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A STUDY OF THE METALLURGICAL PROPERTIES THAT ARE NECESSARY FOR SATISFACTORY BEARING PERFORMANCE AND THE DEVELOPMENT OF IMPROVED BEARING ALLOYS FOR SERVICE UP TO 1000 F.

GOPAL K. BHAT
ALVIN E. NEHRENBERG

CRUCIBLE STEEL COMPANY OF AMERICA

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FOREWORD

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ABSTRACT

The use of bearings made from hot work steels and other tool steels in experimental engines has resulted in a few premature engine failures. Unfortunately, very little has been known about the elevated temperature properties such as hot hardness, compressive yield strength, resistance to softening and structural and dimensional stability of these hot work and other tool steels. This report describes the work done to obtain these material properties for 29 steels ranging in type from SAE 52100, its modifications, to hot work and other tool steels. An analysis of the data obtained shows that Halmo, VSM, M50, M10, T1, M2, M1 and two experimental compositions one, Steel B, containing 0.70 carbon, 4.20 chromium, 0.60 vanadium, and 5.30 molybdenum, and the other, Steel G, containing 1.31 carbon, 4.07 chromium, 4.13 vanadium, 5.75 tungsten, and 4.87 molybdenum, are suitable for elevated temperature aircraft bearing application. From a point of view of temperature range of application these steels have been classified as follows:

Room Temperature up to 700 F	Halmo 1
Room Temperature up to 800 F	VSM, M50, M10 and Steel B
Room Temperature up to 900 F	T1, M2, M1 and Steel G

None of the steels investigated appeared suitable for application at 1000 F.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

RRKennedy

R. R. Kennedy
Chief, Metals Branch
Materials Laboratorv

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I. INTRODUCTION

The increase in flight speed and engine power output in jet engines and gas turbine power plants of recent years has forced a steady rise in the engine operating temperatures. These changes, particularly the higher engine operating temperatures, have necessitated the use of materials with superior elevated temperature physical and mechanical properties. For instance, in most present day engines, the maximum bearing temperatures are approaching 500 F. The most commonly used bearing steel, SAE 52100, can no longer be used since it rapidly loses hardness and dimensional stability above 450 F.

Engine operating temperatures are expected to reach 700 F in engines of the near future. Therefore, the need for bearing materials with adequate hot hardness (56 to 58 R_C at the operating temperature) and other required mechanical and physical properties is very urgent. Numerous attempts are being made by the aircraft industry to use hot work die steels and other tool steels for bearing application with varying degree of success. The main drawback of these presently available steels seems to be their unpredictable fatigue life and somewhat lower mean life in bearing tests when compared with that for SAE 52100. Only scant data are available on the behavior of these steels at elevated temperatures. Furthermore, it has been difficult to analyse properly the causes of premature failure of bearings made from hot work and other tool steels.

This program was, therefore, initiated to obtain data on hot hardness, dimensional stability, compressive strength and resistance to softening for various hot work and other tool steels which have been proposed for bearing application in the temperature range 400 to 1000 F. Since the bearing is a vital part in the aircraft engine, it is also deemed necessary to devise means of accurately predicting fatigue life of bearing steels. A full understanding of the material characteristics and their behavior in simulated and actual bearing performance tests could then lead to the selection of suitable elevated temperature bearing steels and also to the development of new and improved bearing steels.

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II. OBJECTIVES OF THIS STUDY

This program comprises three phases. In Phase I, efforts were directed toward, (a) making a literature survey of all available information on high speed rolling contact bearings; (b) collecting in a single report the views expressed by bearing manufacturers and aircraft engine builders on property requirements of high temperature bearing materials; (c) tabulating the steels currently selected for bearing applications above the temperature range covered by SAE 52100 steel; and (d) accumulating all existing data on the results of bearing tests using hot work and other tool steels.

The work on Phase II consisted of a study of the metallurgical properties to include resistance to softening, hot hardness, dimensional stability, and elevated temperature compression behavior of some promising steels for elevated temperature bearing application.

Phase III includes an analysis of the data obtained in Phase II and recommendations of steel compositions which are considered applicable for aircraft engine bearings.

III. REVIEW OF THE LITERATURE ON AIRCRAFT BEARING STEELS AND INFORMATION OBTAINED FROM BEARING AND AIRCRAFT ENGINE MANUFACTURERS (Phase I)

The bearings used in the turbine type aircraft power plants are of the rolling contact type. Ball thrust bearings are used on the propeller shaft and these are usually heavily loaded. The most pressing problems are connected with the turbine main bearings and compressor thrust bearings. The compressor rear thrust bearing is exposed to hot air leakage from the last stage of the compressor. It is also subjected to a combination of heavy radial and thrust loads.

The four major items of concern to bearing manufacturers are: (1) the engine speed which determines the size of the bearings; (2) the operating and soak back temperatures; (3) the radial loads; and (4) the thrust loads.

The present trend in bearing design is towards higher stresses and much higher operating temperatures up to 1500 F. Operating temperatures of 700 F, thrust loads up to 50,000 pounds and DN values* of 3.5×10^6 are anticipated in aircraft engines of the immediate future

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*DN value is bearing bore in mm. times shaft speed in r.p.m.

Bearing Steel Requirements

The basic requirement of a bearing is complete reliability for a life of 1000 hours. Also, because of severe cyclic stresses exerted on the rolling elements of aircraft bearings, the material used in bearing balls and races must meet very rigid quality standards. Furthermore, the material must possess superior mechanical and physical properties. In metallurgical quality control tests, bearing steels must meet minimum standards. Tests which are applied include: deep etching, fracture rating, taper or hairline tests, and visual, magnetic and ultrasonic inspection methods for hidden and random inclusions. The bearing manufacturers consider it mandatory that consecutive shipments of steel should respond to heat treatment in a uniform manner.

The quality standards have been further defined by ASTM specifications A 295-46T for carbon-chromium ball- and roller-bearing steels. Since these specifications cover only three types of steel, SAE 52100, 51100 and 50100, these may be inapplicable for hot work die steels and other tool steels. The cleanliness specifications proposed by bearing manufacturers require an inclusion rating not to exceed 1.5 based on the thin series ASTM specifications A 295-46T.

In vacuum melted bearing steels, the aim should be to obtain an inclusion rating below 0.5 in the thin series. The austenitic grain size requirement is between 7 and 8 and decarburization in annealed bars must not exceed .030 inch for bar sizes 1 to 3 inches.

Physical and Mechanical Properties: The following material properties are desired by bearing manufacturers for fully heat treated steel of ideal high temperature bearing composition:

1. A hardness of Rockwell C 58 at the operating temperature for at least 1000 hours.

2. Dimensional stability when exposed to the temperatures developed immediately after a shutdown. (100-200 F higher than the engine operating temperature)

3. A high elastic limit.

4. Good thermal stability and resistance to oxidation and corrosion in environments encountered in engine application.

5. Good wear resistance and the ability to maintain a very highly polished surface.

6. Fairly constant coefficient of thermal expansion.

7. A low friction coefficient.

8. A constant elastic modulus in the range minus 65 F up to the maximum service temperature.

9. A uniform distribution of carbides and freedom from stringer type and large randomly distributed inclusions.

10. A high resistance to rolling fatigue.

11. Freedom from seizing and galling.

At the time this survey was made, the steels listed below along with their nominal composition were being considered for elevated temperature bearing application. Some of these steels were even being used in engine tests.

List of Current Bearing Steels and Their Nominal Composition

Designation	C	Mn	Si	Cr	V	Mo	W	Ni	Al
Halmo	.60	.30	1.2	4.70	.60	5.25	-	-	-
Rex LA	.85	.30	.35	3.00	1.00	3.25	1.50	-	-
M-1	.80	.30	.25	4.00	1.00	8.00	1.50	-	-
M-2	.85	.25	.30	4.00	2.00	5.00	6.00	-	-
M-10	.85	.25	.30	4.00	2.00	8.00	-	-	-
M-50	.80	.30	.30	4.00	1.00	4.00	-	-	-
T-1	.70	.30	.30	4.00	1.00	-	18.00	-	-
VSM	.70	.50	1.00	3.00	-	5.25	-	-	-
8Cr-8W	.55	.60	1.00	8.00	.15	-	8.00	-	-
MHT	1.00	.40	.50	1.50	-	-	-	-	1.25
52100	1.00	.35	.25	1.50	-	-	-	-	-
Bower 315 (carburizing grade)	.15	.50	.25	1.50	-	5.00	-	2.80	-

Since inclusions were considered undesirable in bearing steels, steelmakers were requested to furnish the above compositions induction melted and cast in vacuum, as well as melted by consumable electrode melting practice.

The scant information made available by bearing manufacturers on these steels is summarized below:

1. Ease of grinding was considered important and a partial listing of the relative grindability of some steels using 52100 as standard material is as

follows:

Grade	Grindability Index
52100	1
Halmo	1.3/1.5 (depending upon carbon content)
T-1	1.5/1.8
M-1	1.8/2
M-2	3
Rex LA	3
M-10	4*

2. Dimensional stability and a constant coefficient of thermal expansion are other important considerations. One bearing manufacturer reported that in a ring test used for checking dimensional stability, M-10 and T-1 steels did not give satisfactory results above 600 F. A majority of bearing manufacturers reported that the high speed steels in the above list showed no significant dimensional change up to 600 F.

Notes on Bearing Failures

Because of the complexity of the interacting factors it is difficult to determine the cause of bearing failures. Reports show that it is almost impossible to detect the initial cause of failure. After complete failure has occurred, it may be attributed to one of several causes listed below:

1) Surface fatigue of rolling elements

2) Inadequate lubrication

3) Breakdown of lubricant and increase in acidity accompanied by corrosion of the steel surface

4) Uneven wear of rolling elements and raceways

5) Excessive loading

6) Incompatibility of cage and rolling element material

Rolling fatigue in bearings snould be distinguished from fatigue in materials due to simple rotation. Exact information on factors influencing rolling fatigue is

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* A higher index number denotes increased difficulty in grinding the steel.

still lacking. Hardness and elastic limit have been correlated with rotating beam fatigue life of steels. A material of high hardness normally exhibits a high endurance limit, but it is not known if rolling fatigue has such a relationship to any of the material properties. Therefore, it is difficult to predict with any degree of certainty the normal life of bearings made from hot work and high speed steels.

A great many failures could be attributed to cage or separator material failures or a lack of lubrication at the contact points of rolling elements. Another major cause of failure is wear of rolling elements and raceways when thrust loads, speeds and bore size are increased. In certain instances premature bearing failures have been associated with the presence of large non-metallic inclusions.

Appraisal of Survey Information

This survey indicated that Halmo, MHT, M-1, VSM and M-50 were actively considered for elevated temperature bearing application. Bearing manufacturers reported a somewhat sporadic behavior of these materials in actual bearing tests. Early bearing failures were often associated with the occurrence of large randomly dispersed non-metallic inclusions in the steel. Although the role of inclusions in causing bearing failure was not fully understood there was a widespread desire in industry to use cleaner materials produced either by vacuum induction melting or by vacuum arc remelting. It was also apparent that use of vacuum melted steel increased bearing life by a significant factor. On the other hand, the bearing manufacturers and engine builders pointed out that it is of paramount importance to provide more data on the metallurgical, mechanical and physical properties of steels considered for bearing application in order to facilitate selection of the most suitable compositions.

Hence, this program was initiated to study the properties of bearing steels, namely, their resistance to softening, hot hardness, elastic properties in compression, dimensional stability, in the range room temperature to 1000 F. Furthermore, the size and distribution of carbides in these steels was to be observed in samples given the optimum heat treatment.

It is a further objective of this project to conduct simulated bearing tests on the most promising alloys using testing facilities at SKF Industries, Inc., for final screening of the bearing steels.

IV. EXPERIMENTAL WORK (Phase II)

Material

The experimental steels included in this evaluation program are listed in

Table I along with their chemical compositions. The steels other than those melted in vacuum were made in 30 lb. induction heats. The ingots were forged first to 1-5/8 in. square billets, ground free of any surface defects, and then reforged to either 5/8 in. square or 3/4 in. square bars. Prior to shipment, the bars were stress relieved at 1250 to 1350 F for one hour. The forging temperatures for the steels have been recorded in Table II. The hot workability was judged good for all steels except those marked with an asterisk; the forgeability of the latter was considered only fair.

The vacuum melted steels were obtained from the warehouse stock of Vacuum Metals Corporation in the form of 1 in. round bars. The gas content of the vacuum melted steel was in every case within the limits specified in Table I.

Preliminary Heat Treatment

Annealing: All forged bar stock was annealed in the manner described in Table II. Annealing was done by a continuous cooling procedure and the steels were cooled at a rate of 10 to 25 F per hour. Hardness measurements and microstructural studies were made on all steels to check the effectiveness of the annealing treatment.

Austenitizing for Hardening: The optimum austenitizing procedure for most steels included in the current program had been previously established. However, an austenitizing survey was carried out on those compositions on which information was lacking in regard to a proper austenitizing temperature to obtain an austenitic grain size between ASTM 6 and 8 and an optimum carbide size and distribution. The determination of a suitable austenitizing temperature involved quenching samples from various austenitizing temperatures. Subsequently, a check was made of the response of the quenched specimens in developing a maximum secondary hardness. Tempering temperatures were selected as high as was consistent with hardness requirements. The austenitizing procedures for all steels have been listed in Table III.

Resistance to Softening Studies

For this study, 3/4 in. thick specimens were cut from the annealed bar stock, austenitized as specified in Table III, oil quenched and tempered at various temperatures in the range 400 to 1100 F for progressively increasing times. In the case of 52100, MHT and the silicon bearing MHT, tempering above 800 F was not done since their useful range of application is well below this temperature. Tempering up to 800 F for these steels was done merely to develop a useful master tempering curve.

The effect of varying austenitizing temperature upon the peak secondary hardness and the temperature range of occurrence of secondary hardness was studied in .9C Halmo, UC, 440 C and 440 BM. In Tables IV and V it will be seen that the austenitizing temperatures used for these steels are different from those used in the tempering survey. This change in the austenitizining temperature was necessary in order to extend the useful range of application for these steels by pushing the secondary hardness peak to higher tempering temperatures. This is illustrated in the case of .9C Halmo and UC by two tempering curves (Figs. 10 and 27) shown for two different austenitizing temperatures. The results of a short time tempering survey using various austenitizing procedures for 440 C and 440 BM have not been shown.

Hot Hardness Studies

Specimens, approximately 3/4 in. in length, were cut from the annealed bar stock of all steels. These were quenched and tempered as described in Table IV. After the heat treatment, two parallel surfaces were ground along the length of the specimen.

The hardness tester shown schematically in Figure 1 is a modified Rockwell Hardness Machine. A front view of the machine with accessories is shown in Figure 2. At the start of the hot hardness test, the specimen is placed on the anvil; this anvil has a rectangular slot which acts as a guide to facilitate lateral movement of the specimen. Thus it is possible to obtain several readings without removing the sample from the furnace enclosure. The furnace, which surrounds the anvil and the indentor is screwed tightly at the bottom to the anvil. The top opening of the furnace is sealed with liquid Wood's metal. The indentor is a conventional diamond "Brale" fastened with high temperature cement to an 8 in. long shaft attached to the loading mechanism.

A 150 kilogram load is then applied in measuring hot hardness of bearing steels and the hardness data are read on the "C" scale. The specimen temperature is measured and controlled by a thermocouple which is welded to the specimen and connected to an electronic temperature controller. Scaling of the specimens in the furnace is prevented by protecting them with an argon atmosphere throughout the test. The hardness measuring techniques need no further explanation since they are no different from the standard room temperature hardness measuring procedures.

Dimensional Stability Studies

The specimens used in this study measured 3/8 in. in diameter by 4.000 plus or minus 0.001 in. long, with ends ground to the contour of a 4 in. diameter sphere. The spherical ends were to prevent errors that might result from a slight tilting of a squared-end cylindrical specimen during the length measurement. A drawing of this specimen is shown in Figure 3. Duplicate samples from each bar were machined slightly oversize to the dimensions given above; these specimens were austenitized, quenched and tempered as specified in Table IV. The samples were then finish ground to the specified dimensional tolerance. Precision length determinations were made on a Johansson Comparator by fastening specimens to a jig to keep them vertical. In this apparatus, the standard gage block is 4.2 inches and the difference in length between the sample and the standard block is made up by inserting small gage blocks.

The precision of the measurement is of the order of 10×10^{-6} inch per inch. The specimens used in this study were held for 1000 hours at 400 F and 600 F by submerging them in a neutral salt bath. The 1000 hours exposure at 800 F and 1000F originally was also carried out in a neutral salt bath. However, it was found that at the higher temperatures the salt was not sufficiently neutral toward the steel so that scaling occurred on the specimens. Consequently, in later tests, specimens were sealed in evacuated Vycor bulbs and then held for 1000 hours in neutral salt baths.

Elevated Temperature Compression Tests

A schematic diagram of the subpress used for elevated temperature compression tests is shown in Figure 4. A photograph of this subpress mounted in position in a Riehle Testing machine is shown in Figure 5. Originally, it had been planned to use high temperature SR-4 strain gages in the compression tests; however, elevated temperature strain gage application technology has not been perfected to the point where the readings are reliable. Since this development work involved considerable time, a compressometer which is standard equipment for measuring compressive strains has been used. The use of a compressometer requires more care, as well as time, in aligning the specimen. Except for this disadvantage it is capable of providing more accurate readings than the high temperature SR-4 strain gages in their present form of development.

Metallographic Studies

It is evident that fatigue life of the steel may be affected by the size and distribution of carbides in the microstructure. Fatigue cracks have been associated with flaws in the material. The steels included in this program, therefore, were examined for uniformity of microstructure with respect to size and distribution of carbides produced by different austenitizing temperatures. Photomicrographs are used to illustrate the microstructure of the different steels in a state of optimum heat treatment.

V. RESULTS

The hardnesses of the annealed bars are shown in Table II. Microstructures of all annealed steels were checked to ascertain that all steels were in a completely spheroidized condition prior to hardening.

The results of the studies on the resistance to softening of the various bearing steels have been summarized in Table III. These results have also been plotted as master tempering curves for each of the steels in Figures 6 to 34 inclusive. In these curves, the tempering temperatures and time at these temperatures have been combined in a single parameter by using the expression $T(20 + \log t)$ in which T represents the absolute temperature, degrees Rankine, and t equals the tempering time in hours.

Hot work steels are double tempered in commercial practice (two, 2 hour tempers) to transform retained austenite that is generally present after hardening. At any selected temperature, the two consecutive two hour tempers will result in equivalent hardness to a single four hour tempering operation at the same temperature. Hence, in the master tempering curves for secondary hardening steels, a scale has been added to read directly the hardness for a four hour temper at various temperatures in the range 400 to 1100 F.

The results of hot hardness surveys of quenched and tempered bearing steels are shown in Table IV. This table includes hardness values of various bearing steels at room temperature and at elevated temperatures after a 1000 hour exposure at 400, 600, 800, and 1000 F respectively. These results have also been summarized graphically in Figures 35 to 63 inclusive.

In Table V the results of dimensional stability tests have been tabulated for all bearing steels exposed for 1000 hours at 400, 600, 800 and 1000 F respectively. The parameter used is length change in micro-inches per inch.

Data from compression tests are tabulated in Table VI. This table gives the details of heat treatment and yield strength in compression at 0.1 percent and 0.2 percent offset. Yield strengths in compression at these offset points were determined from the stress-strain curve for each steel tested (except 52100 and modified 52100 steels) at 400, 600, 800, and 1000 F. The hot hardness values at these temperatures have also been recorded.

Typical microstructures illustrating the size and distribution of carbides in steels given the optimum heat treatment, are shown in Figures 64 to 92 inclusive.

VI. ANALYSIS OF RESULTS (Phase III)

The effect of elevated temperatures on the hardness of quenched and tempered steels can be predicted from master tempering curves for these steels. Such curves are also useful in planning commercial tempering treatments.

It may be seen from the master tempering curves presented in Figures 11 and 12 that SAE 52100 rapidly loses its hardness above 400 F and MHT begins to lose hardness slowly at 600 F and rapidly above this temperature. Therefore, it is imperative that steels capable of secondary hardening be considered for bearing application above 600 F.

Steels containing large amounts of alloying elements e.g. chromium, molybdenum, tungsten, vanadium, in the quenched condition will consist of highly alloyed tetragonal martensite, highly alloyed retained austenite, and undissolved complex carbides. Master tempering curves, Figures 6 to 9 inclusive, illustrate the change of hardness on tempering highly alloyed steels. As the tempering temperature is raised, an initial softening occurs due to the decomposition of tetragonal martensite to cubic martensite and a precipitation of cementite in a highly alloyed ferrite matrix. This phenomenon occurs up to tempering temperatures of 750 F with accompanying softening normally amounting to 2 to 4 Rockwell "C" points. The iron carbide, or cementite, which precipitates at these low temperatures, probably disappears either by re-solution in the matrix or by reaction with the alloy content of the matrix to form a complex carbide, if long tempering times and high tempering temperatures are employed. At temperatures above 750 F secondary hardening is encountered. That is, increased tempering increases the hardness. This secondary hardening is the result of a precipitation hardening reaction involving alloy carbides. In the final stage of the tempering process, the alloy carbides coagulate into relatively large particles. This stage, which entails rapid softening of the steel, occurs on tempering for long times at temperatures of about 1000 F or on tempering for relatively short times above 1100 F.

The master tempering curves shown in Figures 30 to 33 inclusive vary in accordance with the alloying elements in the steel, in particular with respect to the shape and size of the secondary hardness peak. By varying the austenitizing temperature this point of maximum secondary hardness can be made to occur at any temperature between 900 and 1150 F. The master tempering curves in this study have also been used to establish the optimum austenitizing temperatures for the various steels. The objective here is to use an austenitizing temperature that would push the secondary hardness peak to higher tempering temperatures. This would tend to minimize an accidental softening of the steel due to minor overshooting of the soak back temperature or long exposure of the bearing at somewhat higher than normal operating temperatures.

These master tempering curves can be used also to select steels that show a flat secondary hardness peak. A steel showing a narrow secondary hardness peak will not be suitable for bearing application. In this case small deviations in austenitizing and tempering temperatures which must be expected in commercial heat treating practice may cause permanent loss of hardness in bearing balls or races. For example, in steel E, Figure 32, without precise control, it would be difficult to obtain the same peak hardness consistently in quenched and tempered steels. In order to insure against these occurrences an ideal high temperature bearing steel must have a flat secondary hardness peak as exemplified by curves for Halmo, M2, M10, M50, T1. (Figures 6, 18, 20, 23, 26) All hot work die steels and high speed tool steels investigated possess adequate resistance to softening.

Bearing steels must also be able to withstand wear at elevated temperatures and for this reason they should have adequate hot hardness. It is also probable that elevated temperature strength may be dependent on hot hardness. Based on bearing fatigue and performance tests, bearing manufacturers have fixed the hot hardness at 56-58 Rockwell "C" at the operating temperature. Using this hot hardness criterion and also the room temperature hardness after 1000 hours exposure at the various temperatures, the steels included in this study may be grouped as follows:

Approximate Bearing Operation Temperature Range	Group of Steels
Room Temp. up to 400 F	52100
Room Temp. up to 500 F	MHT, MHT + Si, 440 C, 440 BM, UC
Room Temp. up to 700 F	Halmo-1, Experimental Compositions A, C, and E
Room Temp. up to 800 F	Halmo-2, .8C Halmo, .9C Halmo, VSM, M50, M10, Experimental Compositions B, D, and F.
Room Temp. up to 900 F	T1, T5, M2, M1, HiC-M10 and Experimental Composition G

In this arrangement, the specified bearing operation temperatures allow a margin of 100 to 150 F increase in temperature due to soak back heating.

Next the hot hardness drop in various steels was studied as it is affected by temperature increases. The average hardnesses for all hot work die steels and other tool steels were calculated at the various test temperatures from the results obtained in the hot hardness studies. Subsequently, the standard deviation of hardness in these steels was computed. The curve shown in Figure 93 portrays the mean hardness values and the standard deviation from the mean hardness value computed for 22 steels at temperatures varying from room temperature to 1000 F.

It may also be noted that with rising temperature a nonlinear hardness drop was observed in these steels. The average hardness drop in the 22 steels investigated is 4.3 Rockwell "C" points between room temperature and 400 F, 1.5 Rockwell "C" points between 400 and 600 F, 2.3 Rockwell "C" points between 600 and 800 F and 4 Rockwell "C" points between 800 and 1000 F. From these data one can estimate the hot hardness based on the specific room temperature hardness of the quenched and tempered steels.

