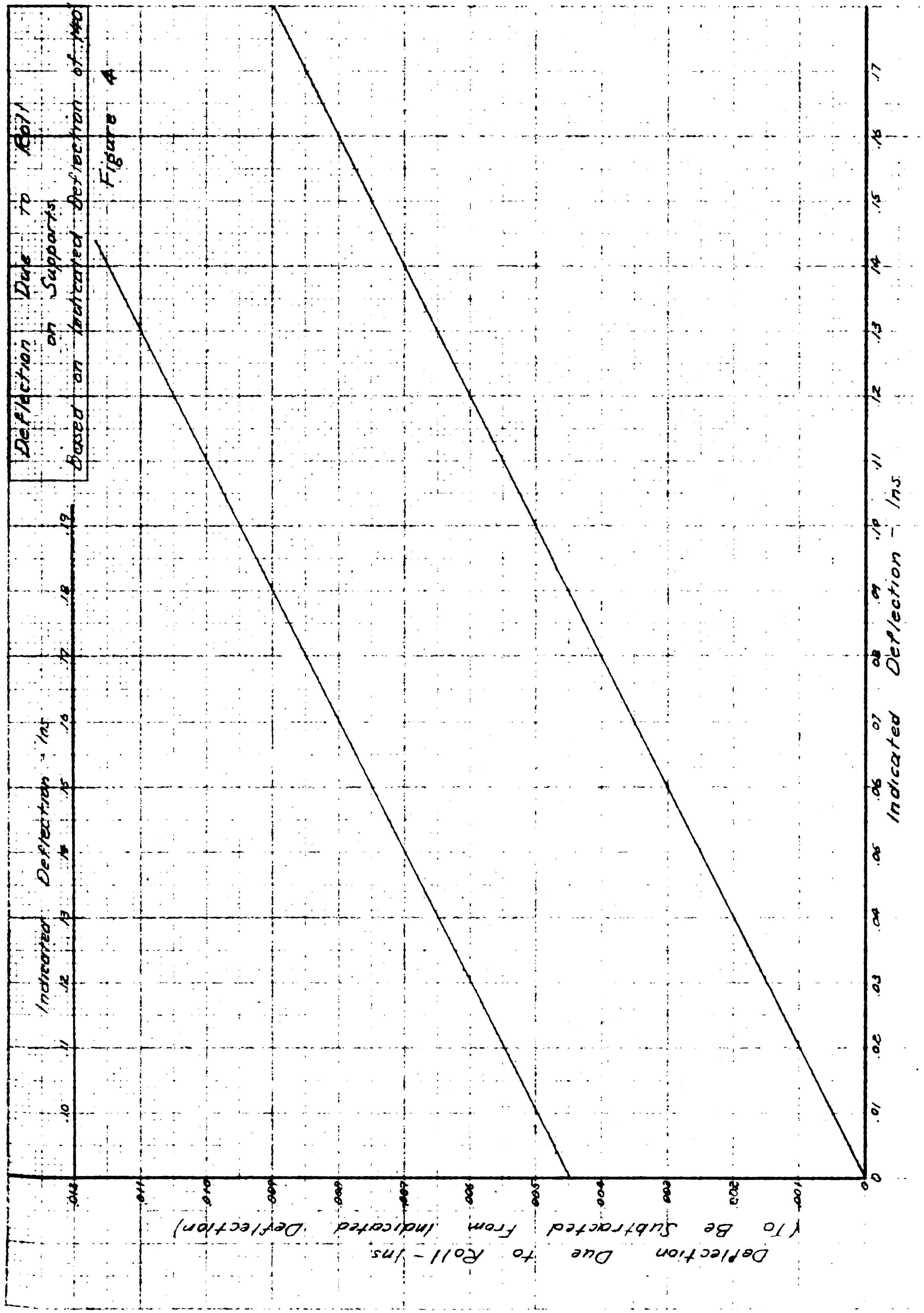
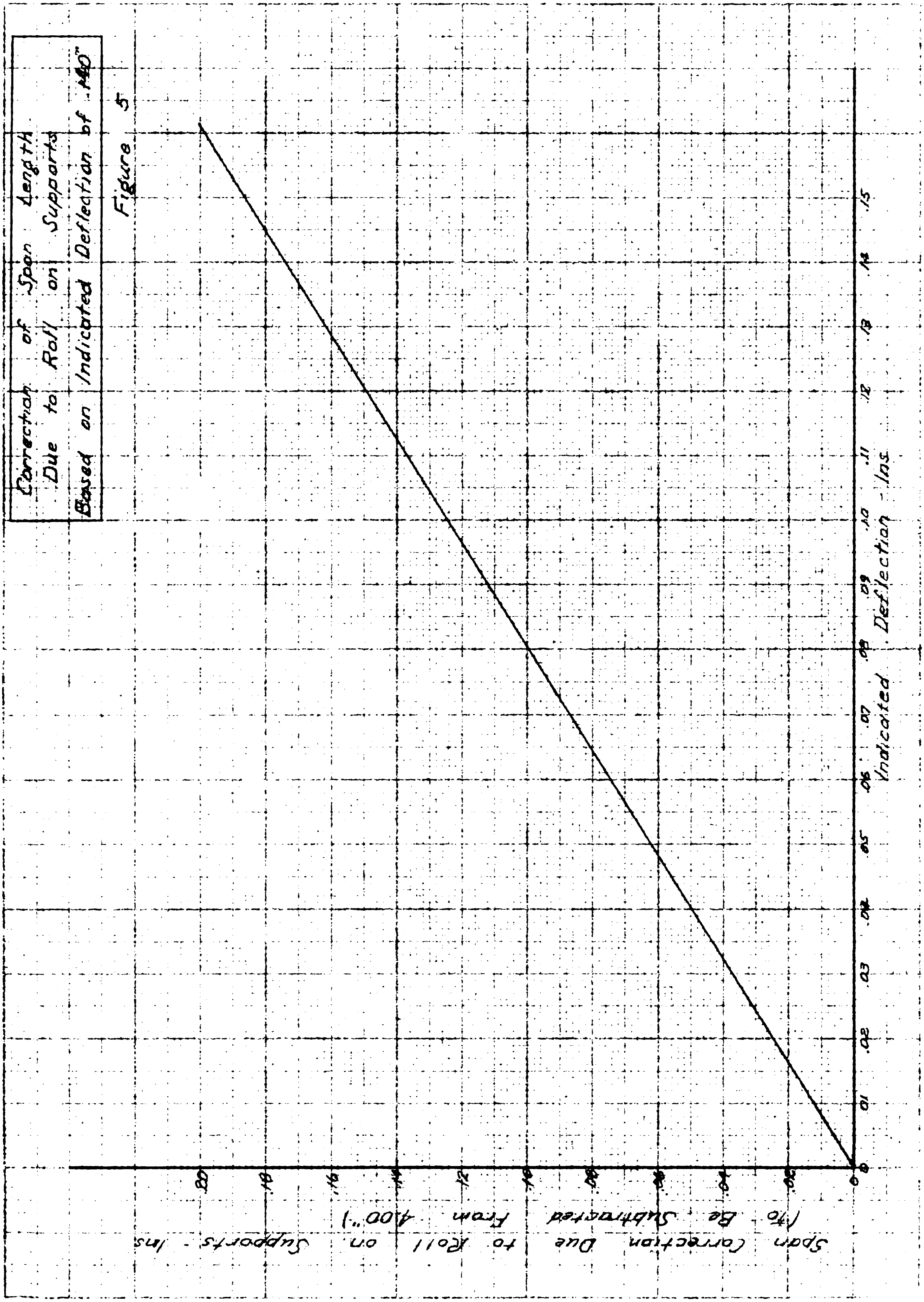

Deflection Due to Roll on Supports
Based on Indicated Deflection of .140
Indicated Deflection - Ins
Deflection Due to Roll - Ins.
(To Be Subtracted From Indicated Deflection)
Indicated Deflection - Ins.
.10 .11 .12 .13 .14 .15 .16 .17 .18 .19
0 .01 .02 .03 .04 .05 .06 .07 .08 .09 .10 .11 .12 .13 .14 .15 .16 .17
0 .001 .002 .003 .004 .005 .006 .007 .008 .009 .010 .011 .012