An inspection of the dimensional stability evaluation for the steels (Table V) indicates that in Halmo, T1, M2, M1, M10, VSM, M50, and Experimental steels B and G, the given heat treatment has established the required dimensional stability. However, much work remains to be done to design optimum heat treatment procedures for the remaining useful compositions in order to obtain good dimensional stability. This is particularly true for the experimental compositions.

"Dimensional stability," as used in this report, refers to the expansion or contraction of steel parts subsequent to hardening and tempering. The differences in dimensional stability between hardened steels can be accounted for on the basis of martensite tempering which results in contraction, and transformation of retained austenite, which results in an expansion. In an unstable steel both these reactions can occur simultaneously. The attainment of dimensional stability in tool and die steels depends on minimizing both the contraction due to martensite decomposition and the expansion due to retained austenite transformation. In high alloy steels retained austenite is minimized by using lower austenitizing temperatures consistent with minimum residual carbides and maximum secondary hardening at the highest tempering temperatures.

An inspection of compression test results in Table VI shows that all the hot work die steels and high speed tool steels possess considerably higher compressive yield strength than that of SAE 52100. It is known that greater flight speed results in exponential increases of bearing loads. Hot work die steels and high speed tool steels, within the suggested temperature range of application for aircraft bearings have compressive yield strengths above 200,000 psi. It is the opinion of bearing manufacturers that these strength levels are sufficient in a high temperature bearing steel.

The microstructures for most steels tested, Figures 64 to 92 inclusive, seem to be characteristic for bearing races or balls, inasmuch as the carbides are evenly distributed and the martensite is uniformly tempered. In Figures 67, 74, 75, and 90 however there is evidence of retained austenite which could not be eliminated without sacrificing some other required properties. From the point of view of microstructure, therefore, .8C Halmo, 440 C, 440 BM, and steel E have been considered unsuitable for bearing application.

Attention of the reader is drawn to commercial grades Halmo, VSM, M50, M10, M2 and M1 and experimental steels B and G. These compositions not only possess optimum metallurgical properties required in high speed aircraft bearings, they are also comparatively lean in alloying elements. In the group of materials suggested for bearings to operate in the range room temperature up to 900 F, (Page 20) the logical choice of steels for further evaluation in bearing tests would be M2, M1 and experimental steel G.

VII. CONCLUSIONS

In conclusion it may be stated that for elevated temperature bearings, Halmo-1, T1, M2, M1, M10, and M50 appear to be the most promising materials. Among the experimental grades, the steels with the following compositions seem to have also fulfilled the preliminary requirements of a bearing material:

	C	Mn	Cr	V	W	Mo
Steel B	.0.7	0.29	4.21	0.59	-	5.31
Steel G	1.31	0.29	4.07	4.13	5.75	4.87

These steels could be further classified from the view point of their temperature range of application in the following manner:

Room Temperature up to 700 F	Halmo-1
Room Temperature up to 800 F	VSM, M50, M10 and Steel B
Room Temperature up to 900 F	T1 M2, M1 and Steel G

VIII. SUGGESTIONS FOR FUTURE WORK

Data of this investigation show some of the major shortcomings of currently available hot work and other tool steels for elevated temperature aircraft bearing application. Furthermore, none of the steels investigated appear suitable for bearing application above 900 F. There is an urgent need for steels specifically suited for bearings to operate in the range room temperature up to 900 F, (Page 12) the logical choice of steels for further evaluation in bearing tests would be M2, M1 and experimental steel G.

The development of new steel compositions specifically suited for aircraft bearings for service in the range room temperature to 1000 F. To achieve this objective a study of basic metallurgical properties must be continued on a range of experimental alloys. In addition to the properties investigated during the last year, particular emphasis must be placed on corrosion and oxidation resistance and fatigue properties. A better understanding of the effect of microstructure, especially carbide content, size, and shape, on fatigue life must be attained.

IX. SELECTED REFERENCES

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2. Preston, J., Mogul, J., and Floroff, G. K. "Anti-Friction Bearing Materials for

Aircraft Power Plants" Society of Automotive Engineers, Preprint #653, January 1956.

3. Styri, H., "Fatigue Strength of Ball-Bearing Races" Proceedings of the American Society for Testing Materials, Vol. 51, 1951, p. 682.

4. Allen, C. M. and Goldthwaite, W. H. "Research in Bearings" Battelle Technical Review, Nov. 1954.

5. Dayton, R. W., Allen, C. M., et al., "A Survey of Rolling Contact Bearings for Aircraft Turbine Power Plants" Battelle Memorial Institute Report, July 1952.

6. Jones, A. B. "The Life of High Speed Ball-Bearings" Transactions of the American Society for Mechanical Engineers, Vol. 74, 1952.

TABLE I

List of Bearing Steels and their Chemical Analyses
(in percent)

Grade	C	Mn	P	S	Si	Ni	Cr	V	W	Mo	Others
Halmo-1	.58	.28	.009	.032	1.18	.08	4.72	.51	-	5.15	-
Ferrovac Halmo	.56	.28	.005	.008	1.18	.04	4.82	.50	-	5.12	-
Halmo-2	.64	.30	.007	.032	1.06	.08	4.60	.54	-	5.09	-
.8C Halmo	.76	.31	.008	.037	1.07	.08	4.57	.59	-	5.06	-
.9C Halmo	.89	.37	.007	.025	1.08	.04	4.42	.52	-	5.02	-
52100	.98	.29	.004	.029	.23	.06	1.52	-	-	.07	-
Ferrovac 52100	1.04	.42	.003	.008	.26	.02	1.50	-	-	-	-
MHT	1.03	.30	.004	.030	.24	.09	1.53	-	-	.03	1.30 Al
Ferrovac MHT	1.03	.43	.004	.008	.46	.02	1.49	-	-	-	1.30 Al
MHT + Si	1.03	.34	.004	.030	1.23	.09	1.58	-	-	.02	1.29 Al
440 C	1.12	.43	.004	.030	.27	.04	16.17	-	-	.01	-
440 BM	1.03	.49	.004	.036	.45	.10	17.15	.14	-	.76	-
T1	.67	.30	.001	.019	.18	.02	3.91	1.37	18.17	.18	-
T5	.83	.30	.017	.032	.29	.18	4.20	2.13	18.30	.13	7.92 Co
M2	.79	.29	.011	.033	.28	.08	3.83	1.79	6.40	4.91	-
Ferrovac M2	.80	.26	.005	.009	.31	.03	4.16	1.96	6.47	5.01	-
M1	.76	.30	.008	.038	.33	.09	3.66	1.19	1.32	8.51	-
M10	.85	.30	.011	.038	.28	.09	4.10	1.68	0.01	7.77	-
HiC-M10	1.06	.33	.008	.041	.30	.08	3.99	1.78	-	7.50	-
VSM	.66	.46	.011	.033	1.30	.09	2.83	.03	.01	5.02	-
M50	.79	.32	.008	.036	.36	.08	4.01	1.05	.01	4.16	-
UC	.91	.32	.007	.019	.31	.03	5.66	.43	-	1.61	-
A	.99	.32	.007	.039	.32	.10	11.22	-	-	4.20	-
B	.71	.29	.007	.035	.31	.11	4.21	.59	-	5.31	-
C	.92	.21	.008	.040	.30	.12	8.18	2.12	-	4.90	-
D	.74	.27	.010	.036	.31	.10	3.42	2.21	-	4.85	-
E	.50	.53	.010	.023	1.23	.10	7.96	.26	7.98	.07	-
F	.79	.24	.009	.033	.26	.14	3.29	1.12	1.56	3.42	-
G	1.31	.29	.008	.041	.32	.09	4.07	4.13	5.75	4.87	-

Gas content of vacuum induction melted and cast steels (Ferrovac) were within the limits specified below.

Nitrogen - .0004
Oxygen - .0005
Hydrogen - less than 1 part per million

TABLE II

Details of Bearing Steel Forging and Annealing Procedures

Grade	Forging Procedure: Forging Temp. F	Forging Procedure: Soaking Time, hrs.	Annealing Treatment: Annealing Temp. & Time	Annealing Treatment: Control Cool	Hardness R_C
Halmo-1	1950	2	1550 F-2 hrs	25 F/hr	15
Ferrovac Halmo	1950	2	Mill annealed		16
Halmo-2	1950	2	1550 F-2 hrs	25 F/hr	17
.8C Halmo	1975	2-1/2	1550 F-2 hrs	25 F/hr	14
.9C Halmo	1975	2-1/2	1550 F-2 hrs	25 F/hr	18
52100	1975	1	1440 F-4 hrs	10 F/hr	8
Ferrovac 52100	1970	1	Mill annealed		6
MHT	1975	1-1/2	1440 F-4 hrs	10 F/hr	16
Ferrovac MHT	1970	1-1/2	1440 F-4 hrs	10 F/hr	11
MHT + Si	1975	1-1/2	1500 F-4 hrs	10 F/hr	19
440 C	1975	2	1650 F-6 hrs	25 F/hr	10
440 BM	1975	2	1650 F-6 hrs	25 F/hr	18
T1	2050	2-1/2	1650 F-2 hrs	25 F/hr	18
T5	2025	2-1/2	1650 F-2 hrs	15 F/hr	27
M2	1950	2	1600 F-2 hrs	25 F/hr	16
Ferrovac M2	1950	2	Mill annealed		16
M1	1950	2	1550 F-2 hrs	25 F/hr	16
M10	1950	2	1550 F-2 hrs	25 F/hr	15
HiC-M10	1950	2	1550 F-2 hrs	25 F/hr	17
VSM	1975	2	1600 F-2 hrs	25 F/hr	18

TABLE II (Continued)

Details of Bearing Steel Forging and Annealing Procedures

	Forging Procedure		Annealing Treatment		
Grade	Forging Temp. F	Soaking Time, hrs.	Annealing Temp. & Time	Control Cool	Hardness R_C
M 50*	1950	2	1550 F-2 hrs	25 F/hr	15
UC	1925	2	1550 F-2 hrs	25 F/hr	16
A*	1960	2-1/2	1650 F-6 hrs	25 F/hr	21
B	1925	2	1650 F-1 hr	15 F/hr	14
C*	1960	2-1/2	1650 F-6 hrs	25 F/hr	21
D	1950	2	1600 F-1 hr	15 F/hr	12
E	1925	2	1650 F-2 hrs	15 F/hr	20
F	1925	2	1600 F-1 hr	15 F/hr	14
G*	1960	2-1/2	1600 F-1 hr	15 F/hr	20

* Forgeability considered fair as compared to other grades.

TABLE III

Results of Tempering Survey

Grade	Hardening Treatment*	As-Quenched Hardness R_C	Tempering Temperature (°F)	HARDNESS (R_C) AFTER TEMPERING — Time at Temperature: 4 hrs	10 hrs	30 hrs	60 hrs	100 hrs	200 hrs	500 hrs	1000 hrs
Halmo-1	2100 F 20 min.	64	400	60	60	58	58	58	58	58	58
			600	58	58	58	58	58	58	59	59
			800	60	61	61	62	62	63	64	65
			1000	66	65	64	63	63	61	56	53
Ferrovac Halmo	2100 F 20 min	64	400	60	60	59	59	59	59	60	59
			600	60	60	60	60	59	59	60	61
			800	62	62	62	62	62	63	64	65
			1000	64	63	62	60	59	65	50	50
Halmo-2	2100 F 20 min	65	400	60	60	60	59	59	59	59	59
			600	59	59	59	59	59	59	60	60
			800	61	62	62	63	63	64	64	65
			1000	65	65	63	62	61	59	53	53
.8C Halmo	2050 F 20 min	63	400	60	59	59	59	58	58	59	59
			600	58	58	58	58	58	59	59	59
			800	59	59	60	61	61	62	64	64
			1000	65	65	65	64	64	62	59	54
.9C Halmo	1850 F 60 min	66	400	61	61	61	60	61	60	61	61
			600	59	60	60	60	60	60	60	60
			800	60	60	60	62	62	62	64	65
			1000	64	62	60	59	57	54	50	46
52100	1550 F 60 min	66	400	60	60	59	'58	58	58	58	58
			600	55	55	54	53	53	52	53	52
			800	49	48	46	45	45	44	43	42
Ferrovac 52100	1550 F 60 min	66	400	61	61	60	60	59	59	60	60
			600	57	57	55	55	55	54	55	54
			800	47	47	46	45	44	43	42	40
MHT	1550 F 60 min	66	400	62	62	61	62	62	62	62	62
			600	60	61	60	60	60	59	59	59
			800	52	52	50	50	49	48	47	46
Ferrovac MHT	1550 F 1 hr	66	400	62	62	62	62	62	62	62	62
			600	60	60	60	60	60	60	59	59
			800	53	53	51	50	49	47	47	46

* All samples were oil quenched

TABLE III (Continued)

Results of Tempering Survey

Grade	Hardening Treatment*	As-Quenched Hardness R_C	Tempering Temperature (°F)	HARDNESS (R_C) AFTER TEMPERING — Time at Temperature: 4 hrs	10 hrs	30 hrs	60 hrs	100 hrs	200 hrs	500 hrs	1000 hrs
MHT + Si	1600 F 60 min	66	400	62	63	61	62	62	62	62	62
			600	60	60	60	61	60	60	61	60
			800	55	54	53	53	53	52	51	51
440 C	1850 F 60 min	62	400	58	58	57	57	57	57	57	57
			600	57	56	56	56	57	57	57	57
			800	57	58	59	59	60	60	60	59
440 BM	1900 F 60 min	62	400	58	58	57	57	57	56	57	56
			600	55	55	56	56	57	56	56	56
			800	55	56	57	58	58	59	60	62
T1	2350 F 5 min	67	400	63	69	62	62	62	62	63	63
			600	62	63	62	63	63	62	63	63
			800	63	64	64	64	64	65	66	66
			1000	67	66	65	65	65	64	63	60

Grade	Hardening Treatment*	As-Quenched Hardness R_C	Tempering Temperature (°F)	4 hrs	10 hrs	20 hrs	50 hrs	56 hrs	95 hrs	100 hrs	200 hrs	1000 hrs
T5	2300 F 5 min	66	400		61					60		62
			500			60				59		
			600		59					59		63
			700				60					
			800	60			62				63	66
			1000	67		67			66			59
			1050				64					
			1100					57				

Grade	Hardening Treatment*	As-Quenched Hardness R_C	Tempering Temperature (°F)	4 hrs	10 hrs	30 hrs	60 hrs	100 hrs	200 hrs	500 hrs	1000 hrs
M2	2250 F 10 min	66	400	63	63	62	62	62	61	62	62
			600	61	61	61	61	61	61	62	62
			800	62	63	63	64	64	64	65	66
			1000	67	67	65	64	64	63	61	61
Ferrovac M2	2250 F 10 min	65	400	63	63	62	62	61	61	62	62
			600	62	62	62	62	62	62	62	62
			800	63	63	62	63	64	64	65	65
			1000	66	65	65	64	63	62	60	60

*All samples were oil quenched.

TABLE III (Continued)

Results of Tempering Survey

Grade	Hardening Treatment*	As-Quenched Hardness R_C	Tempering Temperature (°F)	HARDNESS (R_C) AFTER TEMPERING — Time at Temperature: 4 hrs	10 hrs	30 hrs	60 hrs	100 hrs	200 hrs	500 hrs	1000 hrs
M1	2200 F 15 min	64	400	62	62	61	61	61	61	61	61
			600	61	62	60	60	60	60	61	61
			800	62	62	63	63	63	63	65	66
			1000	67	67	65	65	64	63	61	61
M10	2200 F 15 min	64	400	60	60	59	59	59	59	58	59
			600	58	59	58	58	58	58	59	59
			800	59	60	60	61	61	62	63	65
			1000	67	67	65	65	64	63	61	61
HiC-M10	2300 F 10 min	65	400	61	61	60	60	60	60	60	60
			600	58	58	57	58	58	57	59	59
			800	59	60	60	61	61	62	65	66
			1000	67	68	67	66	66	65	64	63
VSM	2050 F 20 min	63	400	60	60	60	60	60	59	60	60
			600	59	60	59	59	60	59	60	60
			800	60	61	61	62	62	62	64	64
			1000	63	63	61	60	58	55	52	51
M50	2100 F 20 min	64	400	59	59	57	57	58	58	58	58
			600	56	57	56	56	56	56	57	58
			800	57	58	58	59	59	60	62	63
			1000	65	65	64	64	63	61	60	60
UC	1800 F 60 min	66	400	62	61	60	60	60	61	60	60
			600	59	59	58	59	59	59	59	59
			800	59	59	59	60	60	61	61	61
			1000	59	57	55	54	53	51	48	45

EXPERIMENTAL ANALYSES

Grade	Hardening Treatment*	As-Quenched Hardness R_C	Tempering Temperature (°F)	4 hrs	10 hrs	20 hrs	50 hrs	56 hrs	95 hrs	100 hrs	200 hrs	1000 hrs
A	2000 F 30 min	62	400		59					57		57
			500			57				56		
			600		57					57		58
			700				57'					
			800	57			60				61	63
			1000	64		57			53			
			1050				53					
			1100					47				

*All samples were oil quenched.

TABLE III (Continued)

Results of Tempering Survey

Grade	Hardening Treatment*	As-Quenched Hardness R_C	Tempering Temperature (°F)	HARDNESS (R_C) AFTER TEMPERING Time at Temperature 4 hrs	10 hrs	20 hrs	50 hrs	56 hrs	95 hrs	100 hrs	200 hrs	1000 hrs
B	2150 F 15 min	61	400		58					57		57
			500			56				55		
			600		55					55		55
			700				55					
			800	56			59				60	62
			1000	65		65			63			57
			1050				64					
			1100					54				
C	2100 F 20 min	57	400		53					51		50
			500			49				49		
			600		50					49		49
			700				54					
			800	49			53				54	56
			1000	62		65			61			49
			1050				64					
			1100					56				
D	2200 F 15 min	65	400		62					61		61
			500			60				60		
			600		60					60		61
			700				61					
			800	61			63				63	64
			1000	64		63			61			
			1050				60					
			1100					52				
E	2150 F 15 min	61	400		58					56		56
			500			56				55		
			600		56					56		56
			700				57					
			800	57			59				60	61
			1000	63		55			53			
			1050				51					
			1100						49			
F	2200 F 15 min	63	400		60					58		58
			500			58				57		
			600		57					56		57
			700				47					
			800	57			60				61	62
			1000	64		64			64			60
			1050				62					
			1100					56				

* All samples were oil quenched

TABLE III (Continued)

Results of Tempering Survey

Grade	Hardening Treatment*	As-Quenched Hardness R_C	Tempering Temperature (°F)	HARDNESS (R_C) AFTER TEMPERING Time at Temperature 4 hrs	10 hrs	20 hrs	50 hrs	56 hrs	95 hrs	100 hrs	200 hrs	1000 hrs
G	2200 F 15 min	66	400		61					60		62
			500			60				59		
			600		59					59		63
			700				60					
			800	60			62				63	66
			1000	67		67			66			59
			1050				64					
			1100					57				

* All samples were oil quenched

TABLE IV

Results of Hot Hardness Survey

Grade	Heat Treatment*	Hardness after Quench and Temper, R_C	Elevated Temperature Hardness R_C at Temperatures F		Room Temp. Hardness after Hot Hardness Test, R_C	Hardness R_C after 1000 hrs Exposure at Temperatures F		
							Room Temp.	Elevated Temp.
Halmo-1	2100 F/20 min. 1050 F/2+2 hrs	64	400	60	64	400	64	59
			600	59		600	64	58
			800	56		800	64	55
			1000	53		1000	49	35
Ferrovac Halmo	2100 F/20 min. 1050 F/2+2 hrs	63	400	59	63	400	63	59
			600	57		600	62	56
			800	55		800	62	54
			1000	52		1000	48	34
Halmo-2	2100 F/20 min. 1050 F/2+2 hrs	65	400	60	65	400	65	61
			600	59		600	65	60
			800	57		800	64	56
			1000	53		1000	53	40
.8C Halmo	2050 F/20 min. 1050 F/2+2 hrs	66	400	62	66	400	66	62
			600	59		600	65	59
			800	56		800	66	57
			1000	53		1000	54	40
.9C Halmo	2050 F/25 min. 1075 F/2+2 hrs	65	400	60	65	400	65	60
			600	57		600	65	58
			800	56		800	65	56
			1000	53		1000	57	45
52100	1550 F/1 hr 400 F/2+2 hrs	61	400	56	55	400	57	52
			600	51		600	53	47
			800	42		800	-	-

* All Steels were oil quenched from the austenitizing temperature.
Double tempering operation - Two consecutive 2 hr. tempers at the indicated temperature.

TABLE IV (Continued)

Results of Hot Hardness Survey

Grade	Heat Treatment*	Hardness after Quench and Temper, R_C	Elevated Temperature Hardness R_C at Temperatures F		Room Temp. Hardness after Hot Hardness Test, R_C	Hardness R_C after 1000 hrs Exposure at Temperatures F	Room Temp.	Elevated Temp.
Ferrovac 52100	1550 F/1 hr.	62	400	57	59	400	58	53
	400 F/2 hr.		600	49		600	51	45
MHT	1550 F/1 hr.	63	400	58	59	400	63	58
	400 F/2 hr.		600	52		600	59	53
			800	42		800	46	38
Ferrovac MHT	1550 F/1 hr.	62	400	58	62	400	62	57
	400 F/2 hrs		600	52		600	58	52
			800	-		800	44	36
MHT + Si	1600 F/1 hr.	62	400	57	59	400	62	57
	400 F/2 hrs		600	54		600	60	54
			800	-		800	48	40
440 C	1950 F/1 hr.	61	400	57	61	400	61	57
	350 F/1 hr.		600	55		600	61	55
	Refrigerated		800	47		800	59	51
	900 F 2+2 hrs							
440 BM	1950 F/1 hr.	62	400	57	62	400	61	56
	350 F/1 hr.		600	55		600	61	53
	Refrigerated		800	53		800	59	51
	900 F 2+2 hrs							
T1	2350 F/5 min.	66	400	61	66	400	66	61
	1050 F/2+2 hrs		600	60		600	66	60
			800	57		800	66	57
			1000	54		1000	61	49

* All steels were oil quenched from the austenitizing temperature.
Double Tempering operation - Two consecutive 2 hr. tempers at the indicated temperatures.

TABLE IV (Continued)

Results of Hot Hardness Survey

Grade	Heat Treatment*	Hardness after Quench and Temper, R_C	Elevated Temperature Hardness R_C at Temperatures F		Room Temp. Hardness after Hot Hardness Test, R_C	Hardness R_C after 1000 hrs Exposure at Temperatures F		
							Room Temp.	Elevated Temp.
T5	2300 F/5 min. 1000 F/2+2 hrs	67	400	65	67	400	67	64
			600	64		600	67	63
			800	62		800	67	61
			1000	57		1000	61	51
M2	2250 F/10 min. 1050 F/2+2 hrs	66	400	62	66	400	66	62
			600	61		600	66	60
			800	59		800	65	57
			1000	55		1000	61	49
Ferrovac M2	2250 F/10 min. 1050 F/2+2 hrs	66	400	61	66	400	66	61
			600	60		600	66	59
			800	58		800	66	58
			1000	55		1000	60	49
M1	2200 F/15 min. 1050 F/2+2 hrs	66	400	61	66	400	66	62
			600	60		600	66	60
			800	58		800	66	57
			1000	55		1000	62	52
M10	2200 F/15 min. 1050 F/2+2 hrs	66	400	62	66	400	66	61
			600	61		600	66	61
			800	58		800	66	57
			1000	54		1000	57	45
HiC-M10	2200 F/15 min. 1050 F/2+2 hrs	67	400	62	67	400	67	62
			600	61		600	67	60
			800	59		800	66	58
			1000	56		1000	64	53

* All steels were oil quenched from the austenitizing temperature.
Double tempering operation - Two consecutive 2 hr. tempers at the indicated temperatures.

TABLE IV (Continued)

Results of Hot Hardness Survey

Grade	Heat Treatment*	Hardness after Quench and Temper, R_C	Elevated Temperature Hardness R_C at Temperatures F		Room Temp. Hardness after Hot Hardness Test, R_C	Hardness R_C after 1000 hrs exposure at Temperatures F		
							Room Temp.	Elevated Temp.
VSM	2100 F/20 min. 1000 F/2+2 hrs	64	400	62	64	400	64	60
			600	60		600	64	58
			800	57		800	64	55
			1000	53		1000	56	44
M50	2100 F/20 min. 1050 F/2+2 hrs	64	400	62	64	400	64	61
			600	59		600	64	57
			800	57		800	63	55
			1000	52		1000	58	46
UC	1950 F/45 min. 1000 F/2+2 hrs	63	400	59	63	400	62	58
			600	56		600	62	55
			800	53		800	61	53
			1000	48		1000	51	38
A	2000 F/30 min. 1000 F/2+2 hrs	64	400	59	64	400	64	59
			600	59		600	64	57
			800	57		800	62	51
			1000	53		1000	48	34
B	2150 F/15 min. 1000 F/2+2 hrs	66	400	61	66	400	66	61
			600	59		600	66	59
			800	57		800	66	58
			1000	53		1000	55	44
C	2100 F/20 min 1000 F/2+2 hrs	66	400	61	66	400	66	60
			600	59		600	66	58
			800	57		800	66	54
			1000	53		1000	48	36

* All steels were oil quenched from the austenitizing temperature.
Double tempering operation - Two consecutive 2 hr. tempers at the indicated temperatures.