Figure 4


Correction of Span Length
Due to Roll on Supports
Based on Indicated Deflection of
Figure 5
Indicated Deflection - Ins
0
.01
.02
.03
.04
.05
.06
.07
.08
.09
.10
.11
.12
.13
.14
.15
.02
.04
.06
.08
.10
.12
.14
.16
.18
.20
Span Correction Due to Roll on Supports - Ins
(To Be Subtracted From 4.00")

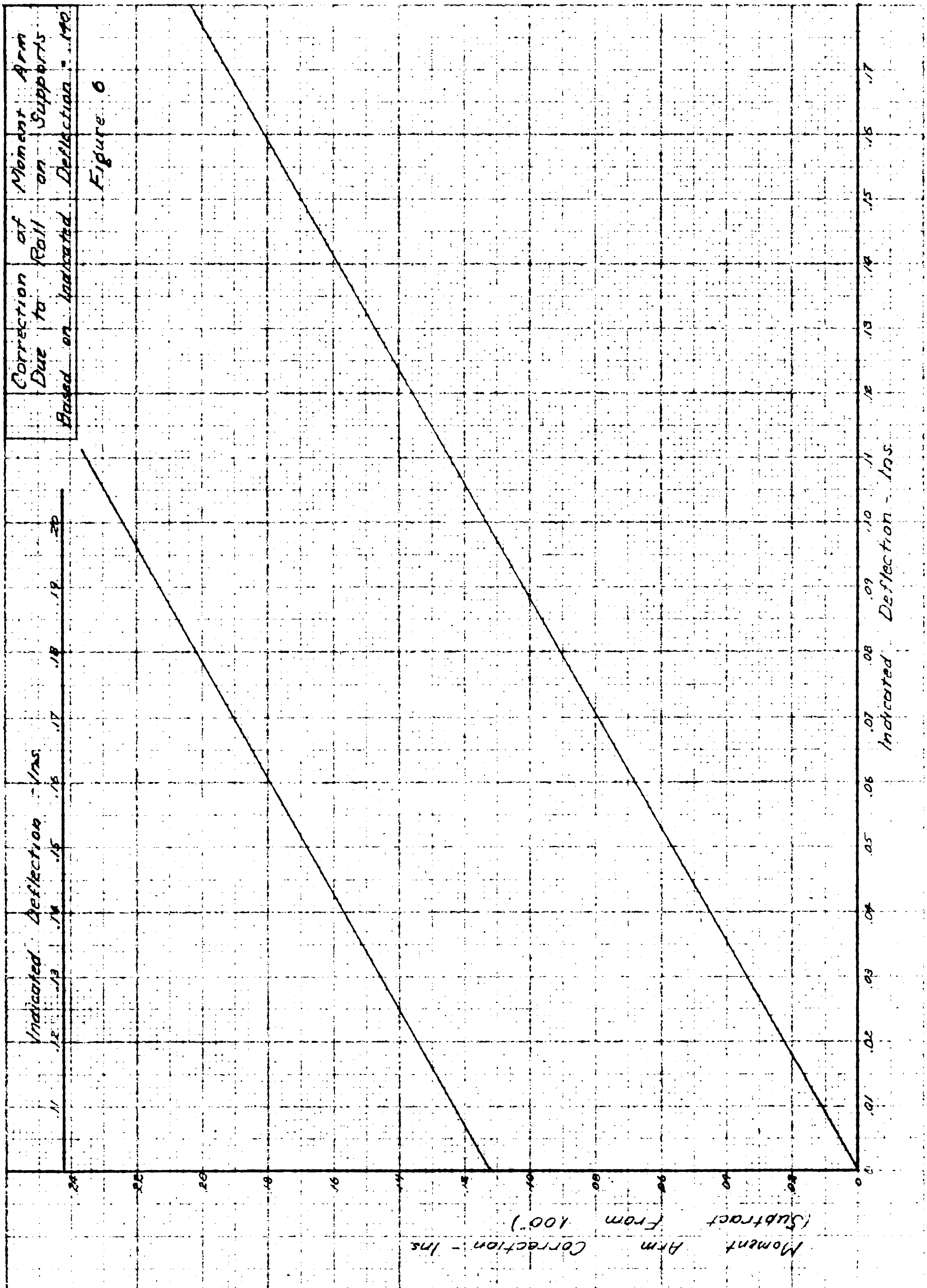

Correction of Moment Arm
Due to Roll on Supports
Based on Indicated Deflection = .140
Indicated Deflection - Ins
Indicated Deflection - Ins
Moment Arm Correction - Ins
(Subtract From 100")

Figure 6

Sample Data for Transverse Bending Test

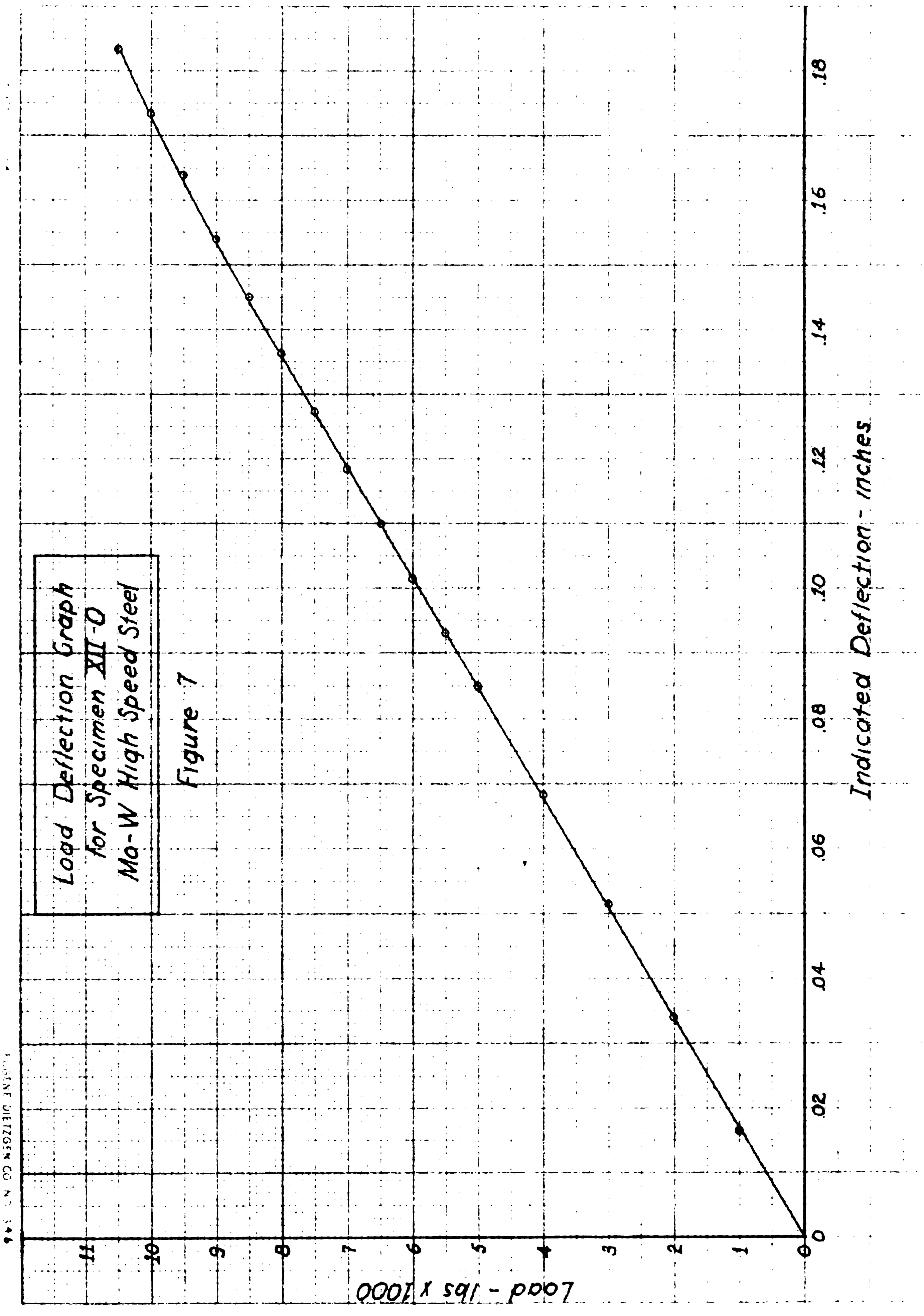
Specimen XII-0

Molybdenum-Tungsten High Speed Steel
Specimen size 0.373 inch square x 4½ inches long
Rockwell "C" Hardness 65.9

Quenched in oil from 2230 F
Tempered 1 hour at 1025 F and air cooled
followed by 1 hour at 1025 F and furnace cooled.