TABLE IV (Continued)

Results of Hot Hardness Survey

Grade	Heat Treatment*	Hardness after Quench and Temper, R_C	Elevated Temperature Hardness R_C at Temperatures F		Room Temp. Hardness after Hot Hardness Test, R_C	Hardness R_C after 1000 hrs exposure at Temperatures F	Room Temp.	Elevated Temp.
D	2200 F/15 min. 1000 F/2+2 hrs	64	400	60	64	400	64	59
			600	58		600	64	57
			800	57		800	63	56
			1000	53		1000	56	45
E	2100 F/20 min. 1000 F/2+2 hrs	63	400	58	63	400	63	59
			600	57		600	63	57
			800	53		800	63	53
			1000	49		1000	48	35
F	2200 F/15 min. 1000 F/2+2 hrs	65	400	60	65	400	65	59
			600	58		600	56	57
			800	55		800	65	55
			1000	51		1000	60	48
G	2200 F/15 min. 1000 F/2+2 hrs	67	400	63	64	400	67	63
			600	62		600	67	61
			800	59		800	66	59
			1000	56		1000	57	45

* All steels were oil quenched from the austenitizing temperature.
Double tempering operation - Two consecutive 2 hr. tempers at the indicated temperatures.

TABLE V

Dimensional Stability Test Results for Bearing Steels

Grade	Heat Treatment*	Length Change Micro inch/inch in Specimens Exposed for 1000 hours at temperatures			
		400 F	600 F	800 F	1000 F
Halmo-1	2100 F/20 min 1050 F/2+2 hrs	No Change	No Change	+ 10	- 36
Ferrovac Halmo	2100 F/20 min 1050 F/2+2 hrs	No Change	No Change	+ 12	- 47
Halmo-2	2100 F/20 min 1050 F/2+2 min	+ 15	+ 12	+ 35	- 62
.8C Halmo	2050 F/25 min 1050 F/2+2 hrs	+ 37	- 7	+ 395	- 57
.9C Halmo	2050 F/25 min 1075 F/2+2 hrs	+245	+ 50	+ 501	+1257
52100	1550 F/1 hr 400 F/2 hrs	+ 55	-742	-1030	-
Ferrovac 52100	1550 F/1 hr 400 F/2 hrs	+ 40	-730	- 895	-
MHT	1550 F/1 hr 400 F/2 hrs	+ 20	+ 20	-1502	-
Ferrovac MHT	1550 F/1 hr 400 F/2 hrs	+242	+ 12	-1440	-
MHT + Si	1600 F/1 hr 400 F/2 hrs	+280	+120	-1375	-57
440 C	1950 F/1 hr 350 F/1 hr Ref. 900 F/2+2 hrs	+ 22	+ 15	+1195	+847
440 BM	1950 F/1 hr 350 F/1 hr Ref. 900 F/2+2 hrs	- 52	- 52	+1137	+458
T1	2350 F/5 min 1050 F/2+2 hrs	+ 7	- 75	+ 30	- 7

* All specimens were oil quenched from the austenitizing temperature. Double tempering operation involved two consecutive 2 hour tempers at the indicated temperature.

TABLE V (Continued)

Dimensional Stability Test Results for Bearing Steels

Grade	Heat Treatment*	Length Change Micro inch/inch in Specimens Exposed for 1000 hours at temperatures: 400 F	600 F	800 F	1000 F
T5	2300 F/5 min 1000 F/2+2 hrs	+ 1	+ 27	+ 46	+ 270
M2	2250 F/10 min 1050 F/2+2 hrs	25	- 17	- 10	+ 32
Ferrovac M2	2250 F/10 min 1050 F/2+2 hrs	- 2	- 12	No Change	+ 15
M1	2200 F/15 min 1050 F/2+2 hrs	- 10	+ 20	- 7	- 25
M10	2200 F/15 min 1050 F/2+2 hrs	- 25	- 17	- 10	No Change
HiC-M10	2200 F/15 min 1050 F/2+2 hrs	- 10	No Change	- 28	+ 76
VSM	2050 F/20 min 1000 F/2+2 hrs	+ 15	No Change	+ 35	- 1
M50	2100 F/20 min 1050 F/2+2 hrs	+ 22	+12	+ 27	- 50
UC	1950 F/45 min 1000 F/2+2 hrs	+ 90	No Change	+ 37	- 132
A	2000 F/30 min 1000 F/2+2 hrs	-168	-120	+315	+1535
B	2150 F/15 min 1000 F/2+2 hrs	+ 1	- 16	+ 5	+ 60
C	2100 F/20 min 1000 F/2+2 hrs	- 65	- 55	+247	+ 467
D	2200 F/15 min 1000 F/2+2 hrs	- 4	- 8	+ 75	+ 447
E	2100 F/20 min 1000 F/2+2 hrs	- 50	- 20	+ 96	+ 100

* All specimens were oil quenched from the austenitizing temperature. Double tempering operation involved two consecutive 2 hour tempers at the indicated temperature.

TABLE V (Continued)

Dimensional Stability Test Results for Bearing Steels

Grade	Heat Treatment*	Length Change Micro inch/inch in Specimens Exposed for 1000 hours at temperatures: 400 F	600 F	800 F	1000 F
F	2200 F/15 min 1000 F/2+2 hrs	+ 105	- 10	+ 25	+ 523
G	2200 F/15 min 1000 F/2+2 hrs	+ 31	- 17	- 20	- 12

* All specimens were oil quenched from the austenitizing temperature. Double tempering operation involved two consecutive 2 hour tempers at the indicated temperature.

TABLE VI

Compression Test Results for Bearing Steels

Grade	Heat Treatment*	Testing Temperature (F)	Hot Hardness R_C	Yield Strength, psi 0.10% Offset	Yield Strength, psi 0.2% Offset
Halmo-1	2100 F/20 min.	400	60	364,000	392,000
	1050 F/2+2 hrs	600	59	318,000	344,000
		800	56	268,000	300,000
		1000	53	244,000	268,000
Halmo Ferrovac	2100 F/20 min.	400	59	368,000	398,000
	1050 F/2+2 hrs	600	57	303,000	327,000
		800	55	290,000	312,000
		1000	52	220,000	236,000
Halmo-2	2100 F/20 min.	400	60	372,000	396,000
	1050 F/2+2 hrs	600	59	332,000	362,000
		800	57	298,000	322,000
		1000	53	267,000	273,000
.8C Halmo	2050 F/25 min.	400	62	388,000	400,000
	1050 F/2+2 hrs	600	49	366,000	390,000
		800	56	283,000	329,000
		1000	53	273,000	296,000
.9C Halmo	2050 F/25 min.	400	60	392,000	406,000
	1075 F/2+2 hrs	600	57	344,000	388,000
		800	56	248,000	380,000
		1000	53	168,000	204,000
52100	1550 F/1 hr	400	56	188,000	232,000
	400 F/2 hrs	600	51	137,000	159,000
		800	42	104,000	119,000
52100 Ferrovac	1550 F/1 hr	400	57	196,000	240,000
	400 F/2 hrs	600	49	152,000	177,000
MHT	1550 F/1 hr	400	58	222,000	303,000
	400 F/2 hrs	600	52	167,000	193,000
		800	42	135,000	157,000
MHT Ferrovac	1550 F/1 hr.	400	58	256,000	294,000
	400 F/2 hrs	600	52	187,000	208,000
MHT + Si	1600 F/1 hr	400	57	240,000	276,000
	400 F/2 hrs	600	52	176,000	216,000

* All Steels were oil quenched from the austenitizing temperature.
Double tempering operation - Two consecutive 2 hr. tempers at the indicated temperatures.

TABLE VI (Continued)

Compression Test Results for Bearing Steels

Grade	Heat Treatment*	Testing Temperature (F)	Hot Hardness R_C	Yield Strength, psi 0.10% Offset	Yield Strength, psi 0.2% Offset
440 C	1950 F/1 hr	400	57	288,000	300,000
	350 F/1 hr	600	55	252,000	282,000
	Refrigerated	800	47	216,000	234,000
	900 F/2+2 hrs				
440 BM	1950 F/1 hr	400	57	270,400	297,600
	350 F/1 hr	600	55	212,000	248,000
	Refrigerated	800	53	160,000	163,000
	900 F/2+2 hrs				
T1	2350 F/5 min	400	61	384,000	410,000
	1050 F/2+2 hrs	600	60	323,000	350,000
		800	57	268,000	288,000
		1000	54	264,000	280,000
T5	2300 F/5 min	400	65	426,000	440,000
	1000 F/2+2 hrs	600	64	402,000	410,000
		800	62	380,000	384,000
		1000	57	332,000	356,000
M2	2250 F/10 min	400	62	384,000	392,000
	1050 F/2+2 hrs	600	61	352,000	367,000
		800	59	287,000	300,000
		1000	55	224,000	248,000
M2 Ferrovac	2250 F/10 min	400	61	376,000	400,000
	1050 F/2+2 hrs	600	60	372,000	392,000
		800	58	308,000	336,000
		1000	55	248,000	256,000
M1	2200 F/15 min	400	61	344,000	368,000
	1050 F/2+2 hrs	600	60	288,000	372,000
		800	58	364,000	364,000
		1000	55	228,000	252,000
M10	2200 F/15 min	400	62	376,000	424,000
	1050 F/2+2 hrs	600	61	372,000	396,800
		800	58	260,000	328,000
		1000	54	270,000	292,000
HiC-M10	2200 F/15 min	400	62	392,000	404,000
	1050 F/2+2 hrs	600	61	328,000	372,000
		800	59	368,000	376,000
		1000	56	312,000	320,000

* All steels were oil quenched from the austenitizing temperature.
Double tempering operation - Two consecutive 2 hr. tempers at the indicated temperatures.

TABLE VI (Continued)

Compression Test Results for Bearing Steels

Grade	Heat Treatment*	Testing Temperature (F)	Hot Hardness R_C	Yield Strength, psi. 0.10% Offset	Yield Strength, psi. 0.2% Offset
VSM	2050 F/20 min	400	62	326,000	346,000
	1000 F/2+2 hrs	600	60	312,000	339,000
		800	57	292,000	316,000
		1000	53	268,000	286,000
M50	2100 F/20 min	400	62	347,500	358,000
	1050 F/2+2 hrs	600	59	280,000	328,000
		800	57	256,000	288,000
		1000	52	248,000	268,000
UC	1950 F/45 min	400	59	248,000	286,000
	1000 F/2+2 hrs	600	56	232,000	264,000
		800	53	216,000	288,000
		1000	48	176,000	188,000
Experimental					
Steel A	2000 F/30 min	400	59	248,000	268,000
	1000 F/2+2 hrs	600	59	228,000	244,000
		800	57	204,000	220,000
		1000	53	144,000	160,000
Steel B	2150 F/15 min	400	61	384,000	384,000
	1000 F/2+2 hrs	600	59	332,000	360,000
		800	57	272,000	288,000
		1000	53	180,000	204,000
Steel C	2100 F/20 min	400	61	292,000	336,000
	1000 F/2+2 hrs	600	59	224,000	252,000
		800	57	190,000	216,000
		1000	53	184,000	204,000
Steel D	2200 F/15 min	400	60	320,000	342,000
	1000 F/2+2 hrs	600	58	298,000	320,000
		800	57	268,000	304,000
		1000	53	196,000	210,000
Steel E	2100 F/20 min	400	58	335,000	348,000
	1000 F/2+2 hrs	600	57	320,000	324,000
		800	53	288,000	304,000
		1000	49	176,000	200,000

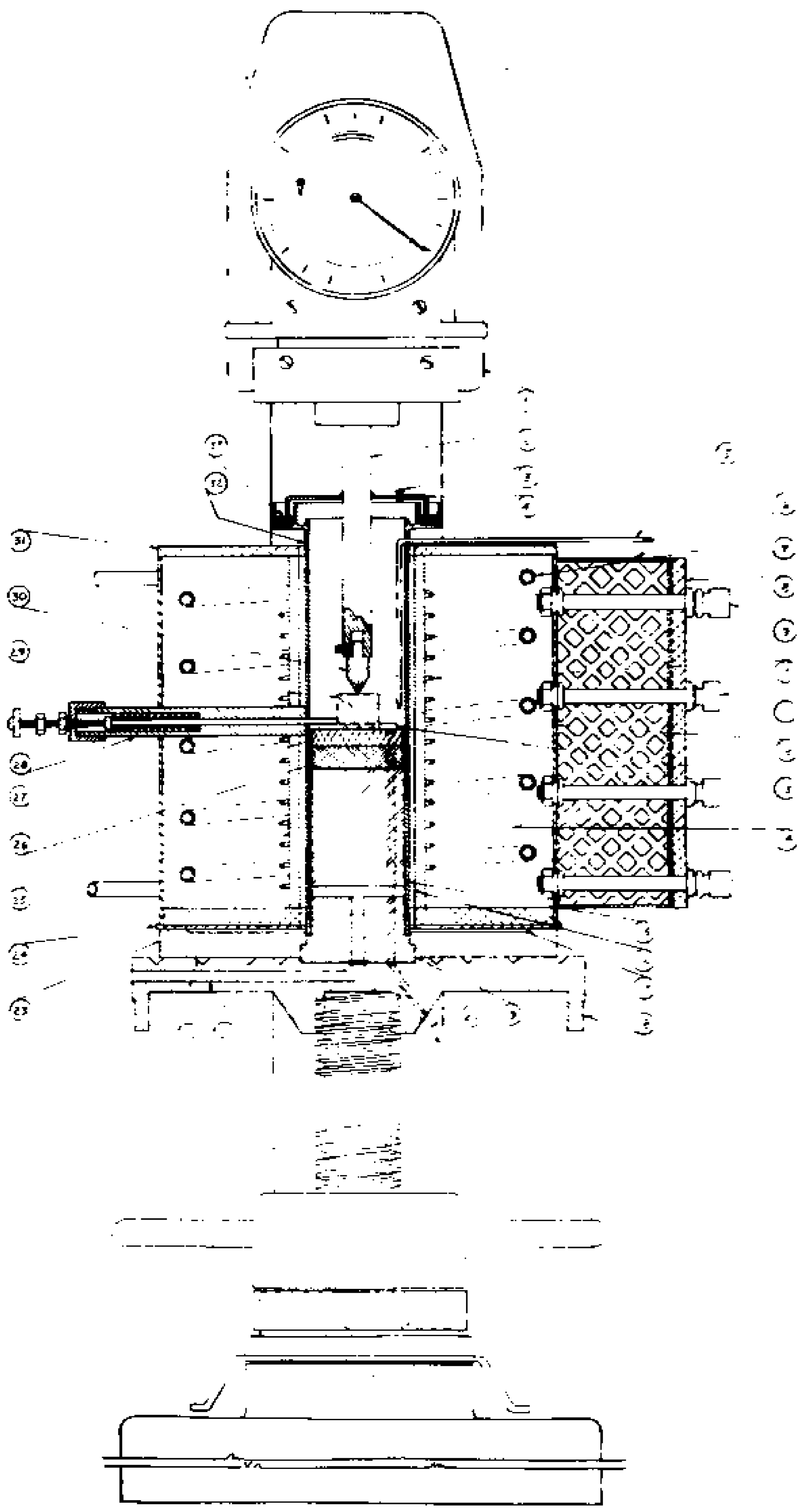
* All steels were oil quenched from the austenitizing temperature. Double tempering operation - Two consecutive 2 hr. tempers at the indicated temperatures.

TABLE VI (Continued)

Compression Test Results for Bearing Steels

Grade	Heat Treatment*	Testing Temperature (F)	Hot Hardness R_C	Yield Strength, psi. 0.10% Offset	Yield Strength, psi. 0.2% Offset
Experimental					
Steel F	2200 F/15 min 1000 F/2+2 hrs	400	60	268,000	304,000
		600	58	256,000	288,000
		800	55	240,000	256,000
		1000	51	228,000	251,000
Steel G	2200 F/15 min 1000 F/2+2 hrs	400	63	400,000	416,000
		600	62	348,000	380,000
		800	59	328,000	344,000
		1000	56	272,000	312,000

* All steels were oil quenched from the austenitizing temperature.
Double tempering operation - Two consecutive 2 hr. tempers at the indicated temperatures.



LEGEND

1. Hardness Tester
2. Indentor Extension Rod (Nichrome)
3. Gas Outlet Screw
4. Seal Cup (Nichrome)
5. Control Thermocouple
6. Holder Box
7. Cooling Coil (Stainless)
8. Insulation (Transite)
9. Heating Power Terminal
10. Heater Windings
11. Shunt Terminal
12. Furnace Shell
13. Specimen Guides
14. Furnace Insulation (Sil-O-Sel)
15. Air Space
16. Air Space
17. Air Space
18. Stage of the Rockwell Tester
19. Anvil (S-816)
20. Thermocouple (Anvil)
21. Gas Inlet
22. Air Space
23. Furnace Support (Transite)
24. Plate (Stainless)
25. Muffle (Ceramic)
26. Spacer (Soapstone)
27. Plate (S-816)
28. Specimen Positioning Screw
29. Specimen
30. High Temperature Indentor
31. Cover (Transite)
32. Muffle (Nichrome)
33. Liquid Metal Seal (Wood's Metal)

FIGURE 1. SCHEMATIC DRAWING OF THE ROCKWELL TYPE HOT-HARDNESS TESTING ASSEMBLY.

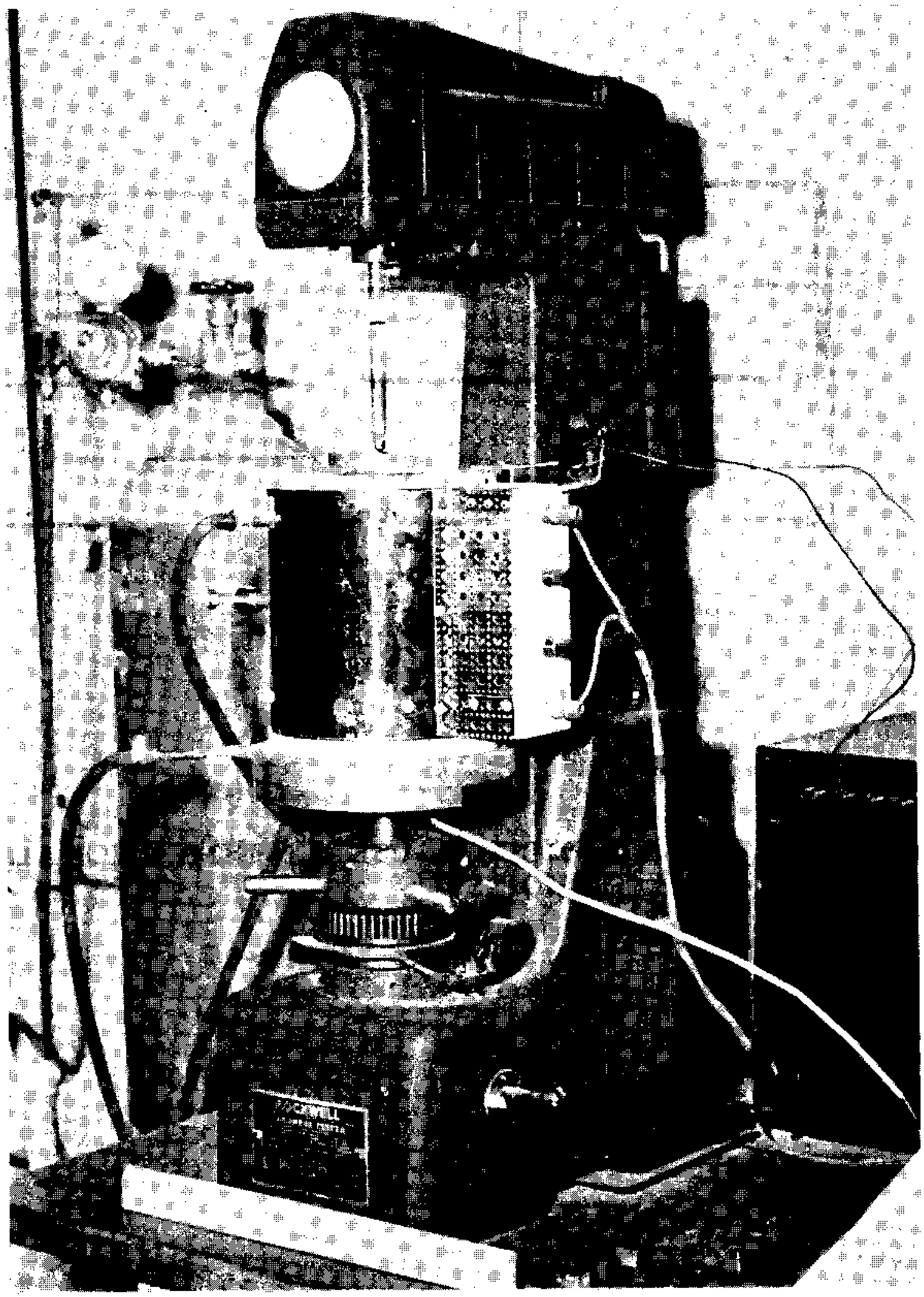
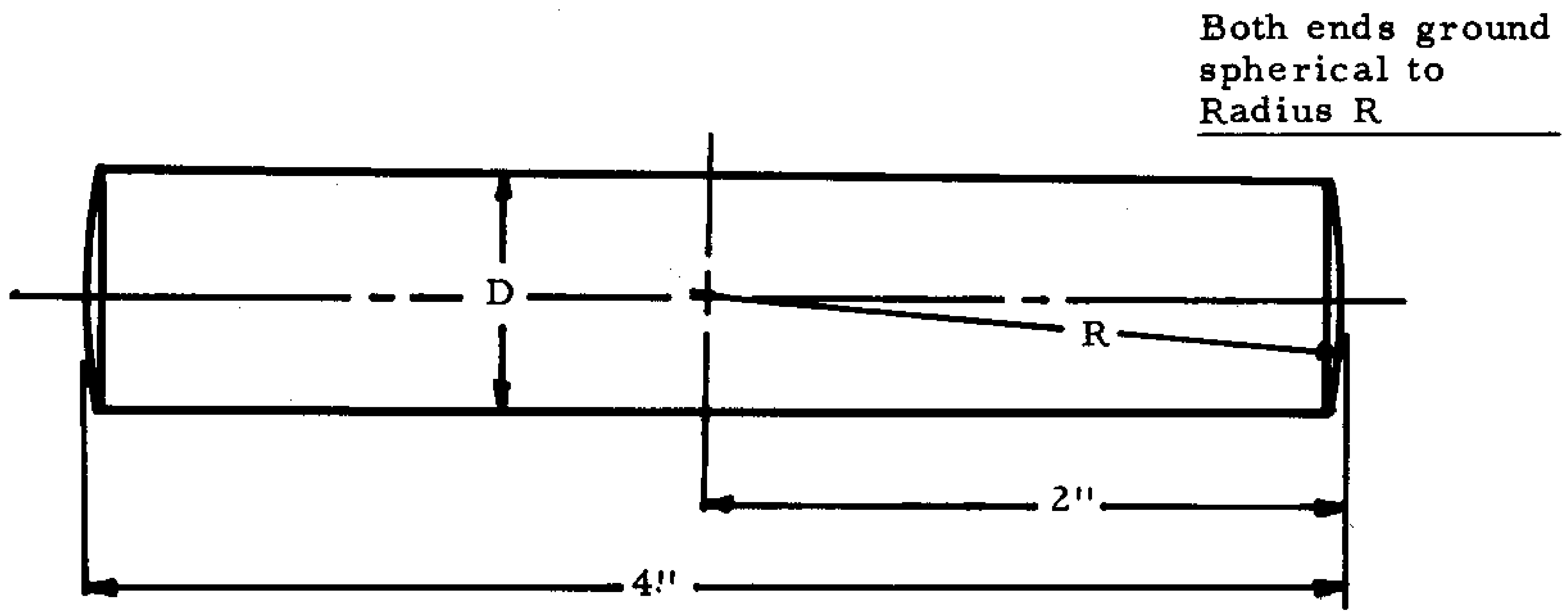


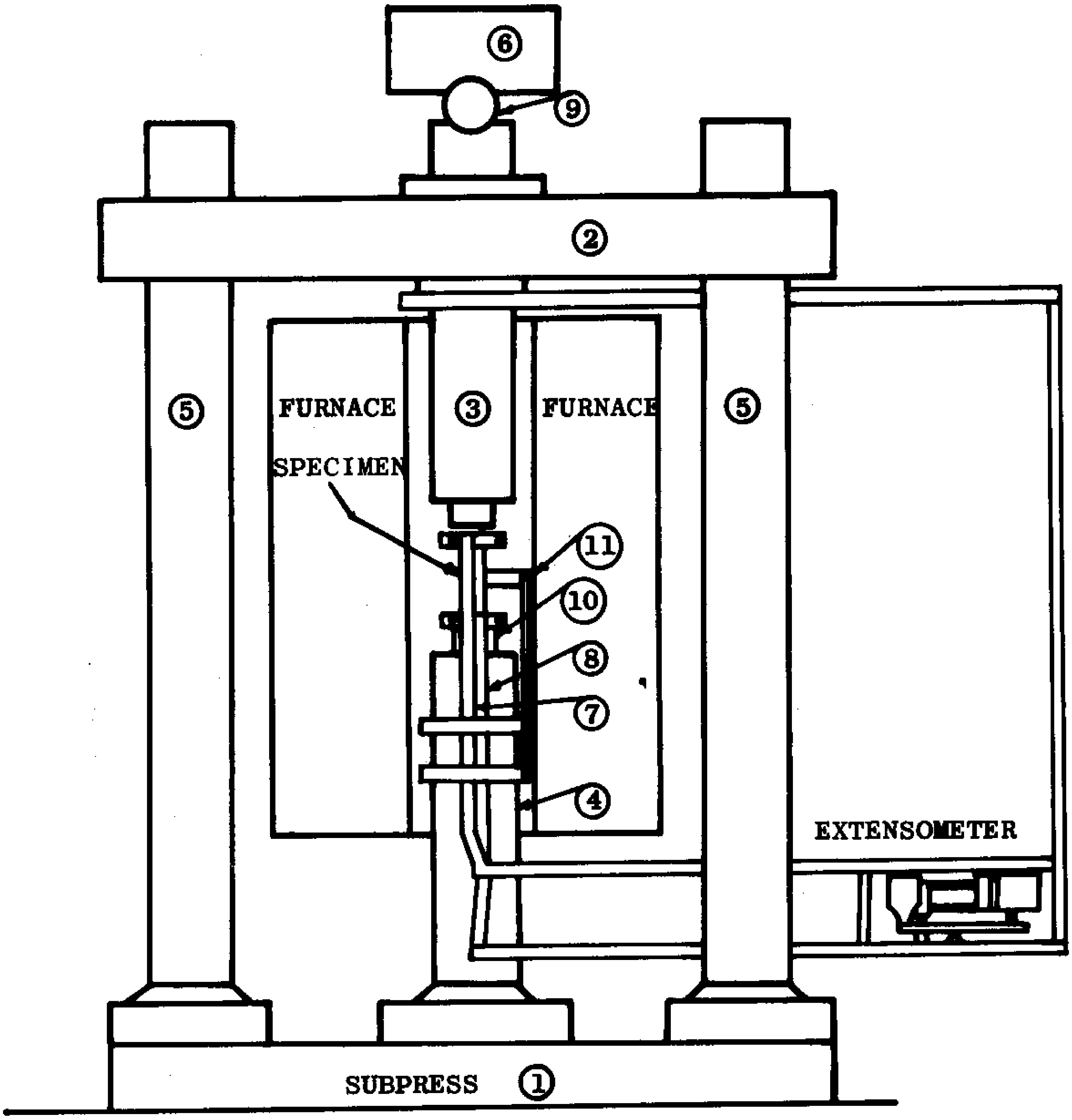
FIGURE 2. HOT HARDNESS TESTER



R = 2 in.

D = 3/8 in.

FIGURE 3. SPECIMEN USED IN DIMENSIONAL STABILITY STUDIES.



(1) Bottom Plate
(2) Top Plate (Fixed)
(3) Upper Compression Rod
(4) Lower Compression Rod
(5) Subpress Guide Rods (3)
(6) Loading Plate-Spherically Seated
(7) Extensometer Upper Assembly
(8) Extensometer Lower Assembly
(9) Load Alignment Ball
(10) Bearing Plate
(11) Specimen Centering Device

FIGURE 4. COMPRESSION TEST FIXTURE
(Schematic Drawing)

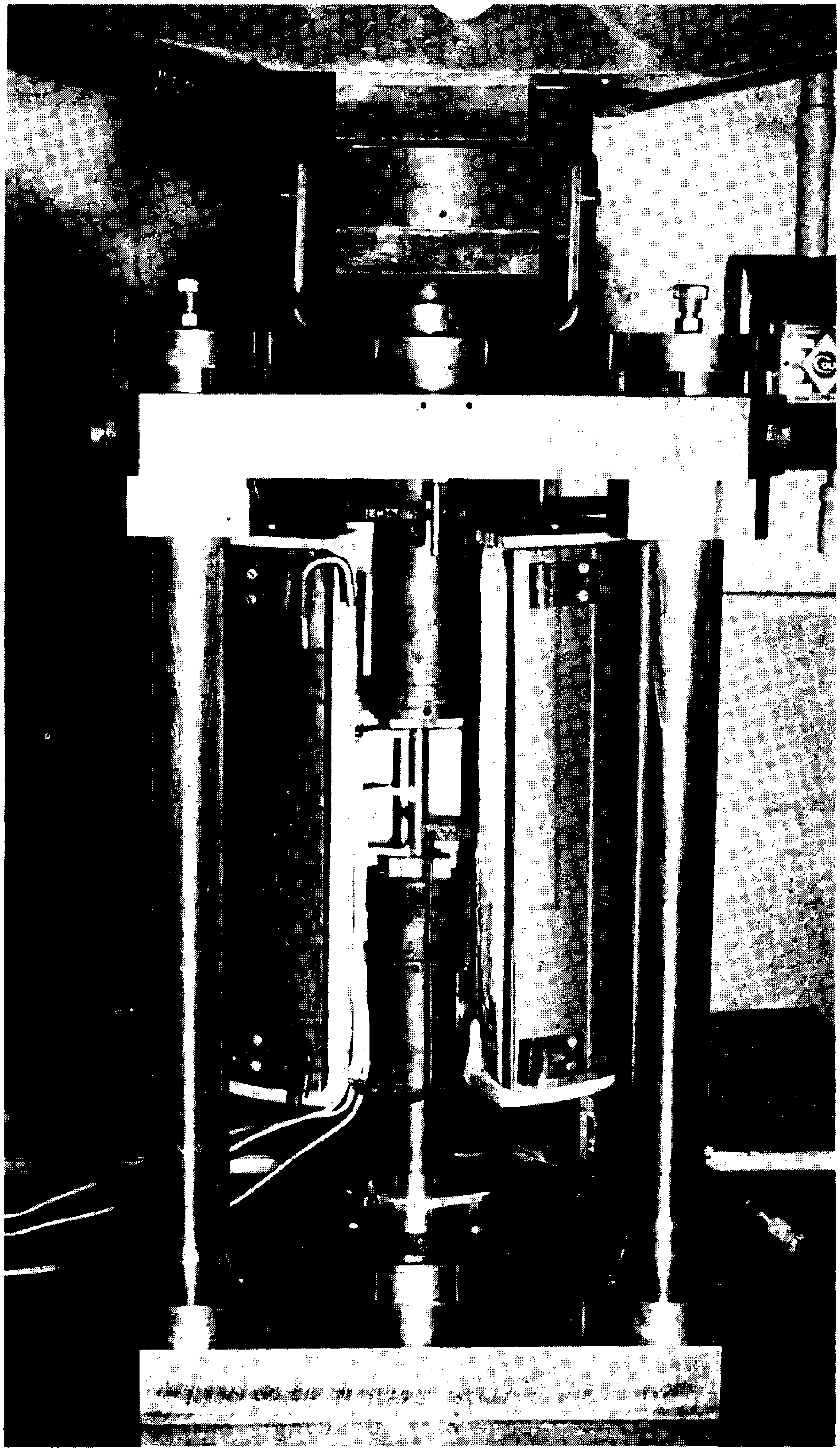


FIGURE 5. SUBPRESS USED IN ELEVATED TEMPERATURE COMPRESSION TESTS.

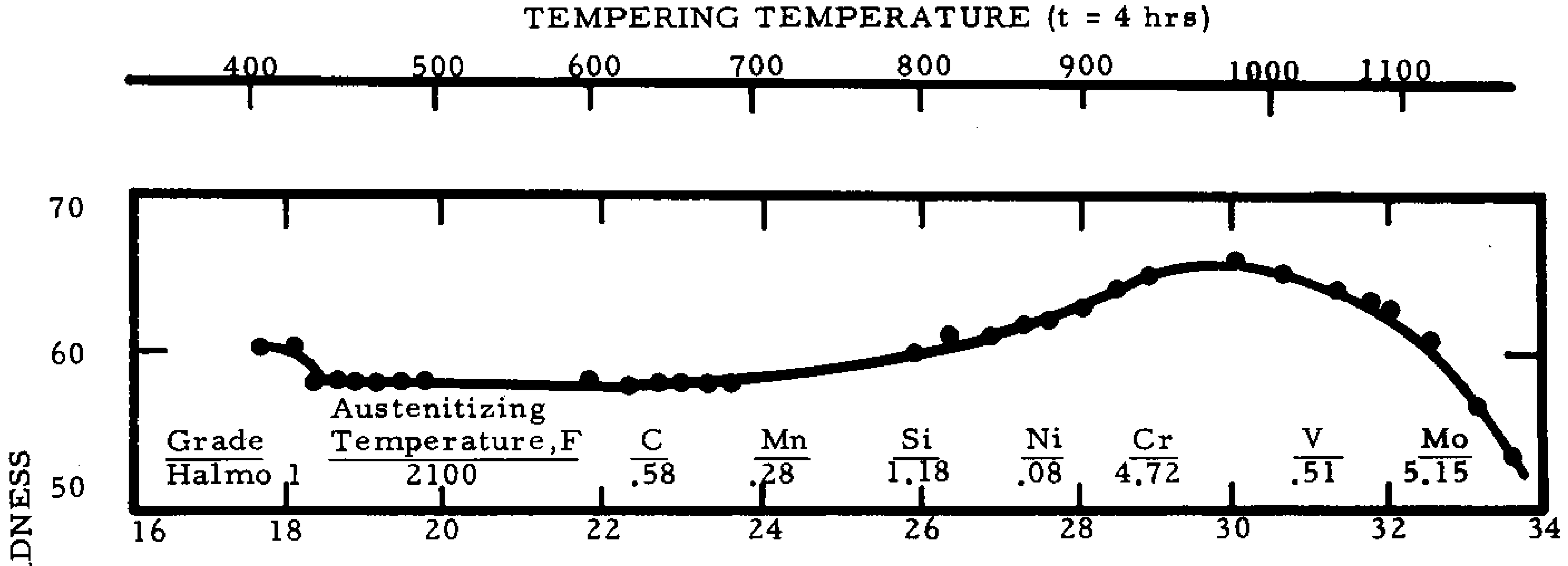


Figure 6.

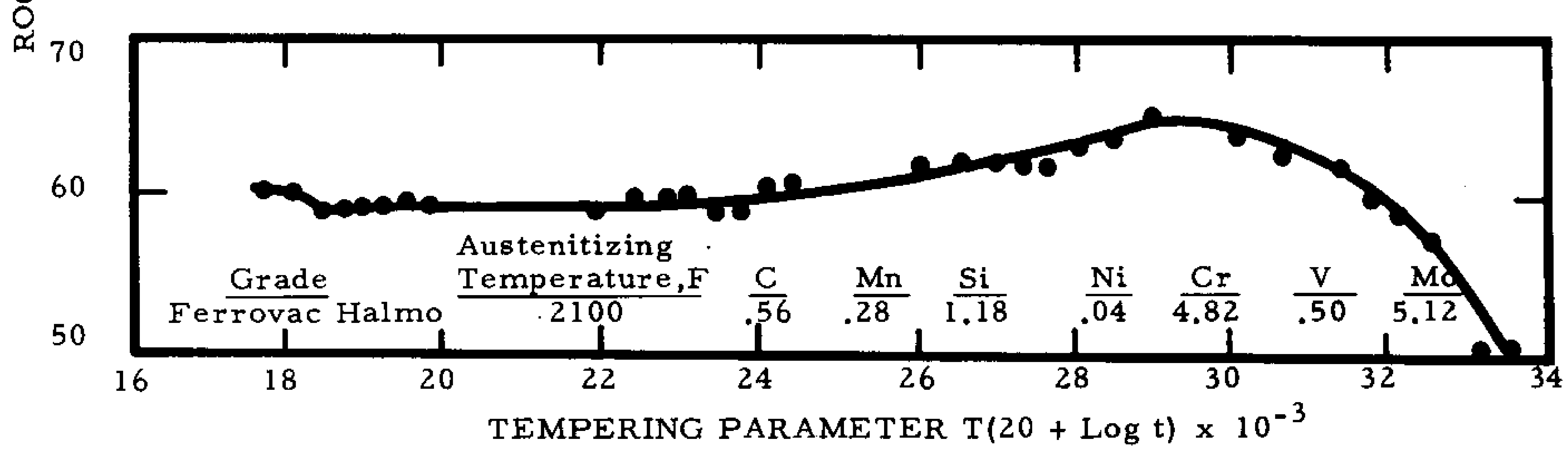


Figure 7.

Figures 6 and 7. Master Tempering Curves for Bearing Steels.

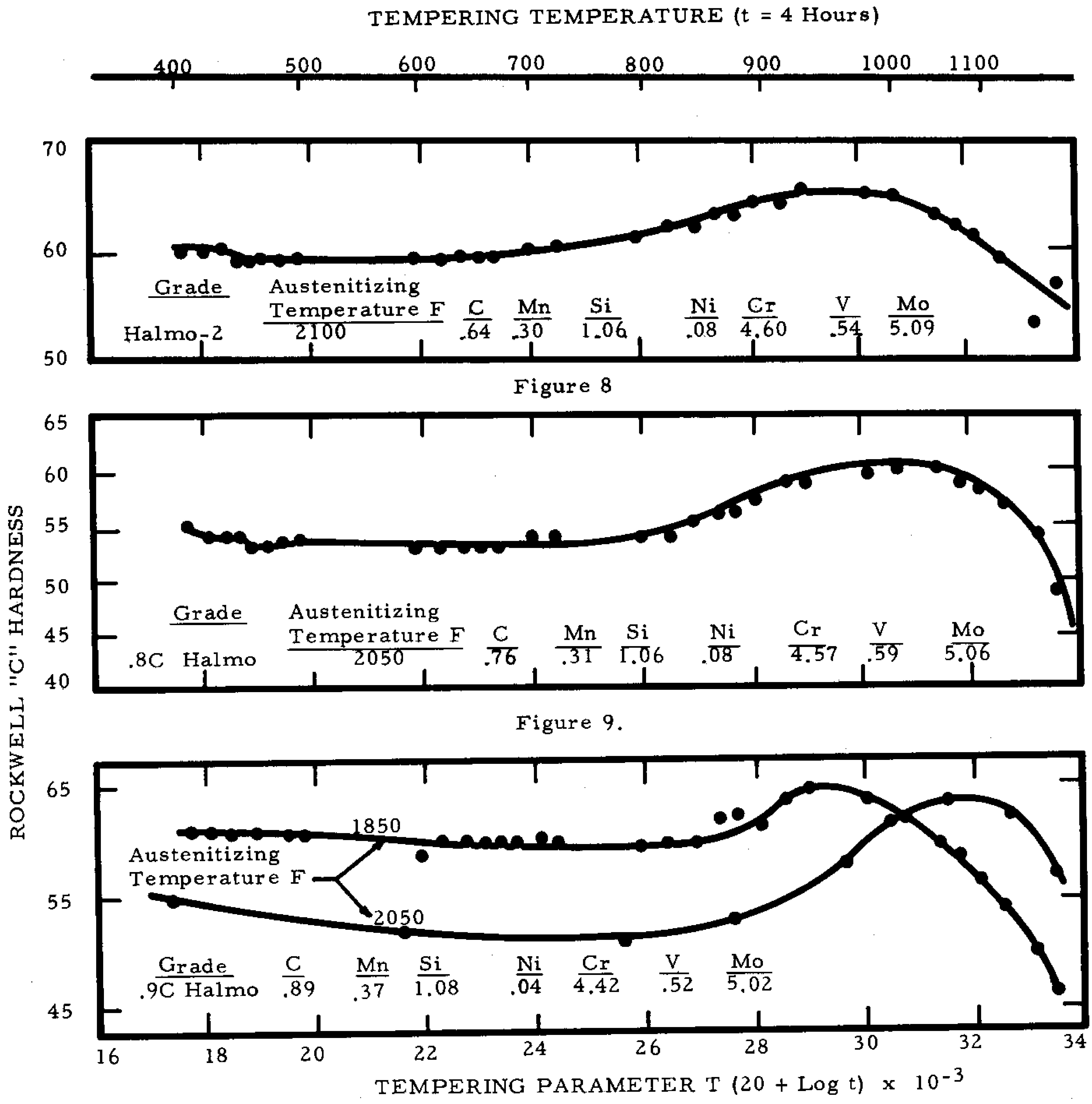


Figure 10

<u>Figures 8 to 10.</u> Master Tempering Curves for Bearing Steels

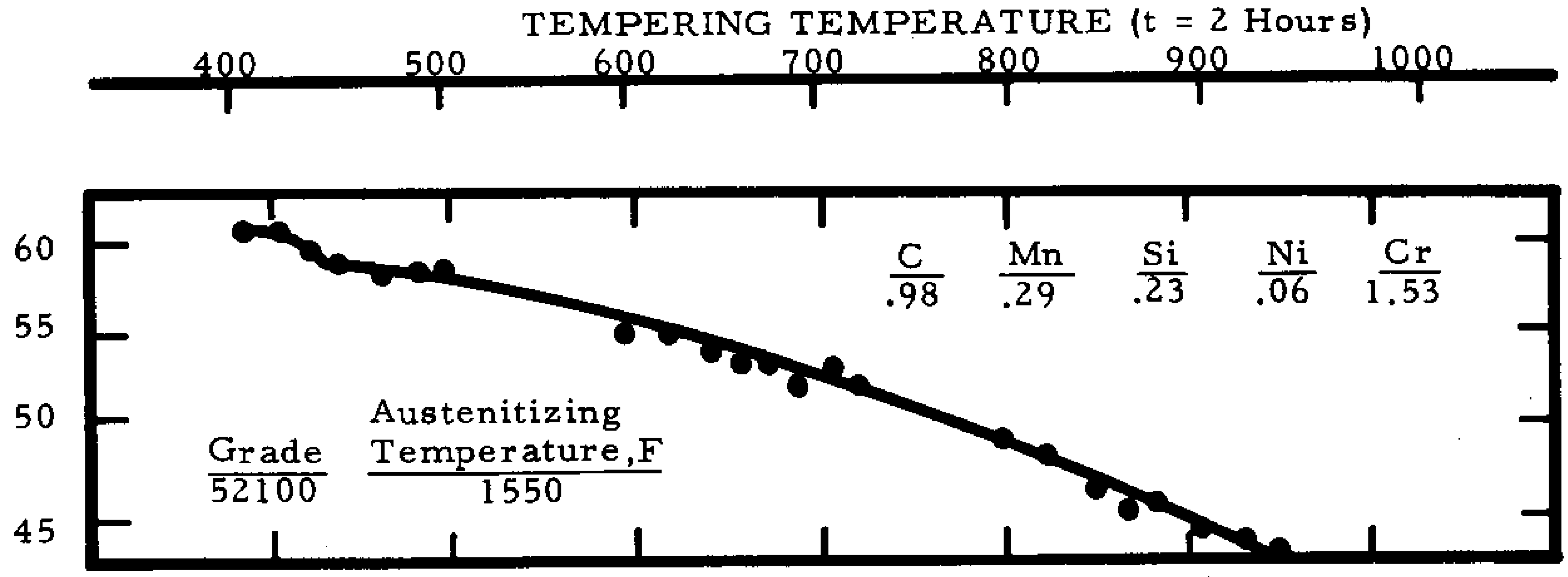


Figure 11.

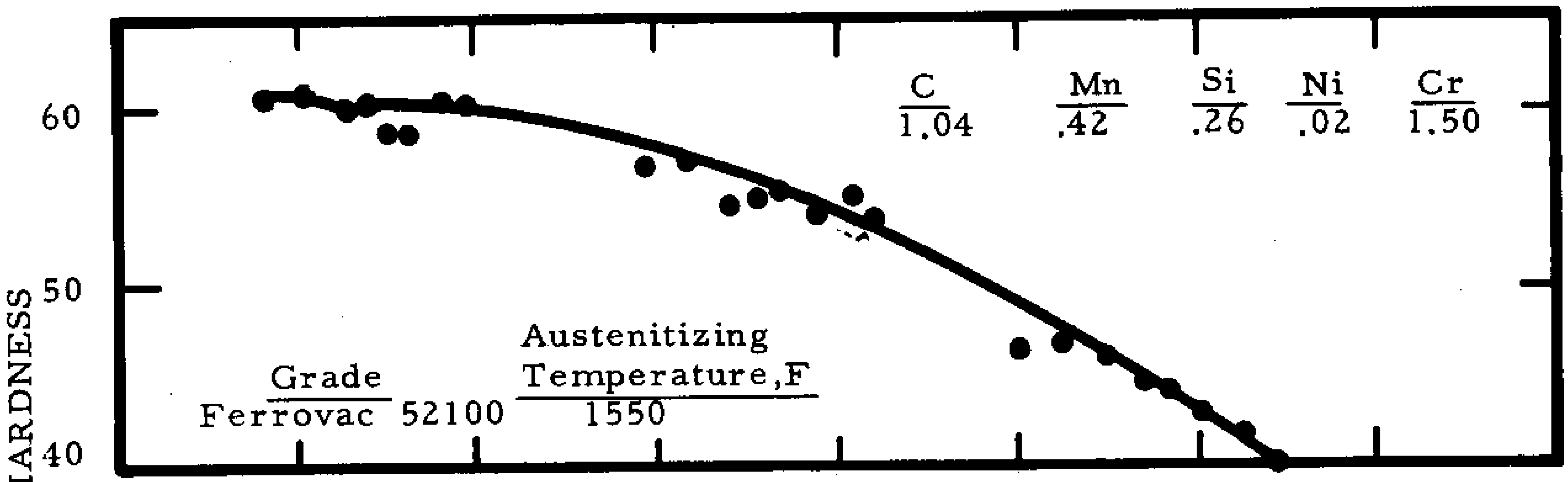


Figure 12.

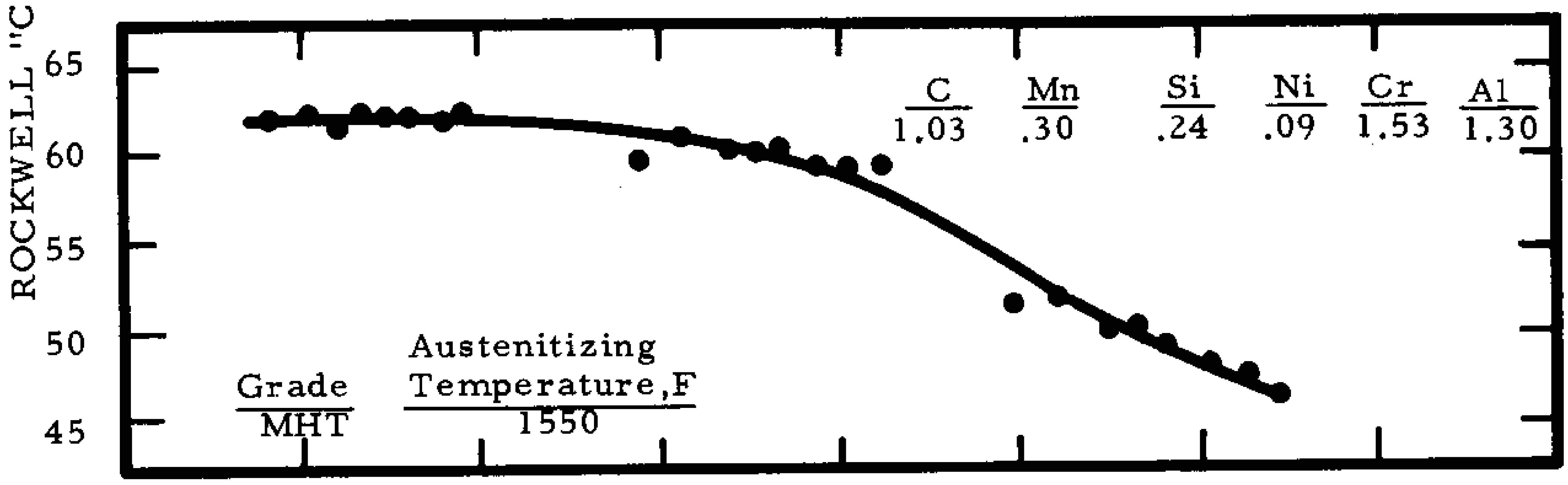


Figure 13.