Load Pounds	Dial Readings 1	Dial Readings 2	Dial Deflection 0.001 inch 1	Dial Deflection 0.001 inch 2	Ave. Deflection 0.001 inch
100	1.000	1.000	0	0	0
1000	0.9835	0.9840	0.0165	0.0160	0.0162
2000	0.9665	0.9655	0.0335	0.0345	0.0340
3000	0.9495	0.9475	0.0505	0.0525	0.0515
4000	0.9330	0.9300	0.0670	0.0700	0.0685
5000	0.9160	0.9140	0.0840	0.0860	0.0850
5500	0.9075	0.9065	0.0925	0.0935	0.0930
6000	0.8990	0.8980	0.1010	0.1020	0.1015
6500	0.8905	0.8895	0.1095	0.1105	0.1100
7000	0.8820	0.8810	0.1180	0.1190	0.1185
7500	0.8735	0.8720	0.1265	0.1280	0.1272
8000	0.8645	0.8635	0.1355	0.1365	0.1360
8500	0.8555	0.8545	0.1445	0.1455	0.1450
9000	0.8465	0.8455	0.1535	0.1545	0.1540
9500	0.8365	0.8355	0.1635	0.1645	0.1640
10000	0.8270	0.8260	0.1730	0.1740	0.1735
10500	0.8170	0.8160	0.1830	0.1840	0.1835

Failed at 10500 pound load immediately after deflection readings were taken.



Load Deflection Graph for Specimen XII-O Mo-W High Speed Steel

Figure 7

Notation Used in Sample Calculations

P = Total applied load, lbs

L = Corrected span length, in.

a = Corrected load moment arm, in.

d = Indicated deflection of neutral axis of beam, in.

d' = Corrected (true) deflection of neutral axis of beam, in.

d_s = Deflection due to vertical shear at loading points, in.

E = Modulus of elasticity, psi

E' = Modulus of elasticity corrected for shear of loading points, psi

E_s = Modulus of elasticity in shear, psi

I = Moment of Inertia of beam cross sectional area, $in.^4$

C = Distance from neutral axis to extreme fiber of beam, in.

S = Modulus of rupture, psi

T = Toughness, in-lb/$in.^3$

A = Area of beam cross section, $in.^2$

Calculations for Transverse Bending Test of Specimen XII-0

Data on Page 23.

Modulus of rupture

$$S = \frac{MC}{I} = \frac{\frac{P}{2}a}{\frac{I}{C}}$$

P at rupture = 10,500 pounds
d at rupture = 0.1835 inch
a at rupture from Figure 6 = 1.000 - .206 = 0.794 inch
I/C for 0.373 inch square section = 0.00865 in.^{3}

$$S = \frac{\frac{10500}{2} \times 0.794}{0.00865} = 482{,}000 \text{ psi}$$

Toughness

$$T = \tfrac{1}{2}\, S^2/E$$

E taken as 30,000,000 psi since the average of all experimental values in this series of tests was found to be 30,021,300 psi

$$T = \frac{1}{2}\,\frac{(482{,}000)^2}{30{,}000{,}000} = 3870 \text{ in.-lb/in.}^3$$

Modulus of Elasticity

Determined for a load of 6000 pounds where d = 0.1015 inch.

$$E = \frac{Pa(3/4\, L^2 - a^2)}{12\, Id'}$$

d' from Figure 4 is 0.1015-0.0051 = 0.0964 inch.
L from Figure 5 is 4.00 - .126 = 3.874 inches.
a from Figure 6 is 1.00 - .115 = 0.885 inch.
I for 0.373 inch square section = 0.00161 $in.^4$

$$E = \frac{6000 \times 0.885\, (3/4\, \overline{3.874}^2 - \overline{0.885}^2)}{12 \times 0.00161 \times 0.0964} = 29{,}750{,}000 \text{ psi}$$

Correction due to vertical shear at loading points

$$d_s = \frac{M}{AE_s} = \frac{\frac{P}{2}a}{AE_s}$$

A for 0.373 inch square section = 0.1391 $in.^2$

E_s = 12,000,000 psi

$$d_s = \frac{6000 \times 0.885}{2 \times 0.1391 \times 12{,}000{,}000} = 0.0016 \text{ inch.}$$

Modulus of elasticity corrected for vertical shear at loading points:

$$E' = 29{,}750{,}000 \times \frac{0.0964}{0.0964 - 0.0016} = 30{,}300{,}000 \text{ psi}$$

RESULTS OF TRANSVERSE TESTS ON BEAM SPECIMENS

Quenching Procedure	Identification	Specimen Size-In. Square	Modulus of Rupture,	True Deflection at Rupture, In.	Toughness in $lb/in.^3$	Corrected Modulus of Elasticity psi x 10^6	Hardness Rockwell C
Oil Quenched	III-1	0.375	276,500	0.0876	1275	30.55	66.9
	II-2	0.389	504,000	0.1778	4233	29.80	64.7
	IV-0	0.375	461,000	0.1600	3540	30.40	65.1
	V-0	0.372	442,000	0.1520	3255	30.25	64.9
	IX-0	0.375	*543,000	0.2185	4915	30.90	65.4
	X-0	0.374	534,000	0.2115	4750	30.00	66.1
	XI-0	0.375	440,000	0.1460	3225	31.05	65.8
	XII-0	0.373	480,000	0.1742	3870	30.30	65.9
	XIII-0	0.375	533,500	0.2121	4740	30.5	65.6
Quenched in Lead at 1025 F and Air Cooled	VI-4	0.375	337,000	0.1083	1893	30.6	67.1
	VII-4	0.375	433,000	0.1486	3125	30.25	66.1
	IX-4	0.375	470,000	0.1625	3690	29.80	66.5
	X-4	0.367	484,500	0.1716	3905	29.70	66.3
	XI-4	0.375	434,000	0.1439	3140	29.60	66.3
	XII-4	0.375	289,000	0.0899	3181	29.30	66.7
Quenched in Lead at 1025 F held 15 minutes. Furnace cool.	II-I	0.392	404,000	0.1256	2720	29.70	66.0
	III-0	0.375	413,000	0.1384	2840	29.70	66.4
	IV-1	0.375	293,000	0.0940	1428	30.40	65.7
	V-1	0.375	477,000	0.1755	3792	29.80	66.3
	IX-1	0.375	432,000	0.1496	3115	29.85	66.6
	XI-1	0.369	306,500	0.0974	1565	30.9	67.0
Quenched in Lead at 1025 F & held 1 hour. Furnace cool.	II-0	0.389	*427,000	0.---	3037	29.30	65.7
	III-2	0.375	324,000	0.1035	1745	30.40	67.3
	IV-2	0.375	387,500	0;1309	2500	29.75	66.6
	V-2	0.372	324,500	0.1037	1752	30.60	66.0
	VII-2	0.375	443,000	0.1588	3272	30.00	67.2
	IX-2	0.375	465,000	0.1710	3805	30.10	66.5
Quenched in Lead at 1025 F Held 2 hr Furnace cool.	III-3	0.375	417,500	0.1387	2905	29.65	66.7
	IV-3	0.375	369,000	0.1259	2270	28.80	66.5
	V-3	0.370	313,500	0.1023	1637	30.00	66.9
	VII-3	0.375	352,000	0.1192	2062	29.50	66.8
	IX-3	0.375	459,000	0.1610	3510	29.95	66.7
	X-3	0.375	498,000	0.1981	4130	29.50	65.7
	XI-3	0.368	331,000	0.1069	1825	29.70	67.1

*Unbroken

Table I.