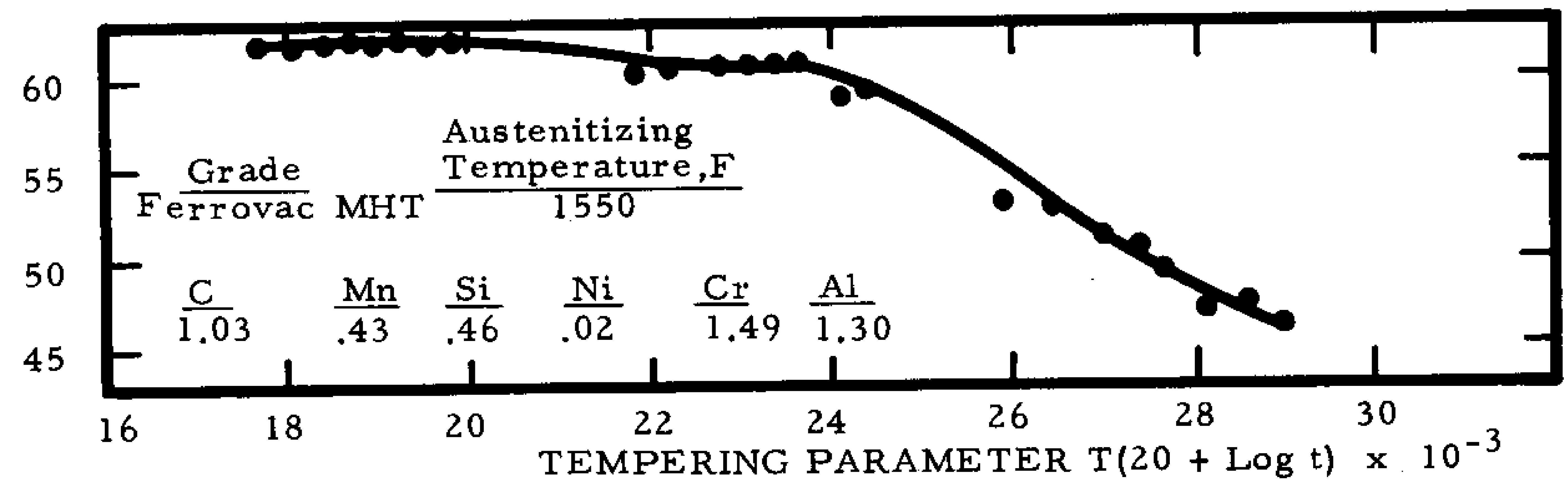


Figure 14.

Figures 11 to 14. Master Tempering Curves for Bearing Steels

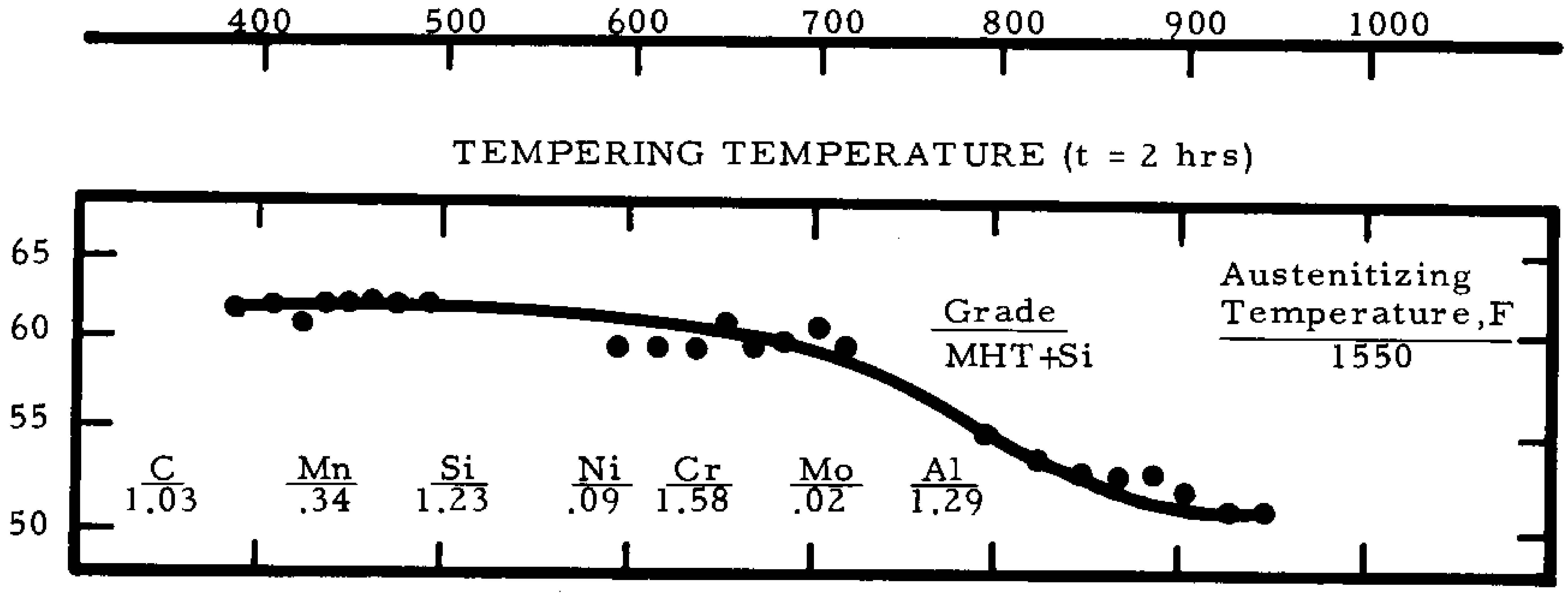


Figure 15.

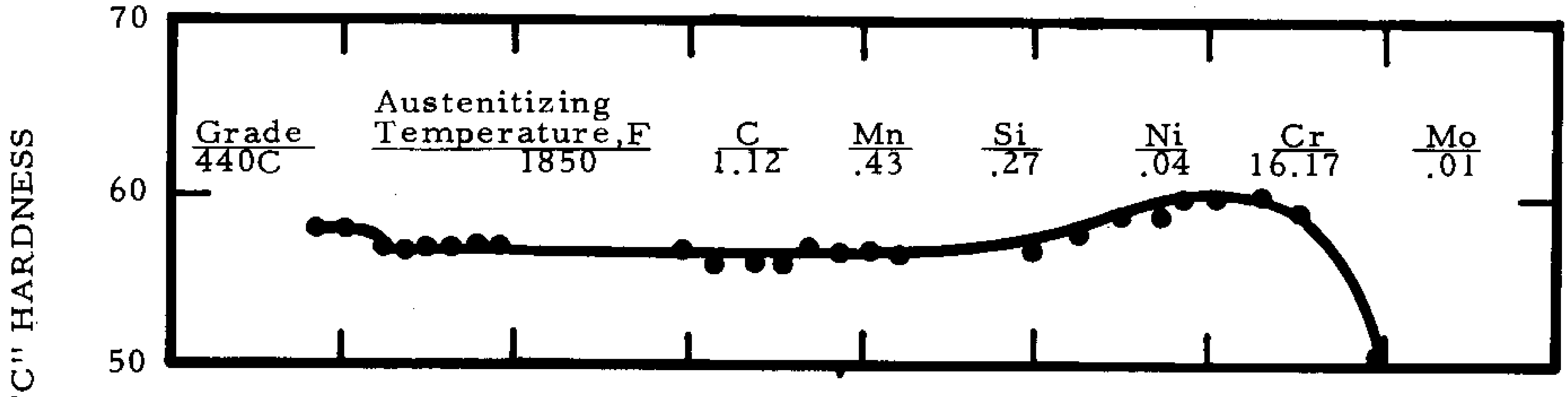


Figure 16.

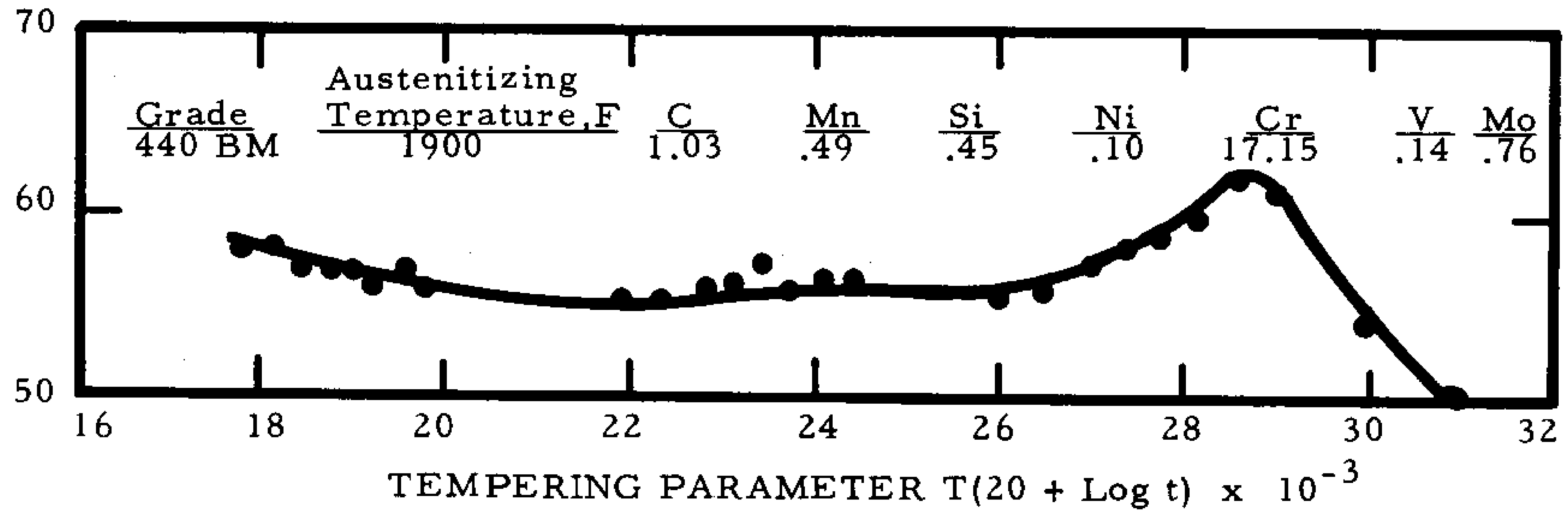


Figure 17.

Figures 15 to 17. Master Tempering Curves for Bearing Steels

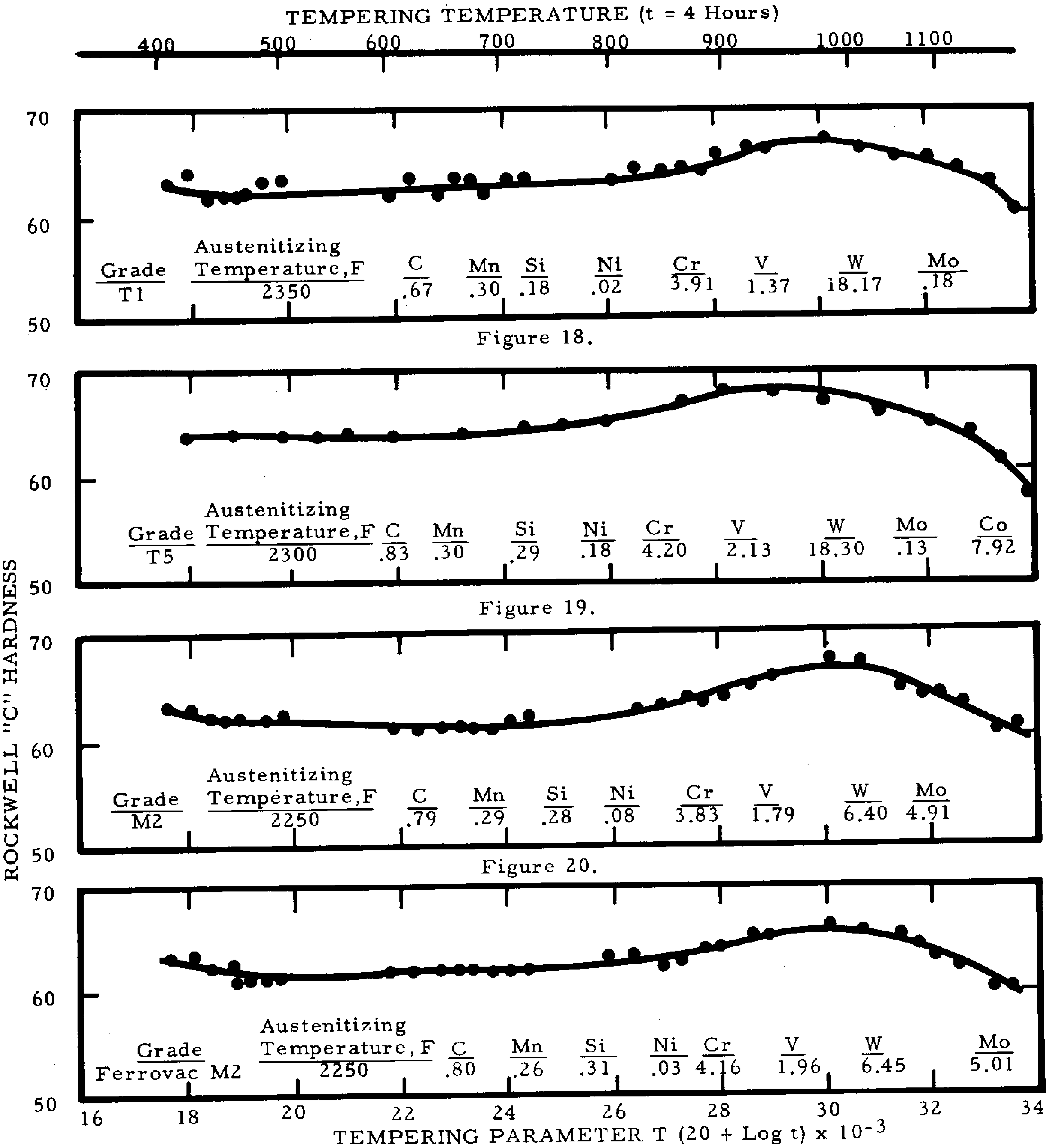


Figure 21.

Figures 18 to 21. Master Tempering Curves for Bearing Steels

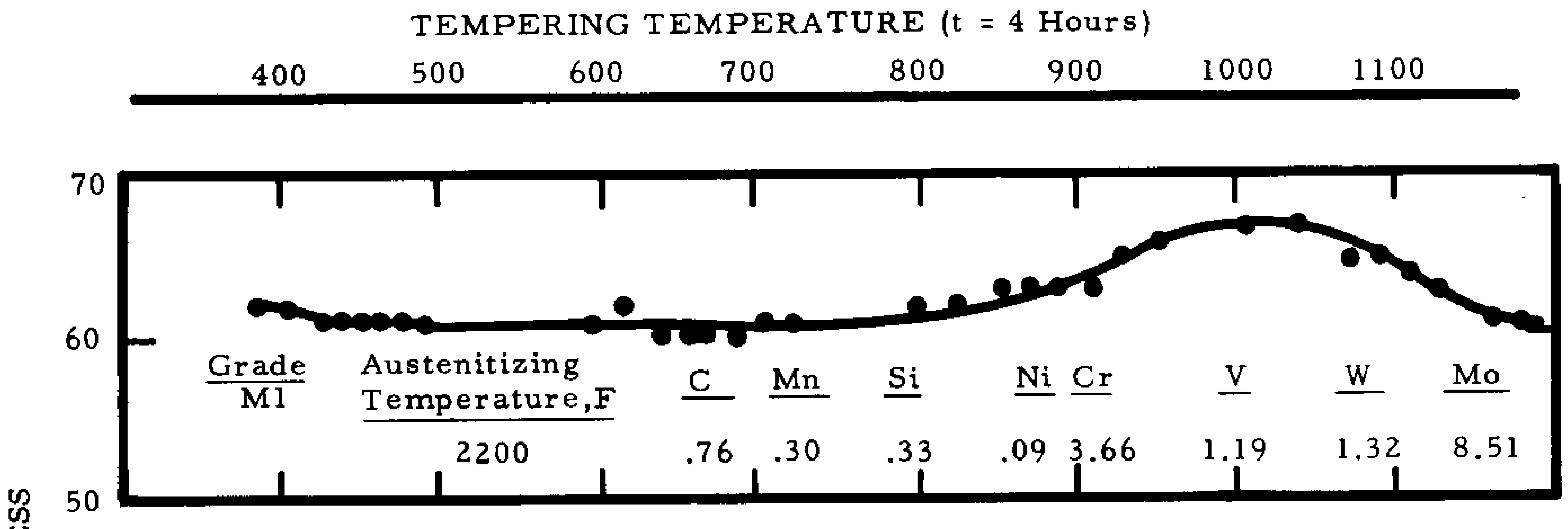
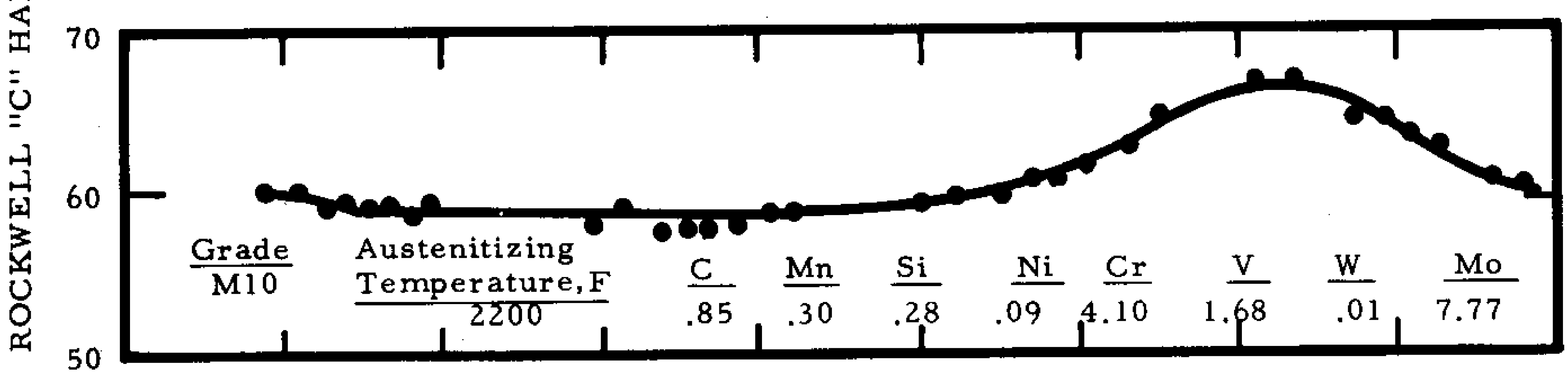


Figure 22.



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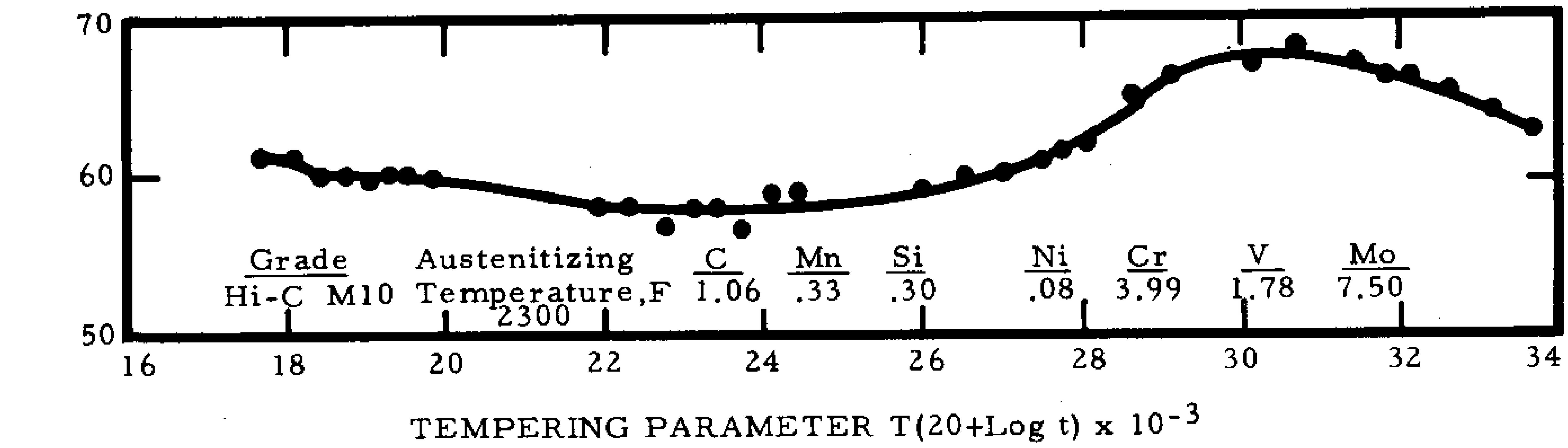


Figure 24.

Figures 22 to 24. Master Tempering Curves for Bearing Steels

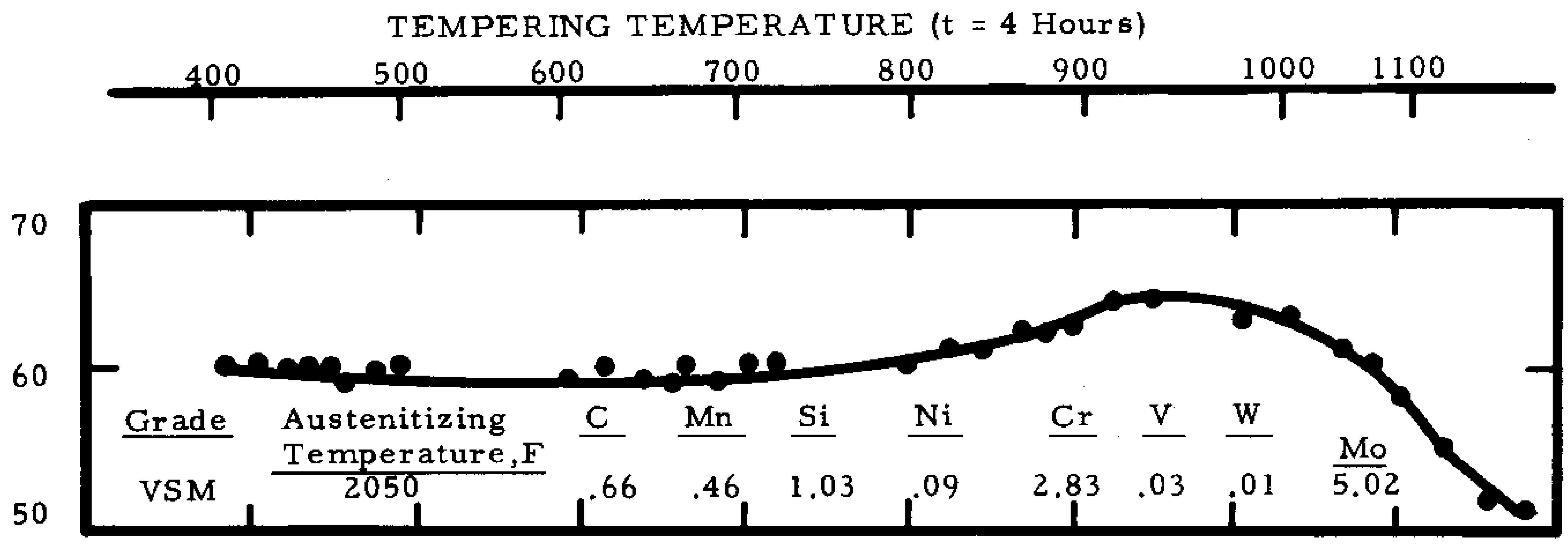
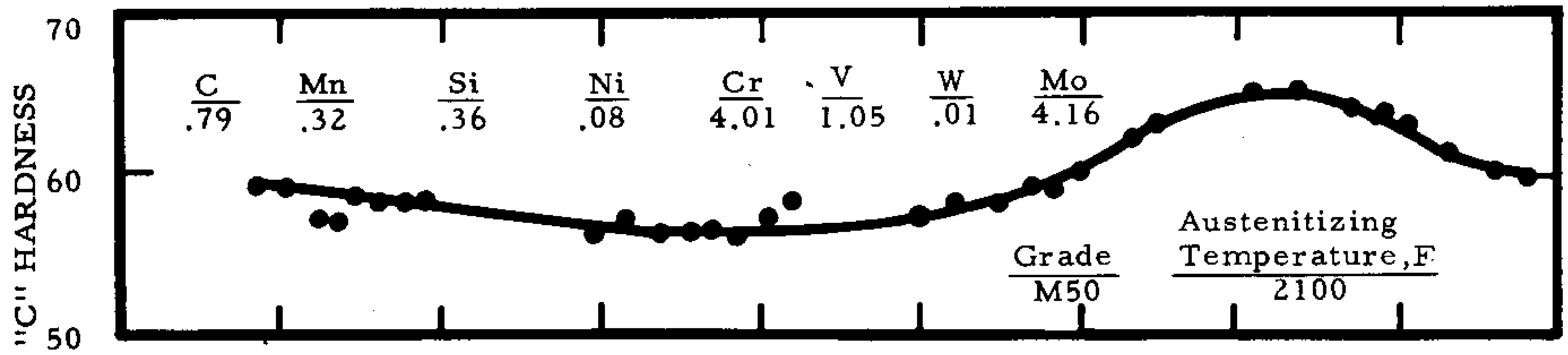


Figure 25.



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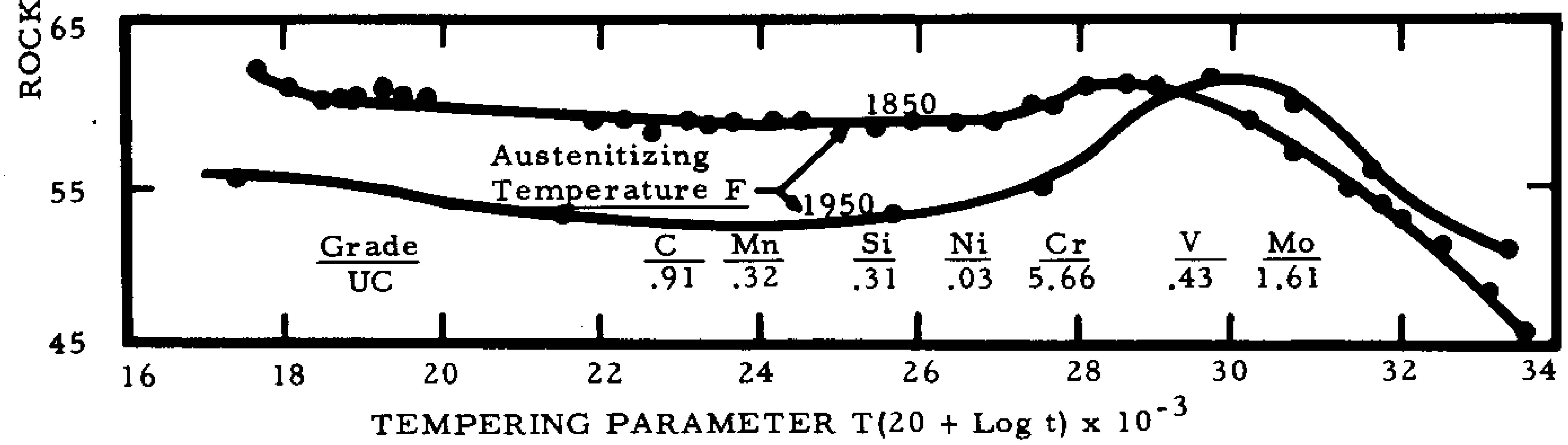


Figure 27.

Figures 25 to 27. Master Tempering Curves for Bearing Steels

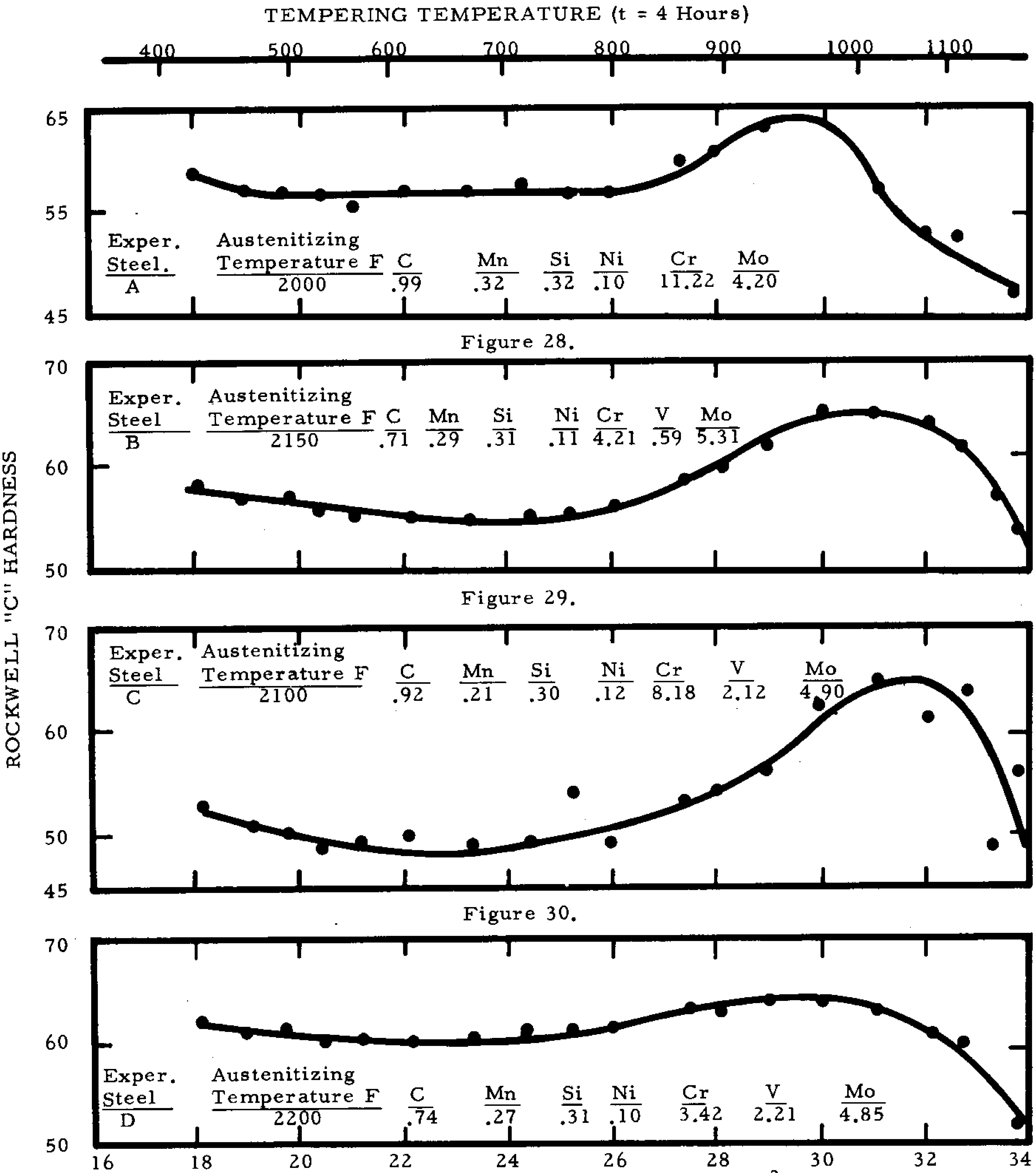


Figure 31.

Figures 28 to 31. Master Tempering Curves for Bearing Steels

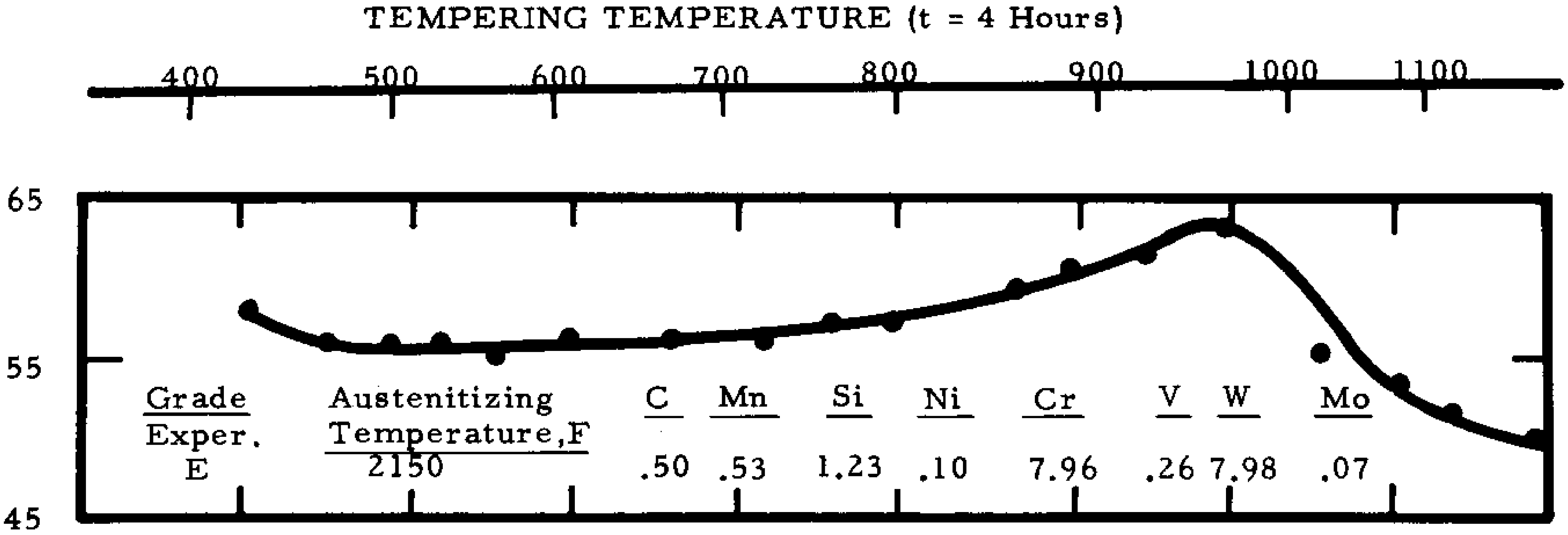
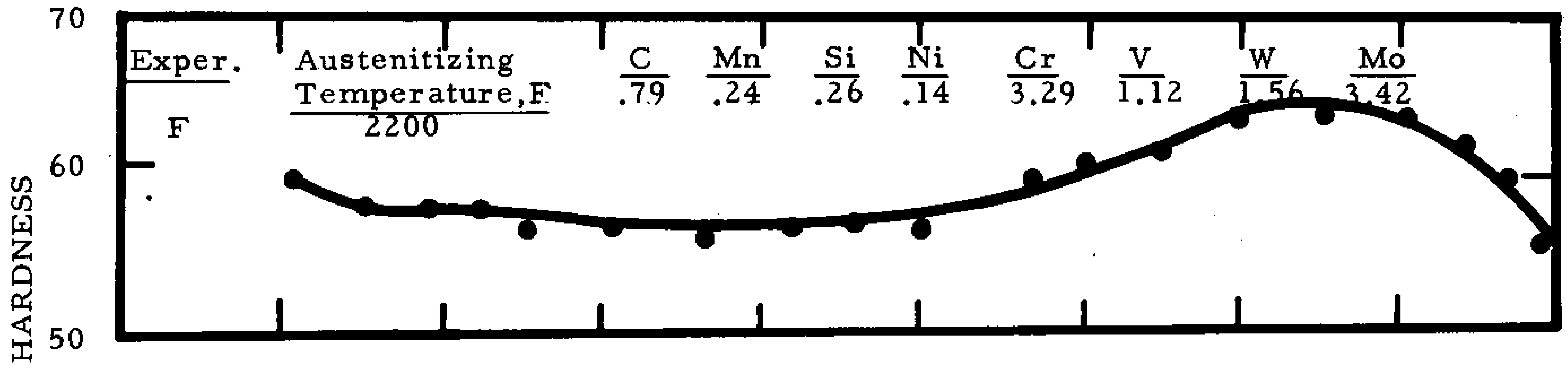


Figure 32.



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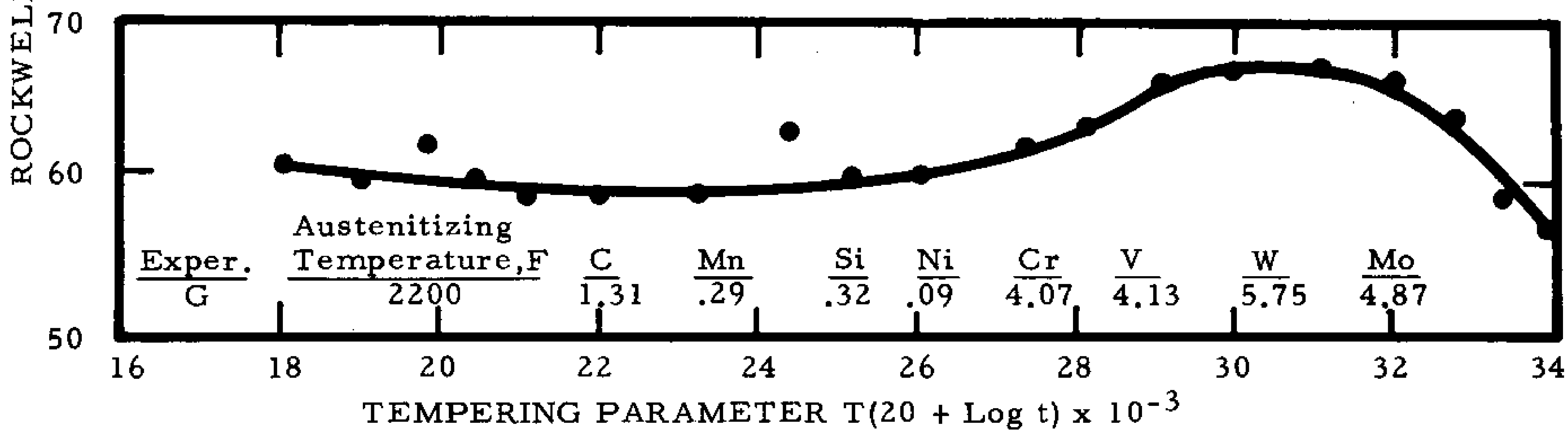
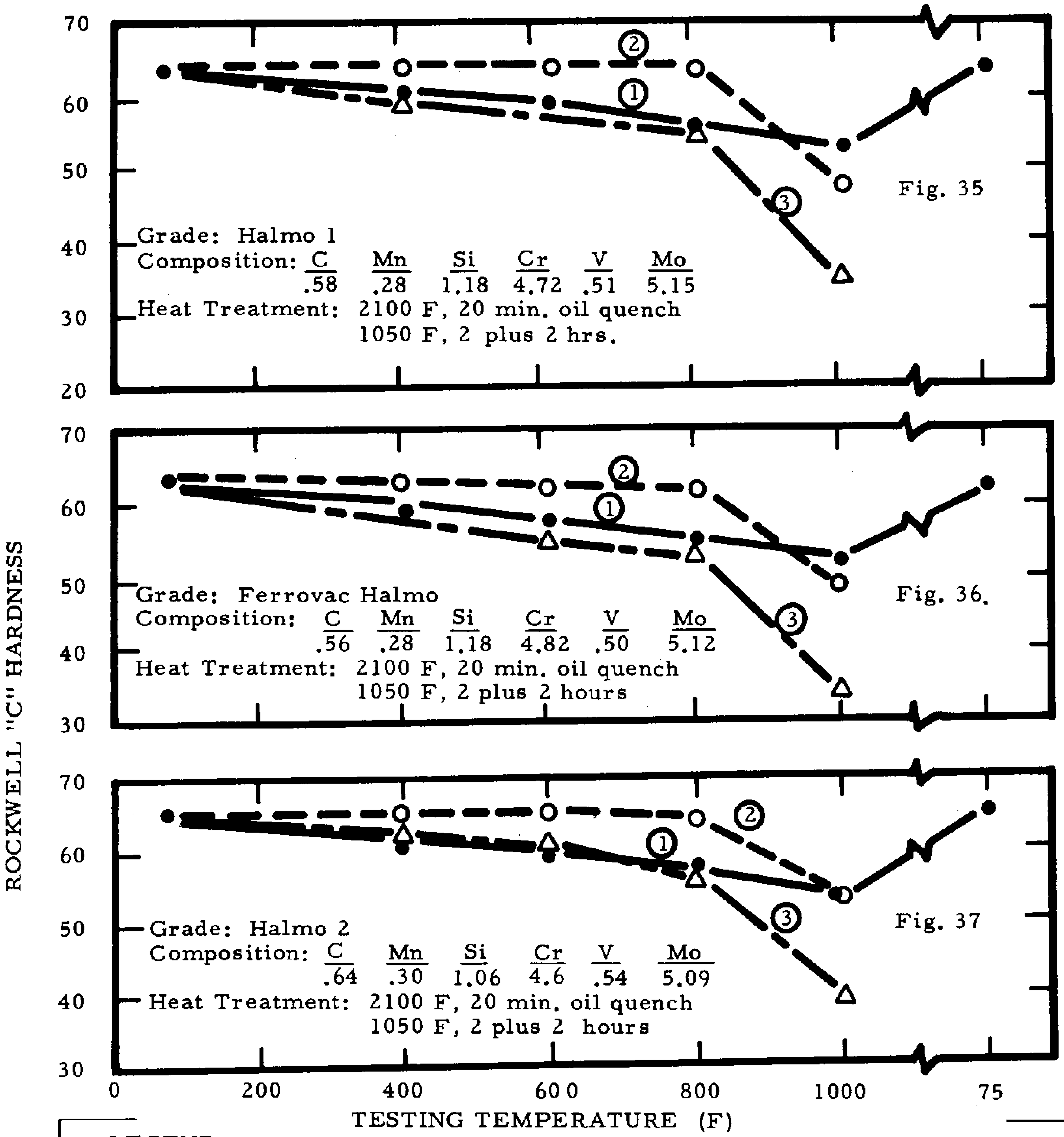


Figure 34.

Figures 32 to 34. Master Tempering Curves for Bearing Steels.



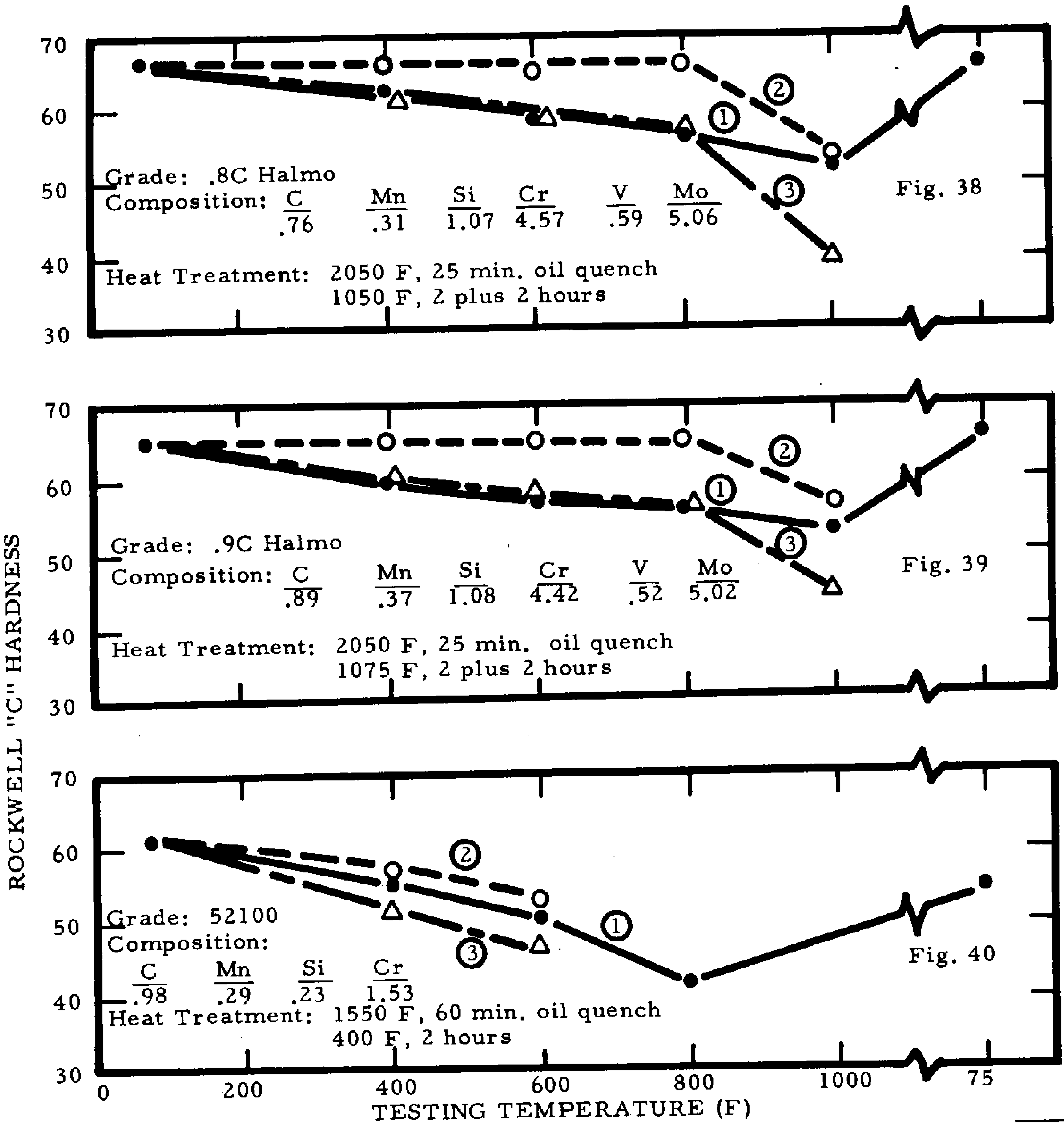
LEGEND

(1) Hot Hardness of Quenched and Tempered Steel

(2) Room Temperature hardness of Quenched and Tempered Steel after 1000 hr. Exposures at Indicated Temperatures.

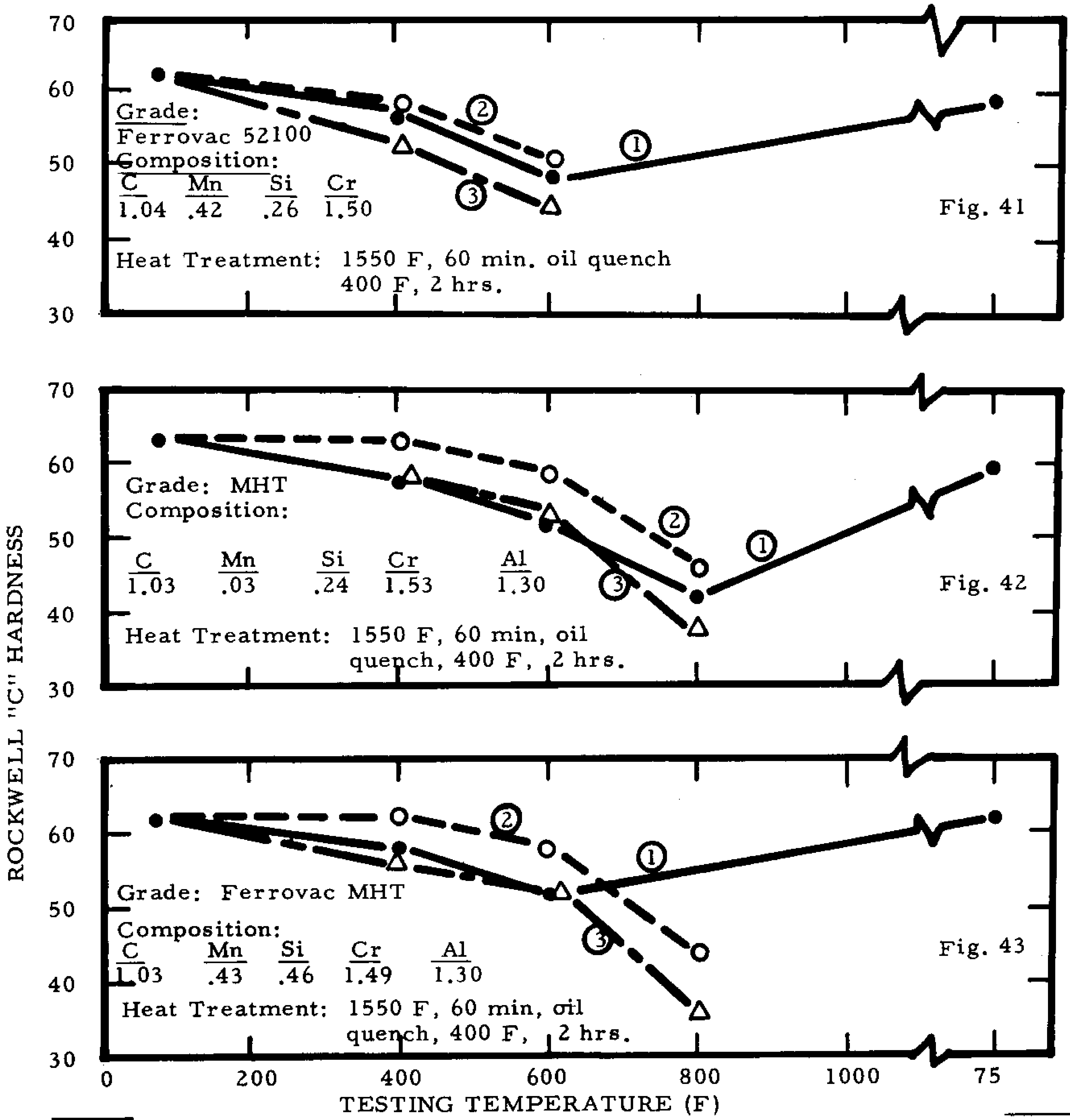
(3) Hot Hardness of Quenched and Tempered Steel after 1000 hr. Exposures at Indicated Temperatures.