SUMMARY OF TRANSVERSE TEST RESULTS

Quenching Procedure	No. of Tests	Modulus of Rupture-psi from S = Mc/I. Average	Maximum	Minimum	Variation	Variation - % Average
Oil quenched.	9	468,200	*543,000	276,500	266,500	56.9
Hot quenched. Air cool.	6	407,900	484,500	289,000	195,500	48.0
Hot quenched. 15 minutes. Furnace cool.	6	387,600	477,000	293,000	184,000	47.5
Hot quenched. 1 hour.	6	395,200	465,000	324,000	141,000	35.7
Hot quenched. 2 hours.	7	391,400	498,000	313,500	184,500	47.2

*Unbroken

Quenching Procedure	No. of Tests	Hardness - Rockwell C *Average	**Maximum	**Minimum	Variation	Variation - % Average
Oil	9	65.6	66.9	64.7	2.2	3.35
Hot quenched. Air cool.	6	66.5	67.1	66.1	1.0	1.50
Hot quenched. 15 min.	6	66.3	67.0	65.7	1.3	1.95
Hot quenched. 1 hour.	6	66.5	67.2	65.7	1.5	2.25
Hot quenched. 2 hours.	7	66.6	67.1	65.7	1.4	2.20

*From 120 to 180 hardness tests.

**From 20 tests.

CALCULATIONS, DATA AND RESULTS

Lathe Breakdown Tests

The relationship which exists between cutting speed and the tool life for any tool, material cut, depth of cut and feed is expressed by the equation $VT^n = C$ (4) where

V = cutting speed, feet per minute

T = tool life between grindings, minutes

n = an exponent which is the slope (negative) of the V vs T graph on log-log coördinates.

C = a constant which depends upon the tool material, tool shape, material cut, cutting speed, depth of cut and feed.

From the equation $VT^n = C$, when $T = 1$, $C = V$ in feet per minute for a tool life of 1 minute. Figure 11, page 49 shows the relation between cutting speed and tool life on modified log-log coördinates for the three sets of tool bits tested.

Determination of "n" and Solution of the Equation $VT^n = C$

(a) For molybdenum-tungsten bits, hot quenched at 1025 F for 2 hours, furnace cooled, then double tempered at 1025 F. From Figure 11,

when $T = 1$ $\quad$ $C = V = 176$ fpm

when $T = 2.7$ min $\quad$ $V = 150$ fpm

$$VT^n = C \quad \text{or} \quad T^n = \frac{C}{V}$$

$$2.7^n = \frac{176}{150} \text{ from which } n = 0.161$$

The equation, therefore, becomes $VT^{.161} = 176$

$$V \text{ for a tool life of 60 minutes} = \frac{176}{60^{.161}} = 91.2 \text{ fpm}$$

(b) For molybdenum-tungsten bits, oil quenched and double tempered at 1025 F. From Figure 11, when T = 1, C = V = 168 fpm n = .161 as before, since the V vs T lines on Figure 11 are parallel. The equation then becomes $VT^{.161} = 168$

V for a tool life of 60 minutes $= \frac{168}{60^{.161}} = 86.9$ fpm

(c) For high tungsten (18-4-1) bits commercially hardened and tempered. From Figure 11, when T = 1, C = V = 162 fpm and the equation becomes $VT^{.161} = 162$.

V for a tool life of 60 minutes $= \frac{162}{60^{.161}} = 83.3$ fpm

The relative cutting efficiencies for the differently treated tool bits and tool bit materials may be (and generally are) expressed by the cutting speed for a tool life of 60 minutes.

Considering the commercially hardened 18-4-1 bit as 100% the efficiencies become

18-4-1 H.S.S. Commercially hardened and tempered....100.0%

Molybdenum-tungsten HSS oil quenched and double tempered..103.7%

Molybdenum-tungsten HSS oil quenched, 2 hours at 1025 F and double tempered..........................108.7%

Table II.

SUMMARY OF LATHE BREAKDOWN TESTS

Metal Cut: 0.4% Carbon Steel, annealed
Tensile strength, 81,900 psi
Elongation, 25½% in 2 in.
Brinell hardness, 159
Yield strength, 42,250 psi
Reduction in area, 38.4%

Cut: Dry; Roughing; Depth of cut, 1/8 in., feed 1/45 in./rev.

Tool: Material, high speed steel as noted; nose radius, 1/16 in.; side cutting-edge angle, 0 deg; end cutting-edge angle, 6 deg; side rake, 14 deg; back rake, 8 deg; relief, 6 deg. Setting angle, 90 deg. All cutting surfaces honed; nose radius honed to a templet. Tool size ½" x ½" x 3½" long.

Tool Material	Heat Treatment	Cutting Speed, fpm	rpm of work piece	Length of Cut-in.	Tool Life, min
	Quenched from 2235	152½	104	4½	2.01
	F in oil	144½	104	6	2.66
Molybdenum Tungsten HSS	Double tempered	128	104	11-5/8	5.12
	@ 1025 F R_c 65.9	172	136	2-5/8	0.88
		158½	147	4¼	1.35
	Quenched from 2235	152½	104	5-5/16	2.39
	F in lead at 1025 F	144½	104	7-1/8	3.16
Molybdenum-Tungsten HSS	& held 2 hr	137	104	10-7/16	4.55
	Double tempered at	172	136	4-1/8	1.44
	1025 F R_c 66.7	158½	147	6	1.85
	As supplied commercially	152½	104	3-9/16	1.58
	oil hardened & tempered	137	104	6-5/16	2.76
18-4-1 Tungsten HSS	R_c 64.0	118½	104	13-7/8	6.10
		157	136	3-1/8	1.06
		147½	147	5-3/8	1.65
		137	136	8¼	2.76
		124	136	15½	5.17

DISCUSSION

Transverse Strength vs Quenching Procedure

Figure 8, page 38 and Table I, page 29 summarize the effect of quenching procedure upon the modulus of rupture of quenched and tempered test beams.

Considering the average strength curve it is evident that on the average the strongest conditions obtain when oil quenching is used. Next in line and some 60,000 psi lower is the hot quench followed by air cooling to room temperature (i.e., 0 holding time). From the remaining points it is evident that hot quenching times beyond 15 minutes have little effect upon the average transverse strength.

The curve showing variation in strength (maximum-minimum) is revealing. Oil quenching is indicated as causing the greatest variation, the magnitude of which is, indeed, nearly equal to the minimum strength obtained. Much less variation is noted for all the conditions of hot quenching with the least variation for a 1-hour hot quench.

The degree to which the variation curve approaches the minimum curve may be regarded as an index of cracking tendency during the quench. As can be observed, oil quenching procedure would be more apt to cause cracking than any of the hot quenching procedures investigated. Conversely, a 1-hour hot quench would be the least apt to cause cracking. Such tendencies would, of course, be greatly accentuated in the hardening of irregularly shaped dies and forming tools wherein cracking of a tool represents an important loss of materials and man hours.

The variations in strength are high but not unexpected when testing

a material of high hardness. Theoretically, strength and hardness vary directly except at the high hardness level where "locked up" or internal stresses bring about localized overstress which is not permitted to readjust itself. Surface condition was a very important factor in the beams tested. Great care was exercised in grinding the specimens prior to testing, but there was no assurance that localized overheating and consequent sub-microscopic grinding checks were absent. (Unfortunately, too, many tool grinders do not appreciate the disastrous effects of grinding a tool until discolored and then dipping in water-heinous practice.)

Stress concentration under the loading and supporting rolls is of necessity high,and also localized carbide segregation in the stock may well cause large differences in strength.

Examination of tested specimens is enlightening. On page 39 is a reproduction of a photoelastic study of a beam loaded in the same manner as that used in this investigation. The photoelastic diagram illustrates the high stress concentration at the loading and supporting points and the constant bending moment existing between the loading points.

Page 40 shows three photographs of tested beams. Beam A deflected nearly 0.22" at the center under the maximum load of the testing machine. The extreme fiber stress was 543,000 psi. Hardened high speed steel is not often thought of as yielding under high stress, yet beam A shows appreciable permanent set. The Rockwell C hardness of 65.4 is typical of high speed cutting tools.

Beam B broke at a maximum fiber stress of 533,500 psi and virtually exploded at failure. Note the fragmentation of the entire center section which was subjected to the same bending moment. Evidence of longitudinal shear is clearly evident. The hardness of this sample was 65.6 R_c.

Beam C was the weakest of the series tested, being about half as strong as beam B. Note the relatively slight fragmentation. R_c hardness was 66.9, the maximum in the oil quenched series.

Since toughness was determined by the expression $T = \frac{1}{2}S^2/E$ the discussion applied to transverse strength also applies to toughness. Had curves similar to Figure 8 been drawn, the slopes would have been more pronounced since toughness is a function of the square of the modulus of rupture.