Figures 35 to 37. Influence of temperature on hot hardness of bearing steels (Curve 1). Also shown is the effect of 1000 hour exposure at different temperatures on the room temperature hardness (Curve 2) and hot hardness of the steels (Curve 3).



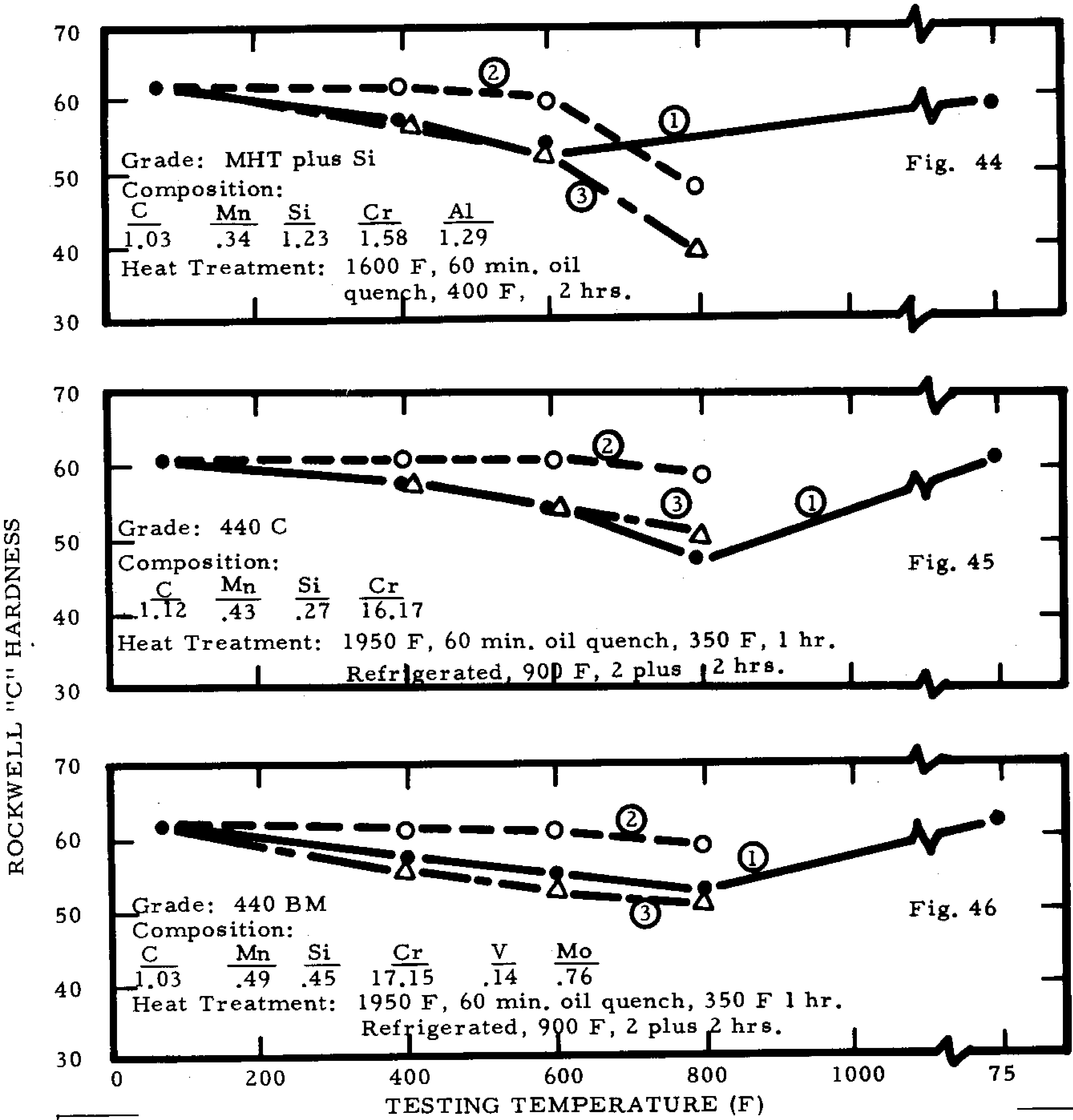
LEGEND
(1) Hot Hardness of Quenched and Tempered Steel
(2) Room Temperature Hardness of Quenched and Tempered Steel after 1000 hr. Exposures at Indicated Temperatures.
(3) Hot Hardness of Quenched and Tempered Steel after 1000 hr. Exposures at Indicated Temperatures.

Figures 38 to 40. Influence of temperature on hot hardness of bearing steels (Curve 1). Also shown is the effect of 1000 hour exposure at different temperatures on the room temperature hardness (Curve 2) and hot hardness of the steels (Curve 3).



LEGEND
(1) ●——● Hot Hardness of Quenched and Tempered Steel
(2) o---o Room Temperature Hardness of Quenched and Tempered Steel after 1000 hr. Exposures at Indicated Temperatures.
(3) Δ---Δ Hot Hardness of Quenched and Tempered Steel after 1000 hr. Exposures at Indicated Temperatures.

Figures 41 to 43. Influence of temperature on hot hardness of bearing steels (Curve 1). Also shown is the effect of 1000 hour exposure at different temperatures on the room temperature hardness (Curve 2) and hot hardness of the steels (Curve 3).



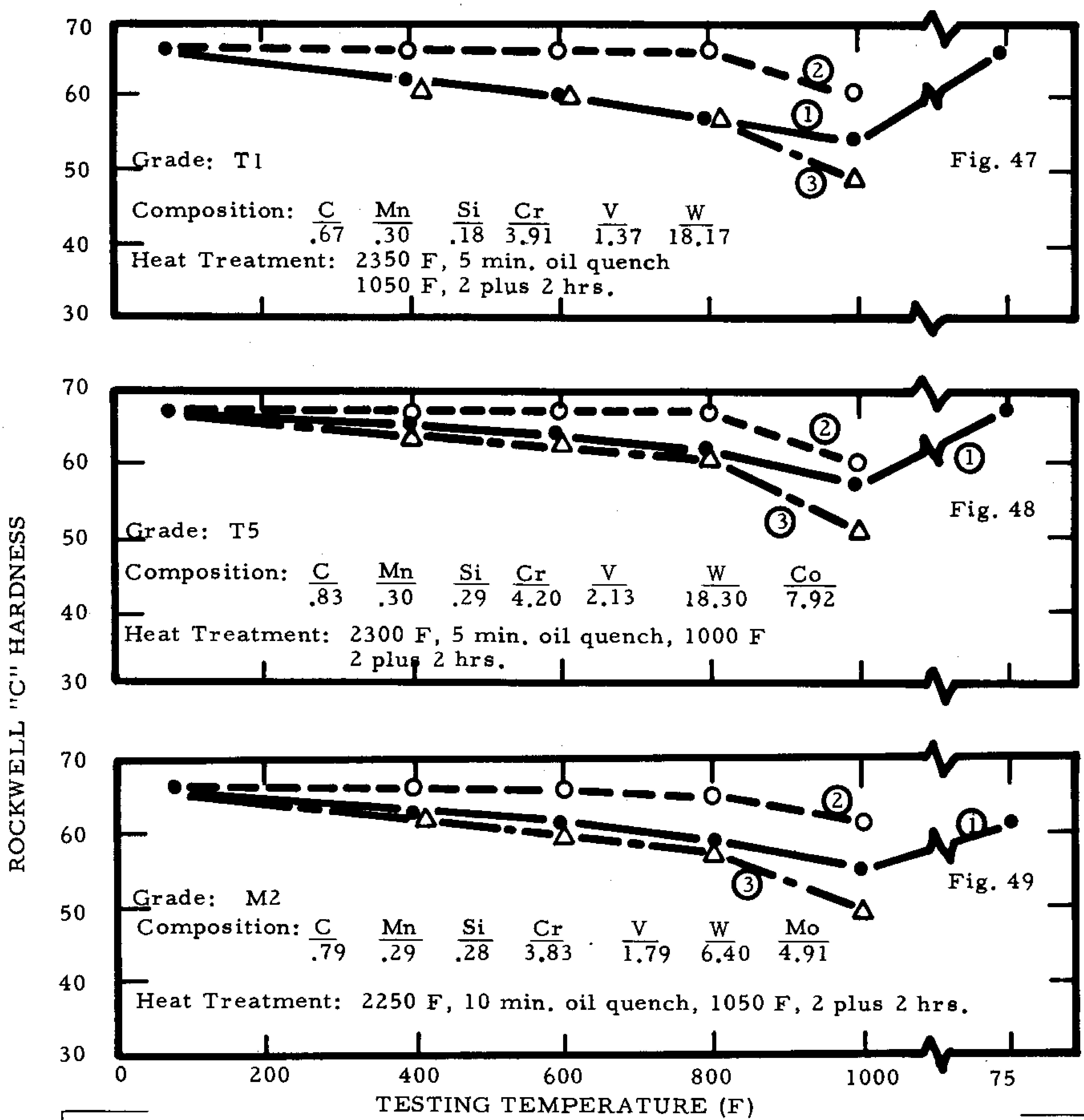
LEGEND

(1) ●——● Hot Hardness of Quenched and Tempered Steel

(2) ○– –○ Room Temperature Hardness of Quenched and Tempered Steel after 1000 hr. Exposures at Indicated Temperatures

(3) △– –△ Hot Hardness of Quenched and Tempered Steel after 1000 hr. Exposures at Indicated Temperatures.

Figures 44 to 46. Influence of temperature on hot hardness of bearing steels (Curve 1). Also shown is the effect of 1000 hour exposure at different temperatures on the room temperature hardness (Curve 2) and hot hardness of the steels (Curve 3).



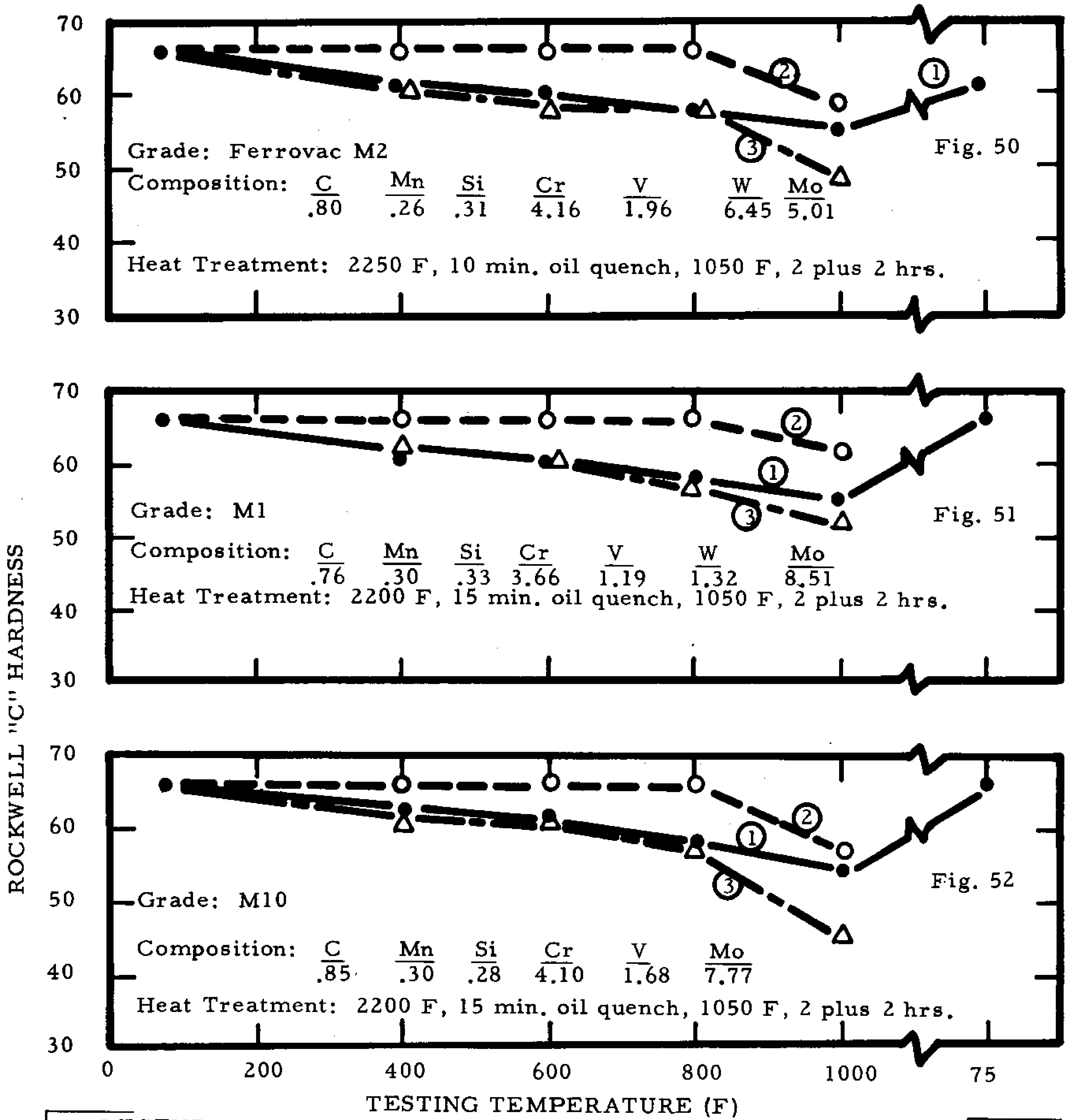
LEGEND

(1) ●——● Hot Hardness of Quenched and Tempered Steel.

(2) o- - -o Room Temperature Hardness of Quenched and Tempered Steel after 1000 hr. Exposures at Indicated Temperatures.

(3) Δ- - -Δ Hot Hardness of Quenched and Tempered Steel after 1000 hr. Exposures at Indicated Temperatures.

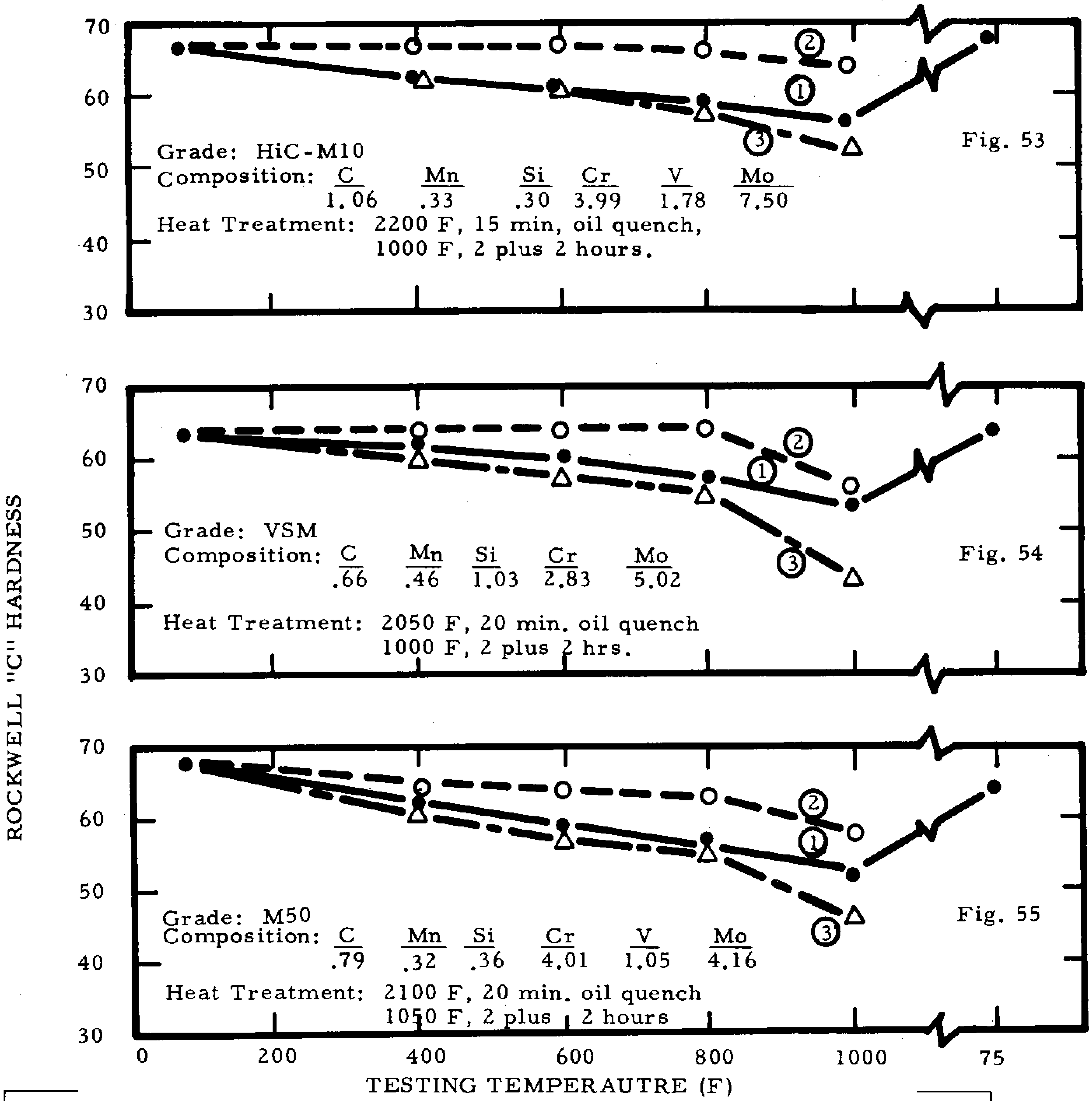
Figures 47 to 49. Influence of temperature on hot hardness of bearing steels (Curve 1). Also shown is the effect of 1000 hour exposure at different temperatures on the room temperature hardness (Curve 2) and hot hardness of the steels (Curve 3).



LEGEND

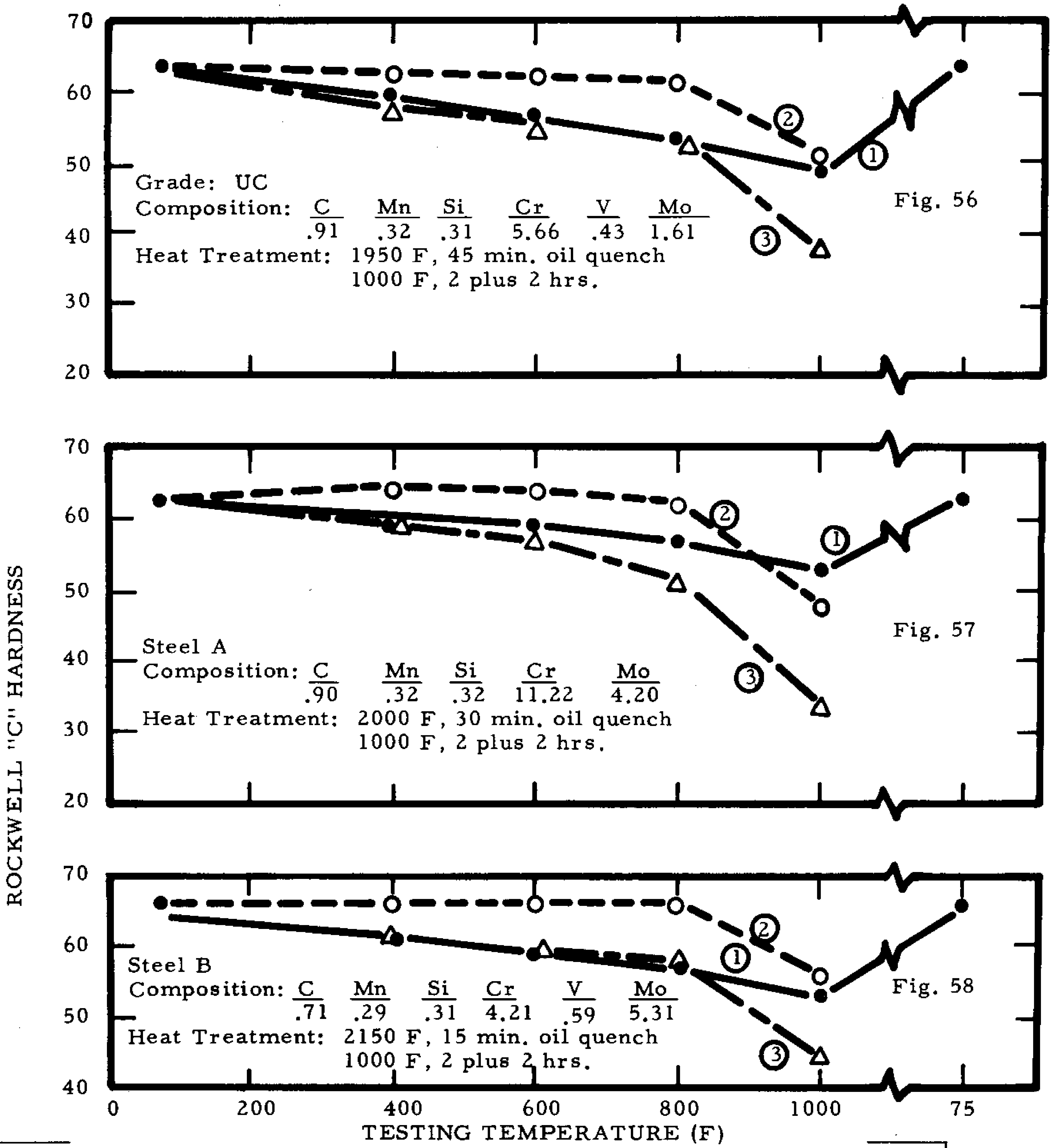
(1) Hot Hardness of Quenched and Tempered Steel.
(2) Room Temperature Hardness of Quenched and Tempered Steel after 1000 hr. Exposures at Indicated Temperatures.
(3) Hot Hardness of Quenched and Tempered Steel after 1000 hr. Exposures at Indicated Temperatures.

Figures 50 to 52. Influence of temperature on hot hardness of bearing steels (Curve 1). Also shown is the effect of 1000 hour exposure at different temperatures on the room temperature hardness (Curve 2) and hot hardness of the steels (Curve 3).



LEGEND
(1) ●——● Hot Hardness of Quenched and Tempered Steel.
(2) ○- -○ Room Temperature Hardness of Quenched and Tempered Steel after 1000 hr. Exposures at Indicated Temperatures.
(3) ▲- -▲ Hot Hardness of Quenched and Tempered Steel after 1000 hr. Exposures at Indicated Temperatures.