Hardness vs Quenching Procedure

Figure 9, page 41 and Table I, page 29 summarize the effect of quenched procedure upon the hardness of quenched and tempered test beams.

Considering the average hardness curve, oil quenching is shown to give the lowest average hardness with the various hot quenching procedures showing little effect on the hardness. In general, the hot quenched beams averaged 1 point R_c harder than those quenched in oil. There was very little difference in the various maxima. The curve showing the variation in hardness indicates that oil quenching is subject to the most variation and hot quenching with zero holding time, the least.

In general, the trend of the average strength and average hardness curves (Figs. 8 and 9) are reversed. Such a condition is not unusual since the harder materials are more subject to localized stress raisers. Exceptions are noted for specimens V-0 and X-0, page 28 which failed at 442,000 and 534,000 psi, respectively, though the hardnesses were 64.9 and 66.1 R_c, respectively.

Figure 10, page 42, depicts the effect of holding time in the hot quench upon the as quenched and the quenched and tempered hardness. Data for Figure 10 were obtained during a preliminary search for the most suitable quenching temperature. Specimen size was 5/8" square x 3/16" thick; high heat temperature was 2250 F (on the borderline of "burning" and too high for general recommendation), and the time at temperature was 1 minute, 45 seconds. A hot quenching temperature of 1025 F was used, and double tempering at 1025 F was resorted to.

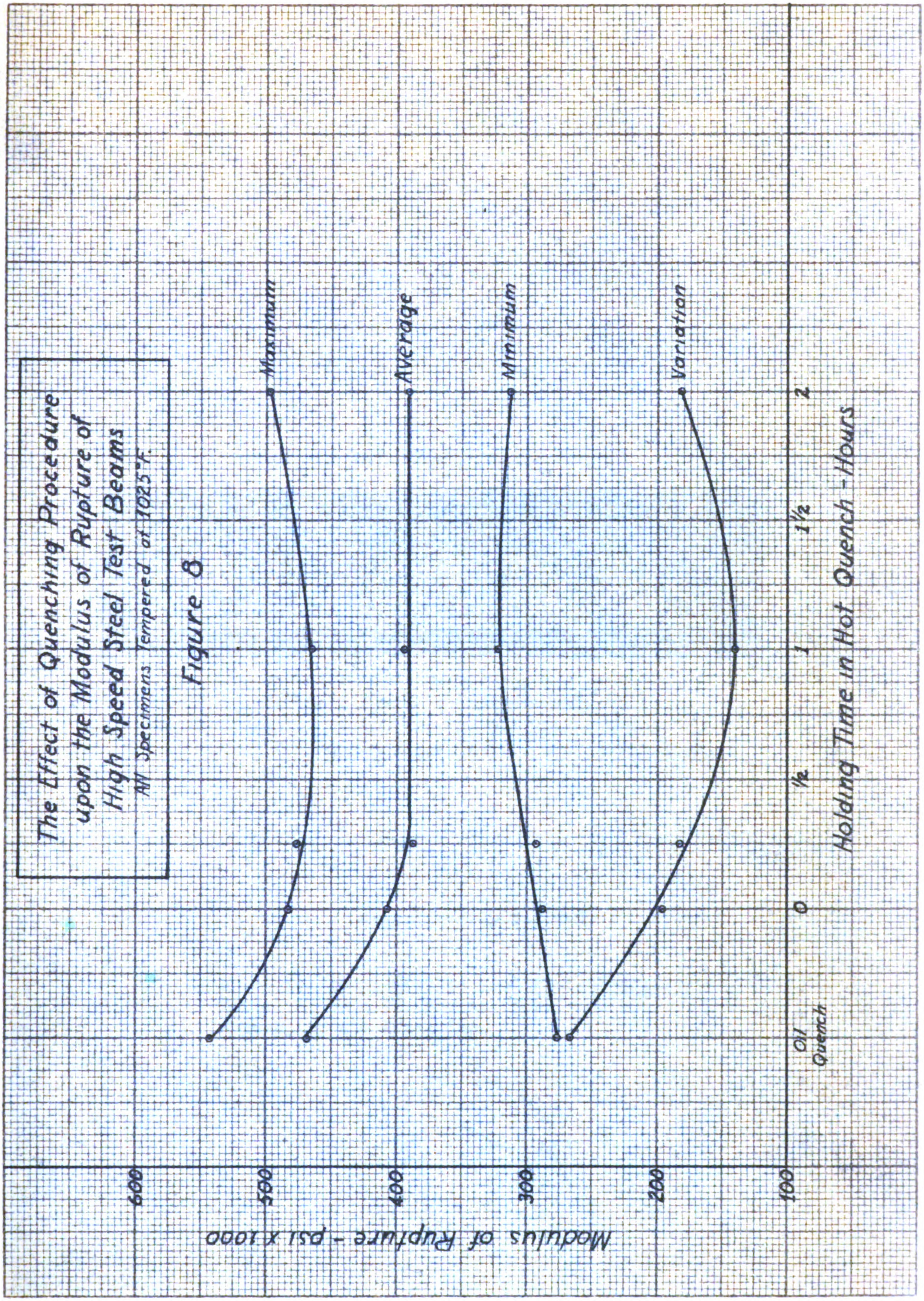
The higher temperature and thinner samples account for the higher, 1 R_c, hardness level of Figure 10 over Figure 9. Considering the as quenched hardness curve of Figure 10, it is apparent that all hot quenching procedures result in a higher hardness than obtains in oil quenching. The effect of hot quenching time is to increase the hardness quite sharply up to about 4 hours holding time after which comparatively little increase occurs up to and including 24 hours.

The higher hardness for the increased holding time is readily accounted for. High speed steel at the high heat temperature is composed of a solid solution, austenite, with most of the high alloy carbides dissolved. When rapidly cooled to the hot quenching temperature (1025 F) by immersion the austenite comes down unchanged, and indeed, will remain essentially stable at 1025 F for more than 10^6 seconds,[(5)] ($11\frac{1}{2}$ days) before any decomposition of the austenite occurs at that temperature.

During the sojourn at 1025 F, however, alloy carbides begin to precipitate in minute particles which exert a definite precipitation hardening effect and also decrease the alloy content of the austenite. This austenite, on cooling to room temperature, transforms more or less, depending upon its alloy content, to hard martensite. Austenite of high alloy content is very apt to be retained, however, and incomplete hardening results. Clearly, then, an oil quenched specimen would arrive at room temperature with considerable (up to 30%) [(6)] retained austenite whereas hot quenched samples may have little (3 to 5%) retained austenite since appreciable carbide precipitation had occurred during the holding time.

The trend of the as quenched curve, Figure 10, shows that carbide precipitation begins almost immediately during the hot quench and proceeds at a fairly uniform rate up to a holding time of some 4 hours with comparatively little precipitation thereafter. Evidently, little retained austenite is present after those samples hot quenched 4 hours or more and have cooled to room temperature, and the higher proportion of martensite together with more pronounced precipitation hardening accounts for the higher as quenched hardness.

That complete austenitic transformation is not obtained even with hot quenching up to 24 hours is shown by the curve of quenched and tempered hardness, Figure 10. The increase due to tempering - i.e., secondary hardening - is considerably less for the samples hot quenched 4 hours or more. The final hardness is, however, not greatly affected by the quenching procedure under the specimen size and temperature conditions employed though the hot quenched samples retain superiority in hardness.


The Effect of Quenching Procedure
upon the Modulus of Rupture of
High Speed Steel Test Beams
All Specimens Tempered at 1025°F.
Figure 8
Maximum
Average
Minimum
Variation
Oil Quench
0
½
1
1½
2
Holding Time in Hot Quench - Hours
100
200
300
400
500
600
Modulus of Rupture - psi x 1000

STRESS DISTRIBUTION IN PURE BENDING

Note: (a) Stress Concentration at the loading and supporting points.

(b) Constant bending moment between the loading points.

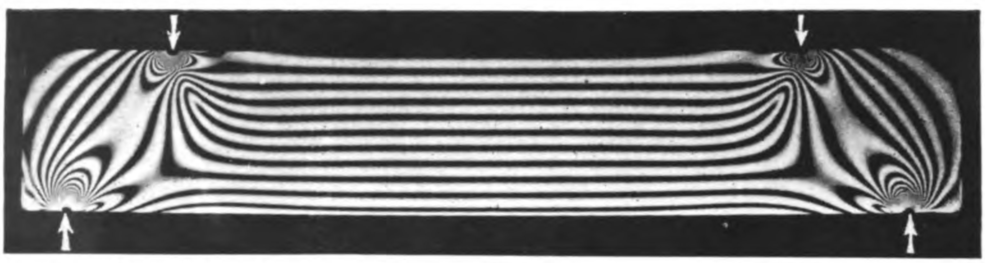
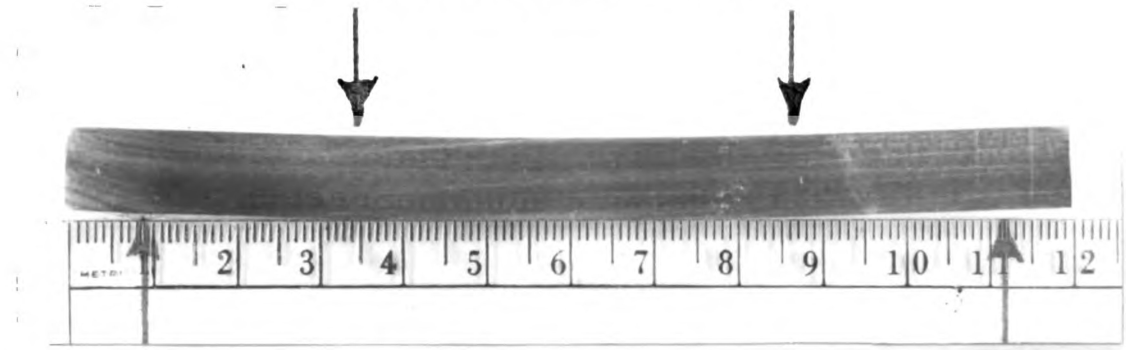


FIG. 6.35 Stress Pattern of a Straight Beam Subjected to Pure Bending by Means of Compressive Loads.

Applied bending moment = 50.0 lb-in.; depth of beam = 0.763 in.; thickness = 0.250 in.; distance between upper loads = 3.00 in.; distance between lower loads = 4.00 in.

Magnification 1-1/8 X

EXAMPLES OF TESTED BEAMS



A

Specimen IX-0. Magnification 1-1/8 X.

Extreme fiber stress 543,000 psi

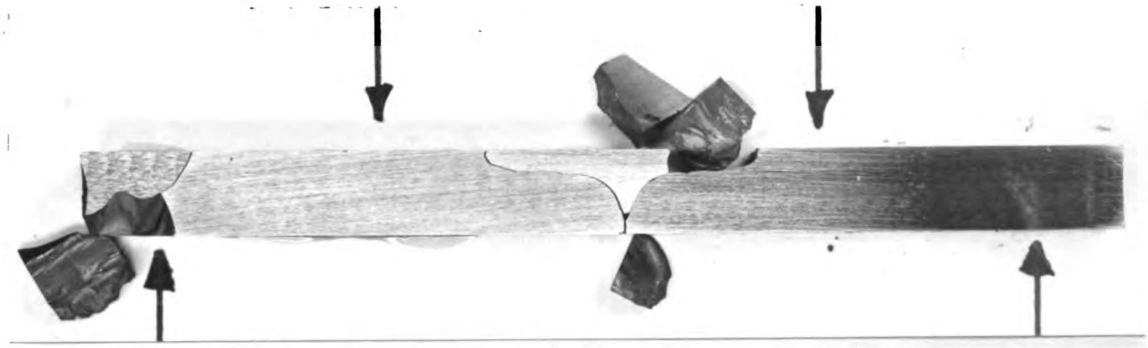
Rockwell C Hardness 65.4

B

Specimen XIII-0. Magnification 1-1/8 X.

Extreme fiber stress 533,500 psi

Rockwell C Hardness 65.6

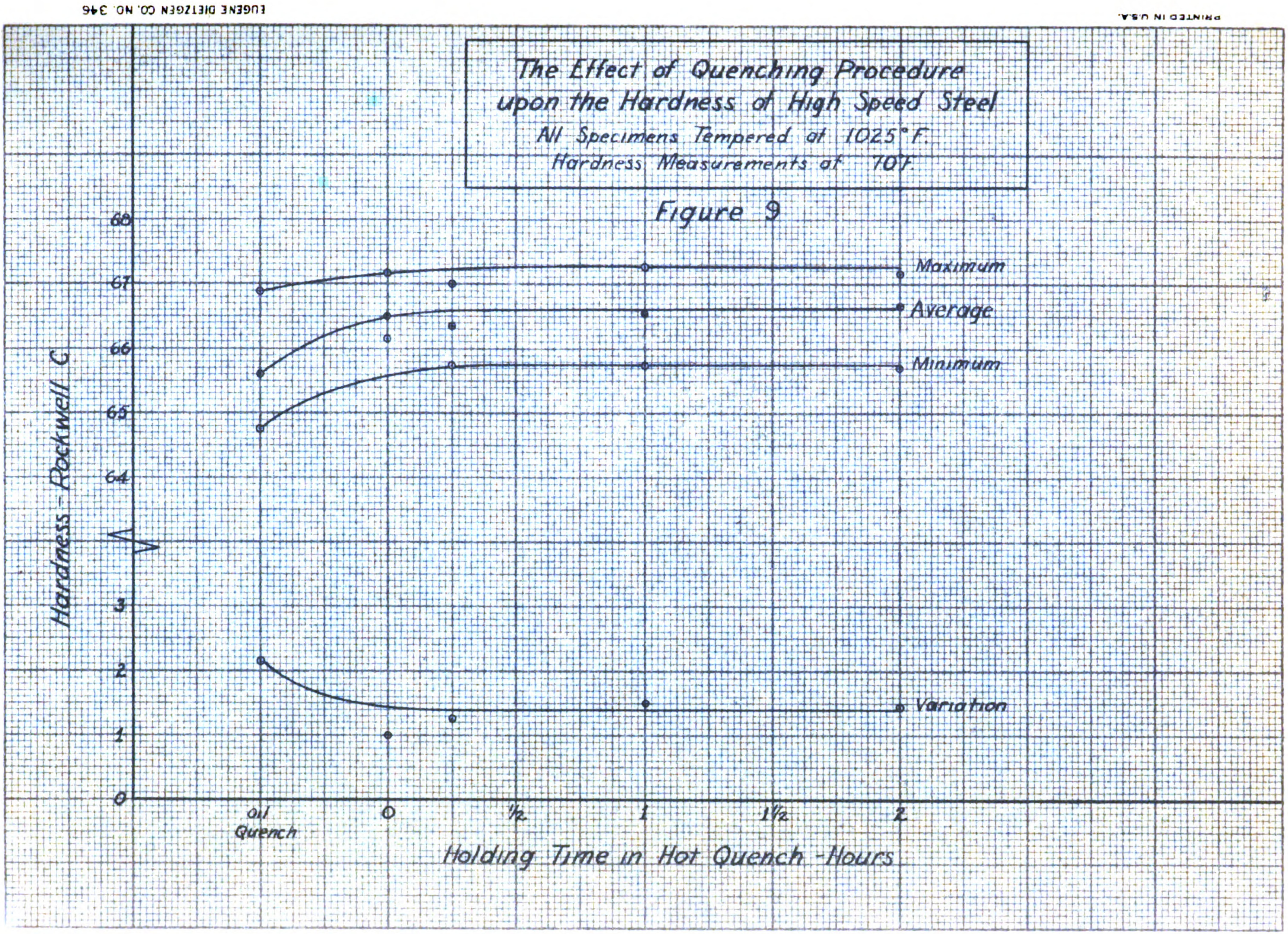


C

Specimen III-1. Magnification 1-1/8 X.

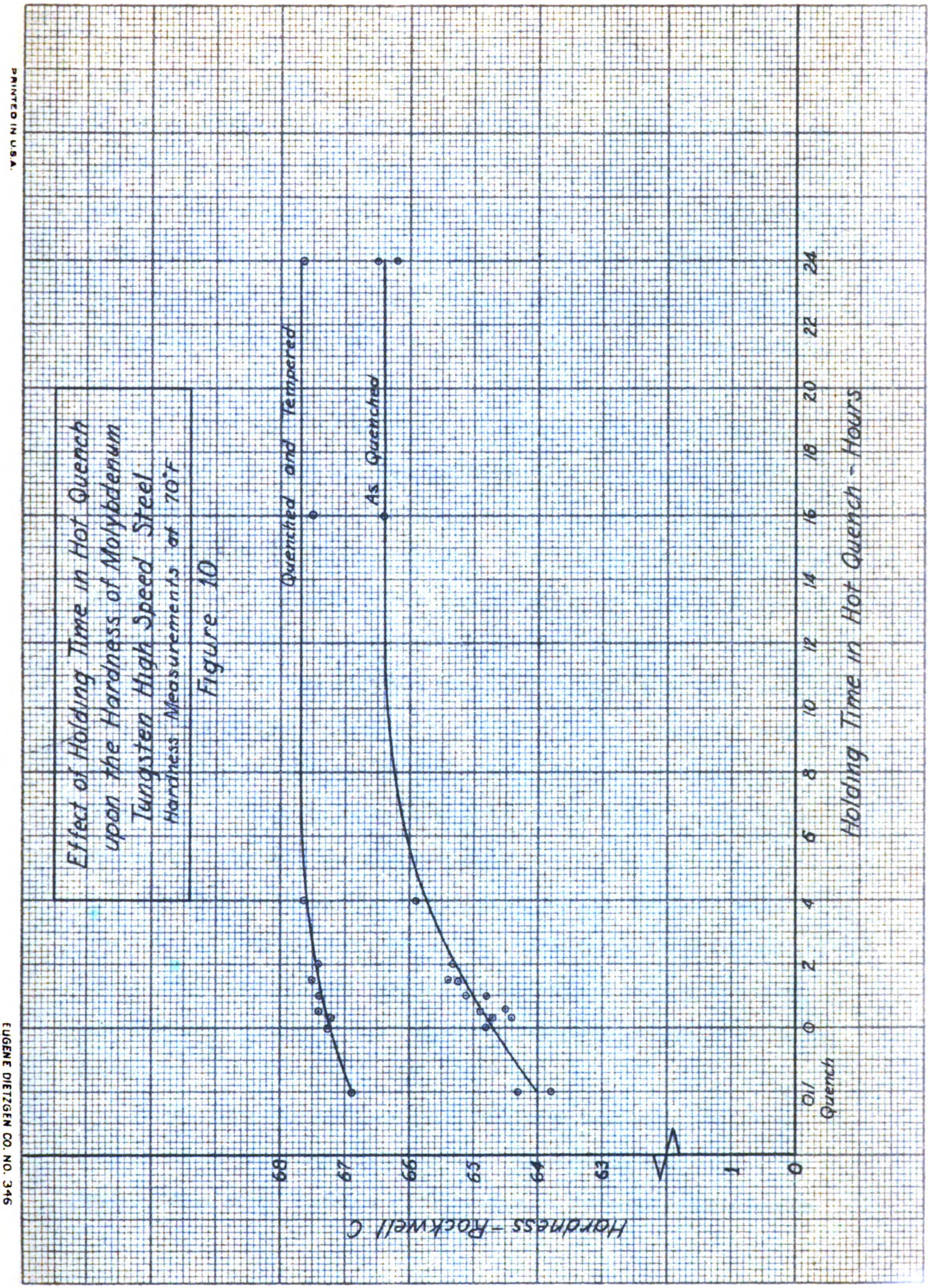
Extreme fiber stress 276,500 psi

Rockwell C Hardness 66.9



The Effect of Quenching Procedure upon the Hardness of High Speed Steel
All Specimens Tempered at 1025° F.
Hardness Measurements at 70F.

Figure 9


Effect of Holding Time in Hot Quench
upon the Hardness of Molybdenum
Tungsten High Speed Steel
Hardness Measurements at 70°F
Figure 10
Quenched and Tempered
As Quenched
Hardness - Rockwell C
68
67
66
65
64
63
1
0
O/I Quench
0
2
4
6
8
10
12
14
16
18
20
22
24
Holding Time in Hot Quench - Hours
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Lathe Breakdown Tests

Regardless of how carefully a tool steel is manufactured, rolled and annealed at the mill and how much time and labor is expended in the fabrication of the tool, the ultimate result will depend upon the proper heat treatment to obtain the maximum service efficiency. Tool and die breakage causes a considerable loss of man hours, material, and production and any hardening practice that would decrease cracking is highly desirable.

One manufacturer of high speed steel hobs and milling cutters has reported a 3% loss due to cracking in hardening and, no doubt, many additional failures, due to the same cause, occur in service which are attributed to other faults. Tools and dies are generally of intricate shape with many abrupt sectional changes. Such conditions enhance the possibilities of cracking during heat treatment and the ideal test of the most suitable heat treating procedure would be a service test of some intricate tool or die. In the absence of such testing facilities new tool steels or heat treating procedures are frequently evaluated by lathe cutting tests of which the lathe breakdown test is probably the most satisfactory.

According to the Manual on Cutting of Metals, the lathe breakdown test, if properly designed, gives a reliable index of the cutting ability of a specific tool material on any type of cutting operation excepting one in which tool strength and toughness is a controlling factor.[7,p.279]

In this investigation the lathe breakdown test was used (1) to compare two-hour hot quenching with oil quenching on molybdenum-tungsten high speed steel, and (2) to compare the molybdenum tungsten high speed steel with the more widely known 18-4-1 type under similar conditions of quenching. The tool shape selected was one commonly used in lathe tests - tool contour No. 2, Manual on Cutting of Metals, page 62.

The work piece was annealed, medium carbon steel, ductile enough to give a continuous chip under the assigned cutting conditions. The continuous chip caused characteristic cratering of the tool face and subsequent breaking through at the cutting edge thereby causing failure. The cratering action of the chip on the tool face is brought about by the high (225,000 ± psi) unit pressure of the chip on the tool together with the tendency of the chip to adhere to the tool. The high friction causes local overheating and softening of the tool material which is then washed out. The smoothness of the tool face is obviously a variable,and accordingly all cutting surfaces of the test bits were honed to a smooth finish.

On page 48 is a photograph of two tool bits. The one on the left shows the appearance of the tool just prior to failure. Note the pronounced crater, the particles of the work piece adhering to the crater, the roughened cutting edge, and discoloration caused by heat.

The history of the crater is interesting. At the beginning of the test (when cutting a ductile material) the chip flows over the tool surface in a nearly straight ribbon. As cratering occurs, the chip gradually changes to a spiral of smaller and smaller radius until eventually the edge of the crater breaks through the cutting edge and failure occurs suddenly. Since the crater increases the effective rake a tool rough cutting steel is most effective just before failure. The tool bit on the right has been completely failed. Note the partial filling of the crater by adhering metal and the dubbing of the nose radius.

Figure 11, page 49, and Table II, page 32, summarize the cutting speed-tool life relationship of the three sets of bits tested.

The straight line relationship is expressed by the equation $VT^n = C$ in which $n = 0.161$. This value agrees well with the generally accepted value of approximately 1/7 for high speed steel tools rough cutting a steel workpiece.

In Figure 11, it is observed that the longest cutting life at any chosen speed was obtained for the hot quenched Mo-W tools, with the oil quenched Mo-W bits second, and commercially hardened 18-4-1 lowest of the three sets tested. It is expected that hot quenching procedures of from 15 minutes up to 2 hours would result in a gradual improvement in cutting life above that for oil quenching though no tests were conducted on bits given intervening hot quenching treatments.

The tool life of the bits tested appears to be associated with the room temperature hardness. Obviously, of course, the hot hardness (or operating temperature hardness) is the important factor. Cohen and Bishop[(8)] in some recent work describe a method of obtaining the hot hardness of high speed steel and present typical values. Their data indicate that there is a fairly definite relationship between hardness at room temperature and the hot hardness of high speed steel.

A higher hardness would help to resist the cratering action of a continuous chip as would also the presence of abrasion resistant alloy carbides. Evidently, the two hour hot quench is advantageous both from the standpoint of higher hardness and better carbide distribution. However, the highest cutting efficiency does not necessarily require the highest hardness but rather a proper balance of hardness and toughness. Excessive hardness for a specific application may result in a crumbling of the cutting edge. Excessive abrasion results and the frictional heat soon weakens and breaks down the tool. The relative rank of the various bits may have been changed had the work piece been a hard alloy steel.

The comparison between the oil quenched Mo-W bits and the oil quenched 18-4-1 tools is subject to a limitation. Tool bits hardened in the laboratory are individually treated under carefully controlled conditions of time and temperature whereas commercially hardened bits are done in batches and may not always be subjected to uniform time and temperature conditions. This factor may have influenced the results obtained though there is plenty of industrial evidence that the Mo-W steel investigated is at least the equal of 18-4-1. Unfortunately, the Mo-W steel was proposed as a substitute thereby implying inferiority,and many shop men have been prejudiced against this new tool steel.

Since the requirements vary when cutting different materials the application should be considered in arriving at the most suitable quenching procedure. In general, non-ferrous metals require extreme hardness and a keen cutting edge with toughness secondary. Cast iron, bakelite, plastics, certain brasses, and other materials which form well broken chips cause tool failure by abrasion on the nose or flank,and tools for such materials should have hardness at the expense of toughness. Intermittent cuts, especially on hard alloy steels, require tools of high toughness which, in general, is obtained at some sacrifice in hardness.

At the expense of some complication, perhaps it would be wise to specify two-hour hot quenching for lathe tools to be used on those materials which cause failure by nose abrasion and on roughing cuts for medium carbon steel and oil quenching or 15 minutes hot quenching for shaper and other intermittent cutting tools or those for use on hard alloy steels.

The most suitable all-purpose treatment is that which gives the best combination of strength (toughness) and hardness with the least cracking tendency. Hot quenching at 1025 for periods of from a few minutes up to 1 hour appears to be the best compromise.

TOOL BIT FAILURES

Magnification $2\frac{1}{2}$ X.

Left: Tool bit just before failure.

(Not one of series tested)

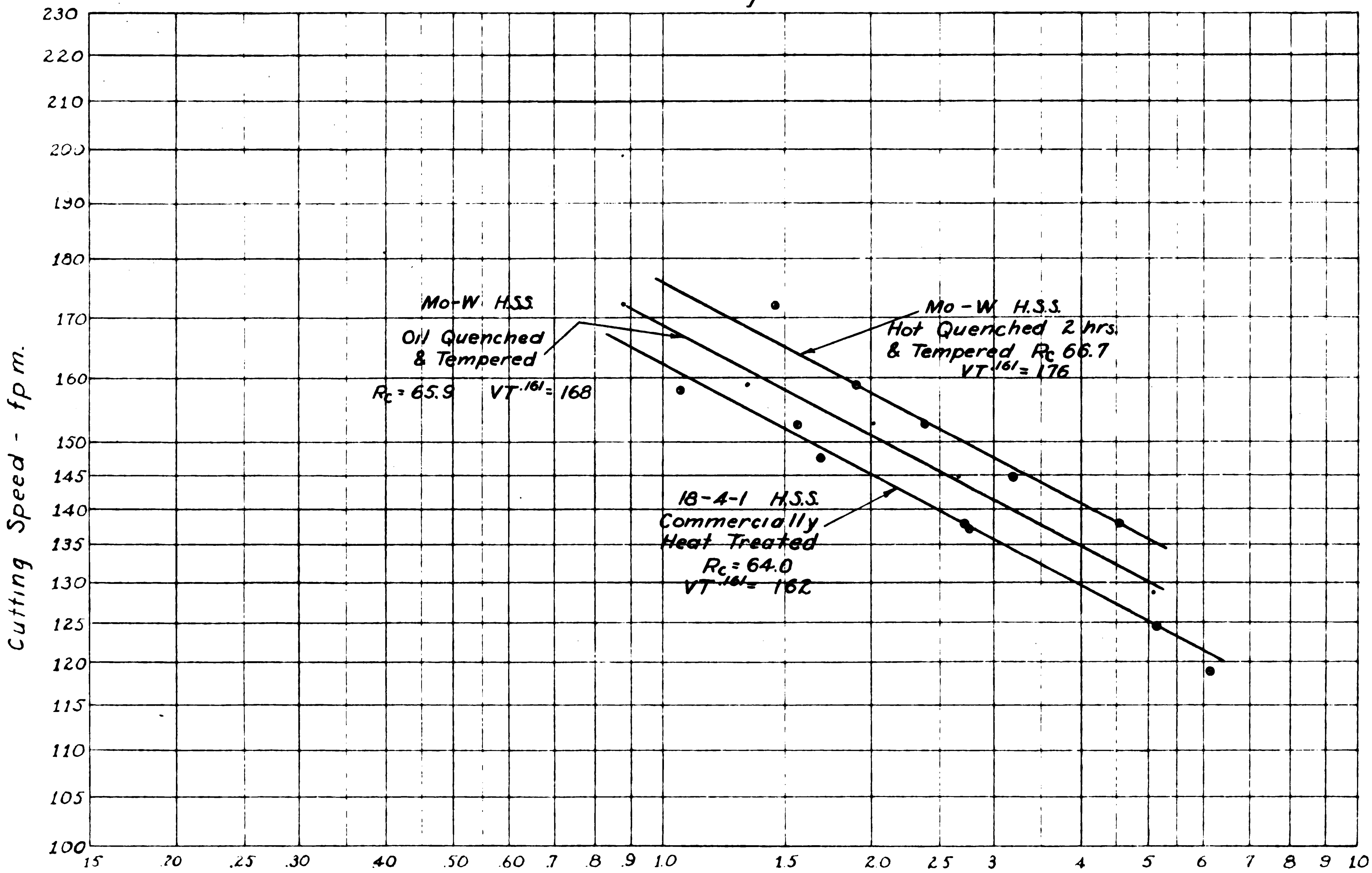
Right: Failed tool bit.

Mo-W H.S.S. Hot quenched 2 hours.

sfpm $158\frac{1}{2}$
Feed 1/45"/rev
Depth of cut 1/8"
Workpiece -0.4%C steel annealed.

Effect of Cutting Speed on Tool Life
Tool Shape 8-14-6-6-6-0-1/16
Metal Cut - Annealed 0.4% C. Steel

Figure 11



CONCLUSIONS

(a) Transverse strength and toughness:

1. The average of the oil quenched test beams is superior to that of any hot quenching procedure investigated.

2. The greatest variation (cracking tendency) is obtained in oil quenching, whereas the least variation is noted for 1 hour hot quenching.

3. As far as the average strength is concerned, hot quenching for more than 15 minutes has no significant value.

(b) Quenched and tempered hardness:

4. The lowest average is obtained in oil quenching while hot quenching for a few minutes up to 2 hours has little effect.

(c) Cutting efficiency:

5. Two hour hot quenching produces more efficient tool bits than oil quenching when the work piece is annealed medium carbon steel.

6. Hot quenching would, in general, be more satisfactory than oil quenching with a 15-minute hot quench proposed as an all purpose recommendation.

7. The cutting efficiency of molybdenum-tungsten high speed steels is at least the equivalent of 18-4-1 under similar conditions of quenching.

BIBLIOGRAPHY

1. On the Art of Cutting Metals, F. W. Taylor, published by A.S.M.E., 1907.

2. "W.P.B. Statement," p. 1204, Metals and Alloys, Vol. 16, No. 6, Dec. 1942.

3. "Tempering of High Speed Steel," Cohen and Koh, Transactions A.S.M., Vol. 27, Dec. 1939.

4. Metal Processing, 1941 ed., O.W. Boston, John Wiley & Sons, Inc.

5. "Kinetics and Reaction Products of the Isothermal Transformation of a Six Per Cent Tungsten - Six Per Cent Molybdenum High Speed Steel," Ham, Parke, and Herzig, Transactions, A.S.M., Vol. 29, Sept. 1941.

6. High Speed Steel, 1st Ed. 1931, Grossman and Bain, John Wiley & Sons, Inc.

7. Manual on Cutting of Metals, 1939 edition, American Society of Mechanical Engineers.

8. "Hardness Testing of High Speed Steel at High Temperatures," Cohen and Bishop, Metal Progress, Vol. 43, No. 3, March 1943.

9. "Heat Treating Molybdenum High Speed Steel," Breeler and Wills, Steel, Vol. 111, No. 15, Oct. 12, 1942.

10. Metals Handbook, 1939 edition, American Society for Metals.

11. "Rough Turning with Particular Reference to the Steel Cut," French and Digges, Transactions, A.S.M.E., Vol. 48, 1926.

12. Photoelasticity, Vol. 1, 1941, M.M. Frocht, John Wiley and Sons, Inc.