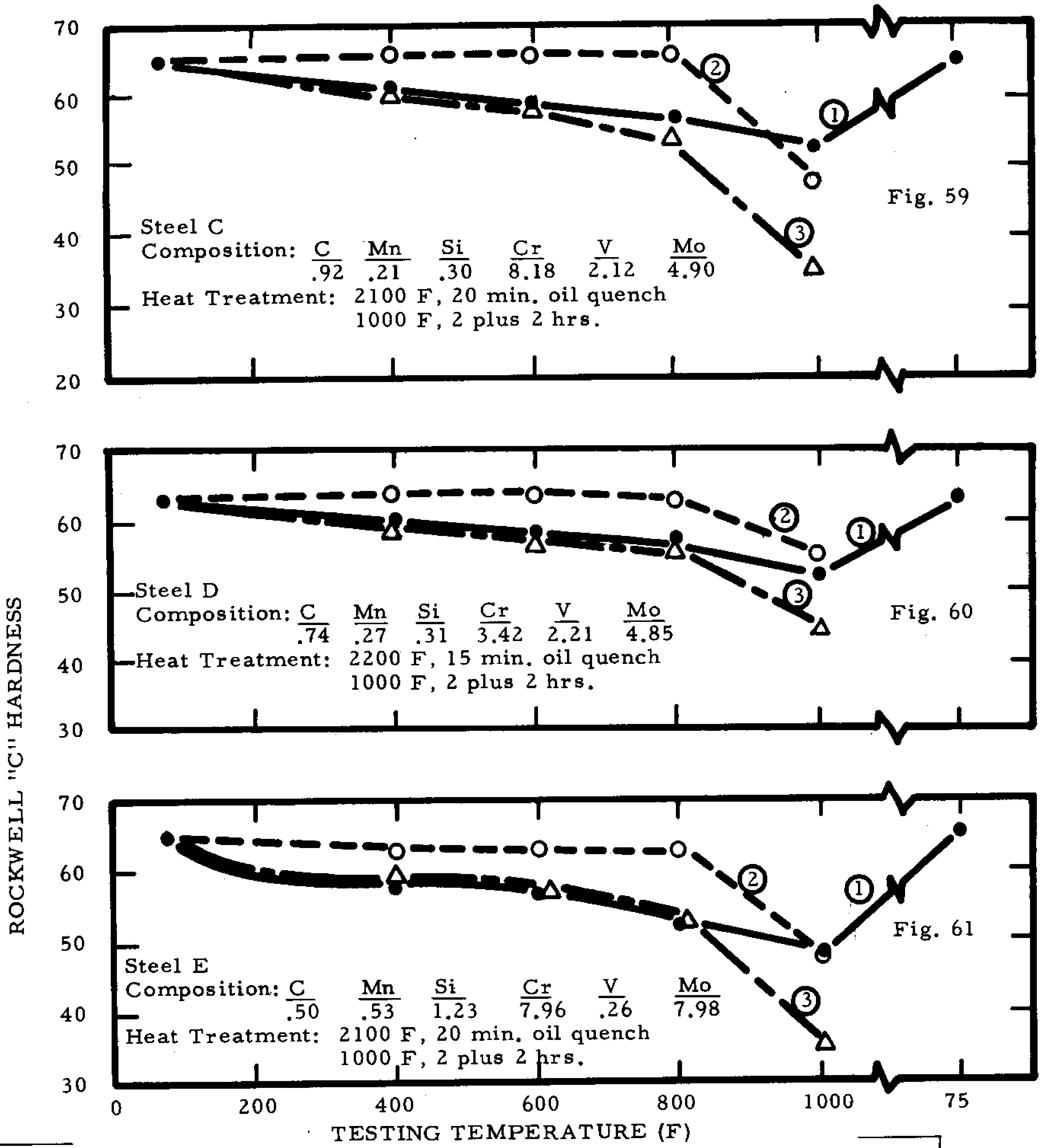
Figures 53 to 55. Influence of temperature on hot hardness of bearing steels (Curve 1). Also shown is the effect of 1000 hour exposure at different temperatures on the room temperature hardness (Curve 2) and hot hardness of the steels (Curve 3).



LEGEND

(1) Hot Hardness of Quenched and Tempered Steel.
(2) Room Temperature Hardness of Quenched and Tempered Steel after 1000 hr. Exposures at Indicated Temperatures.
(3) Hot Hardness of Quenched and Tempered Steel after 1000 hr. Exposures at Indicated Temperatures.

Figures 56 to 58: Influence of temperature on hot hardness of bearing steels (Curve 1). Also shown is the effect of 1000 hour exposure at different temperatures on the room temperature hardness (Curve 2) and hot hardness of the steels (Curve 3).



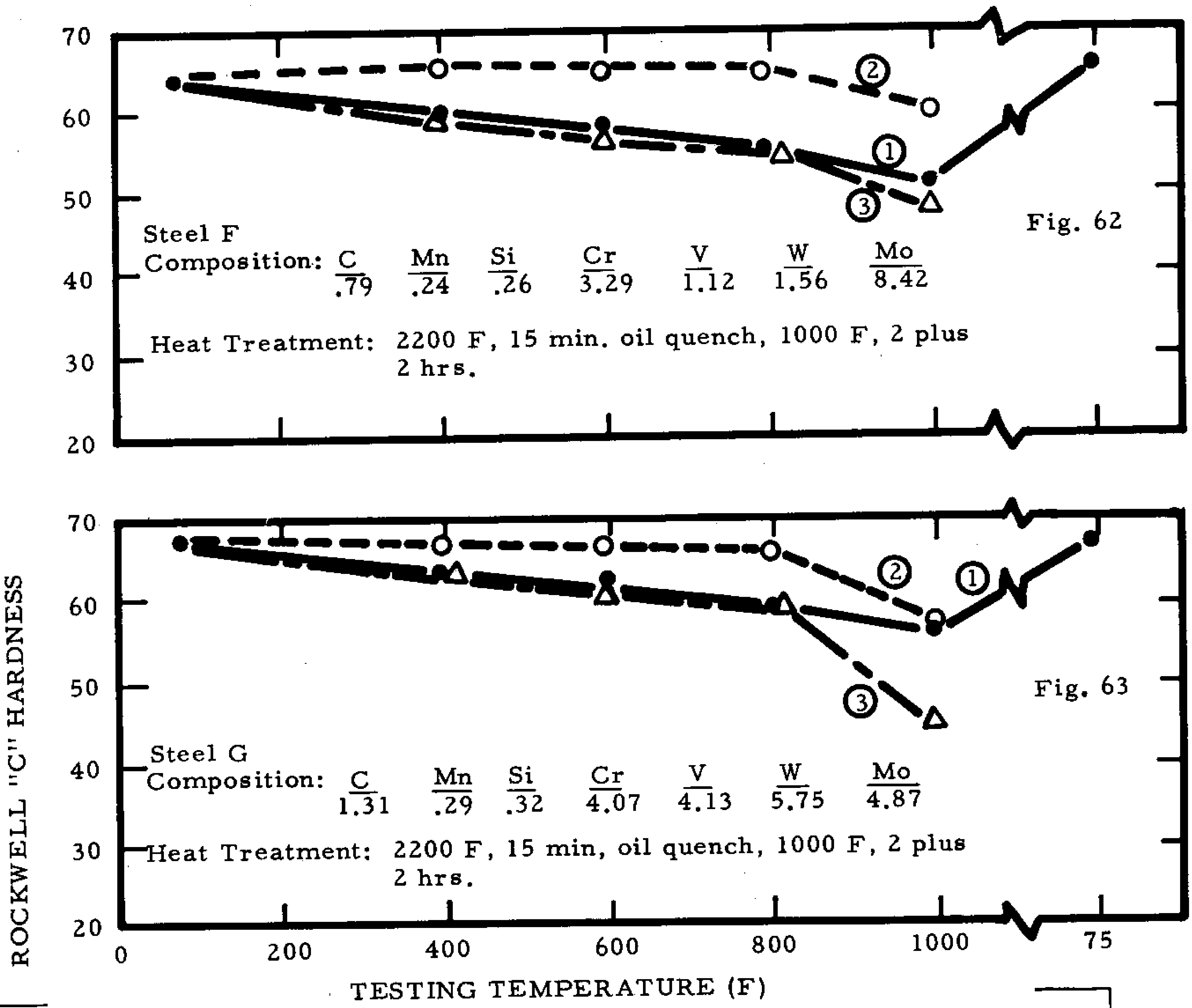
LEGEND

(1) Hot Hardness of Quenched and Tempered Steel.

(2) Room Temperature Hardness of Quenched and Tempered Steel after 1000 hr. Exposures at Indicated Temperatures.

(3) Hot Hardness of Quenched and Tempered Steel after 1000 hr. Exposures at Indicated Temperatures.

Figures 59 to 61. Influence of temperature on hot hardness of bearing steels (Curve 1). Also shown is the effect of 1000 hour exposure at different temperatures on the room temperature hardness (Curve 2) and hot hardness of the steels (Curve 3).



LEGEND
(1) ●——● Hot Hardness of Quenched and Tempered Steel.
(2) o--o Room Temperature Hardness of Quenched and Tempered Steel after 1000 hr. Exposures at Indicated Temperatures.
(3) ▲--▲ Hot Hardness of Quenched and Tempered Steel after 1000 hr. Exposures of Indicated Temperatures.

Figures 62 and 63. Influence of temperature on hot hardness of bearing steels (Curve 1). Also shown is the effect of 1000 hour exposure at different temperatures on the room temperature hardness (Curve 2) and hot hardness of the steels (Curve 3).

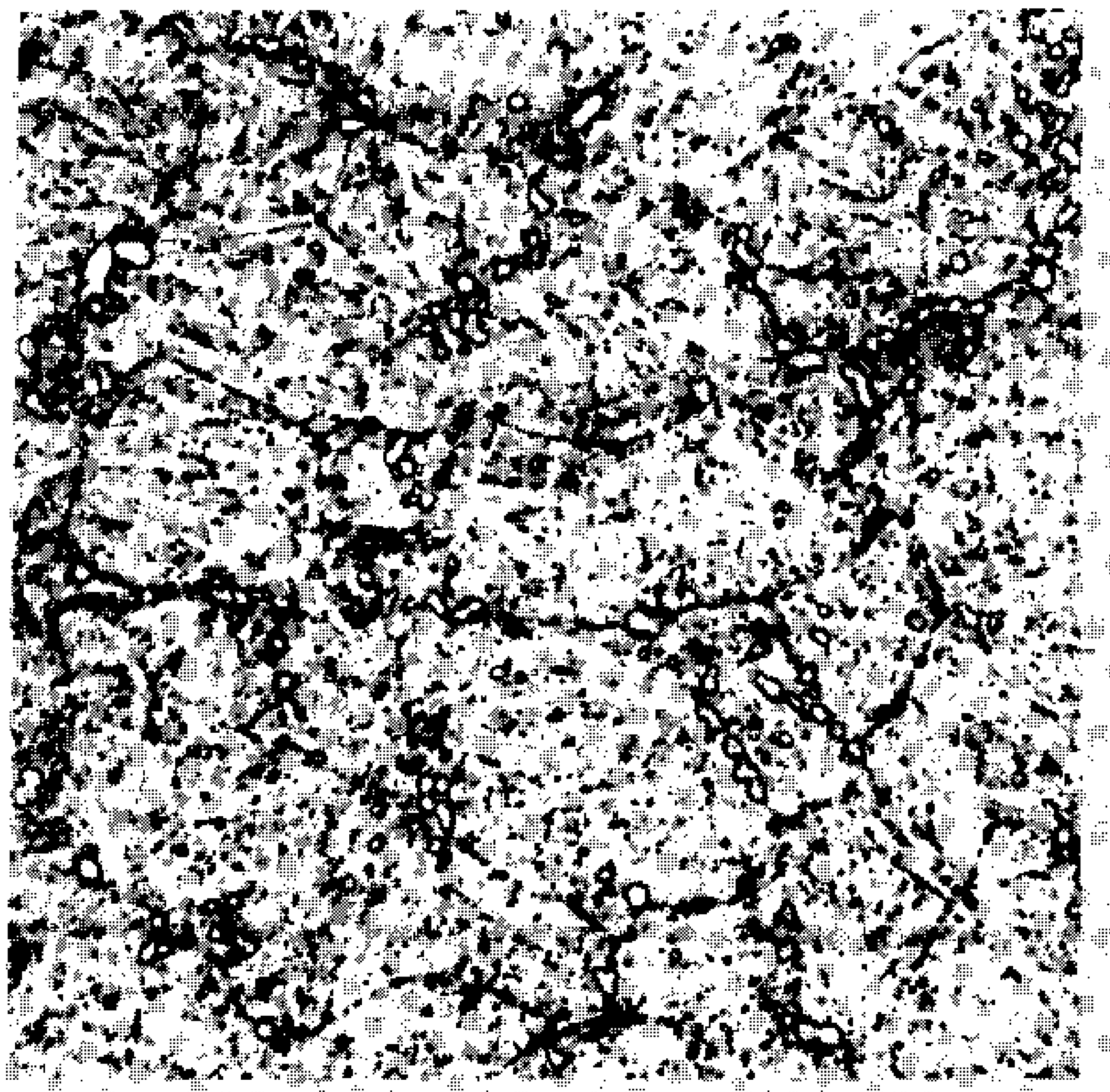


Fig. 64 Halmo-1, austenitized 2100 F, 20 min. oil quench, tempered 1050 F, 2 plus 2 hours.

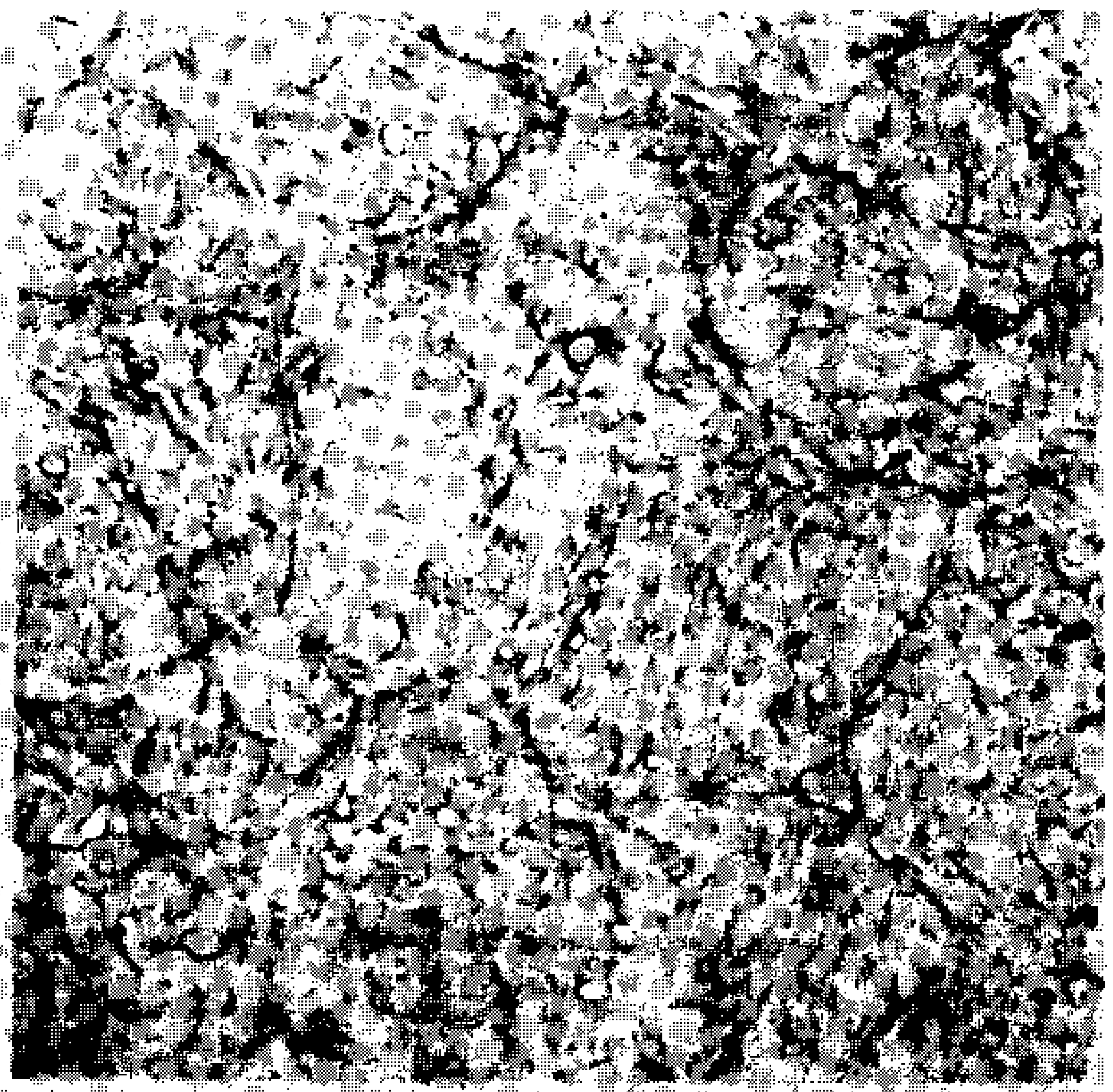


Fig. 65 Ferrovac Halmo, austenitized 2100 F, 20 min. oil quench, tempered 1050 F, 2 plus 2 hours.

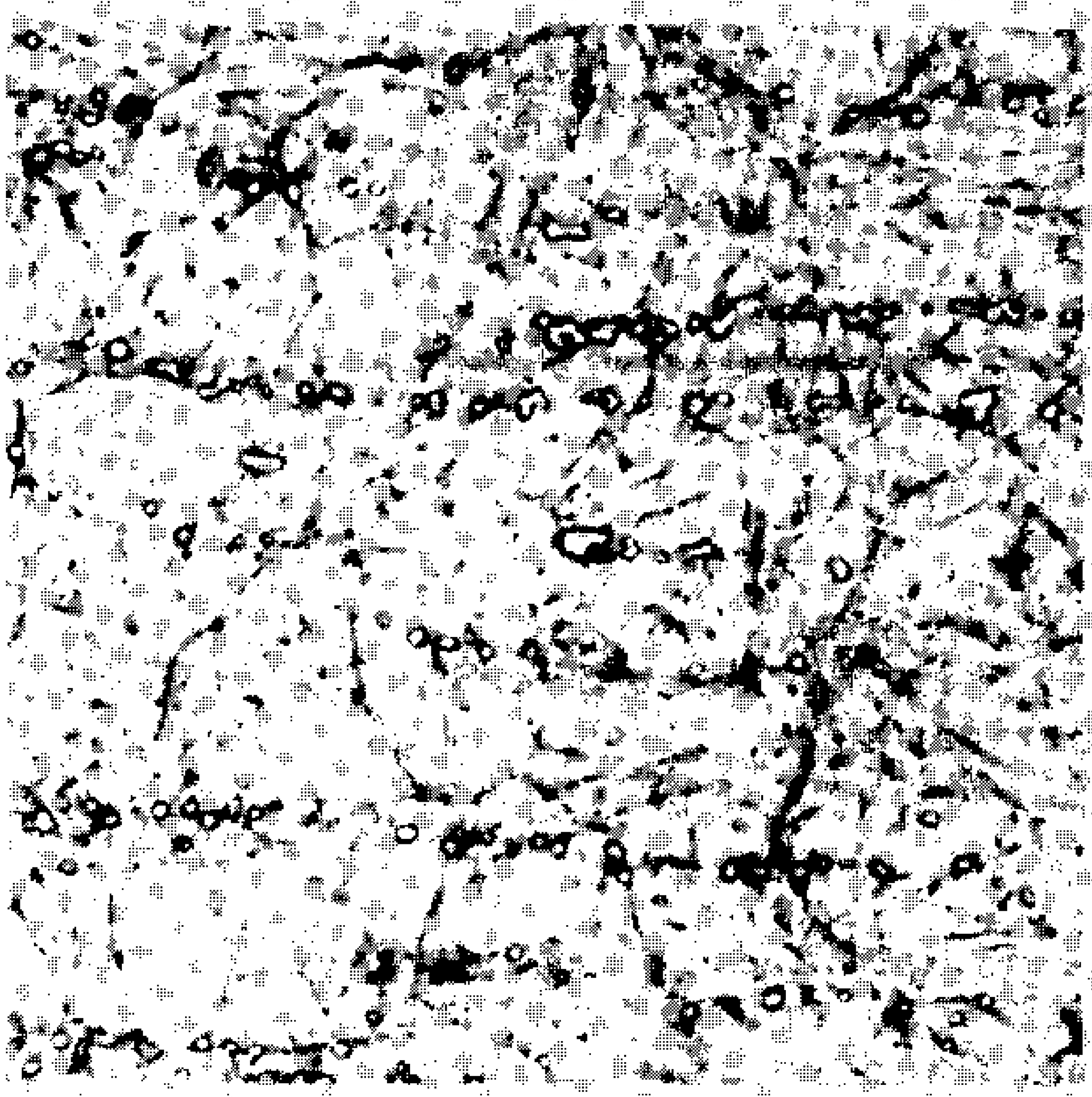


Fig. 66 Halmo-2, austenitized 2100 F, 20 min. oil quench, tempered 1050 F, 2 plus 2 hours.

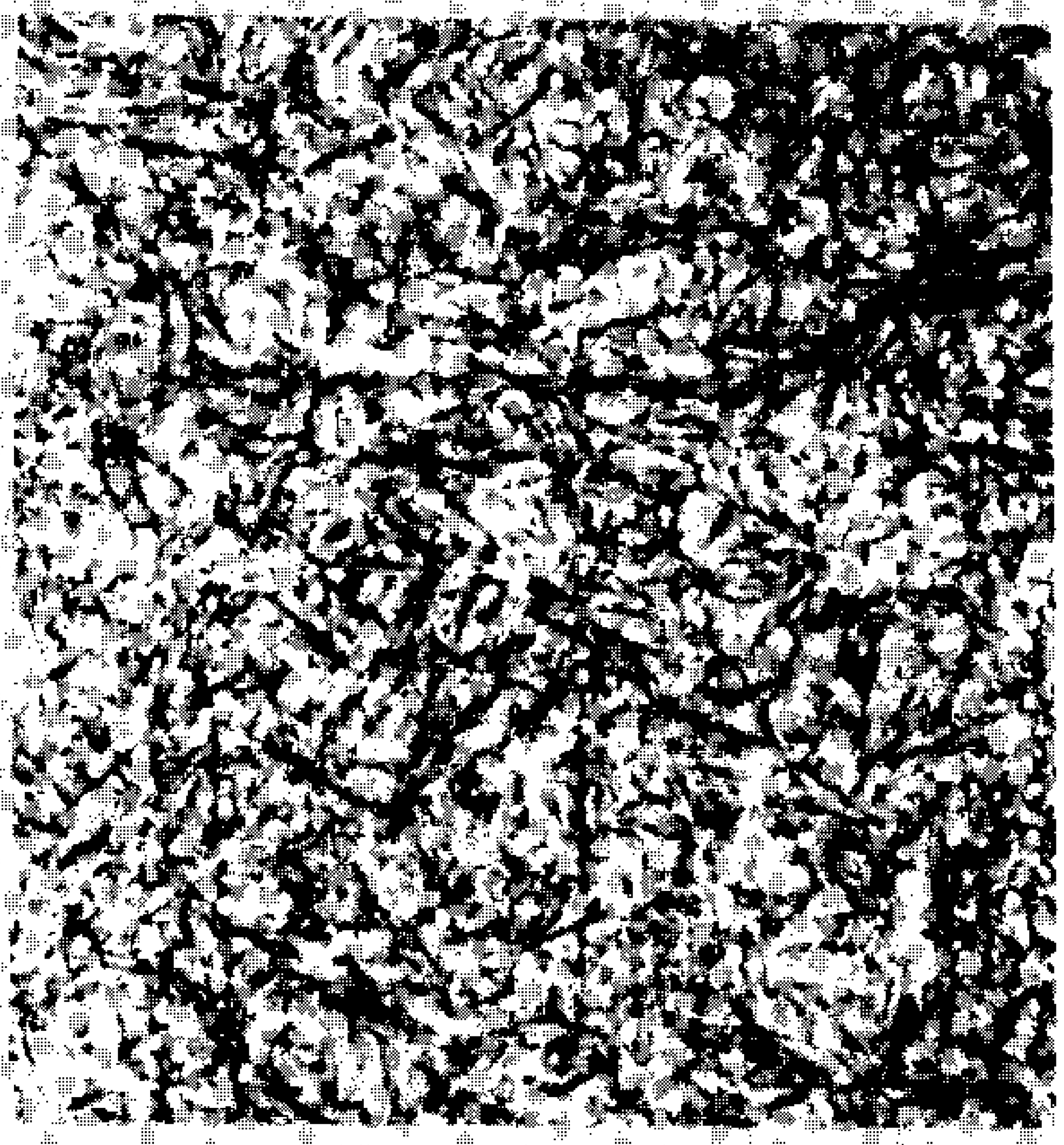


Fig. 67 .8C Halmo, austenitized 2050 F, 25 min. oil quench, tempered 1050 F 2 plus 2 hours.

FIGURES 64 to 67 MICROSTRUCTURES SHOWING CARBIDE SIZE AND DISTRIBUTION IN BEARING STEELS.

Picral + 0.2% HCl Etch Magnification X 750

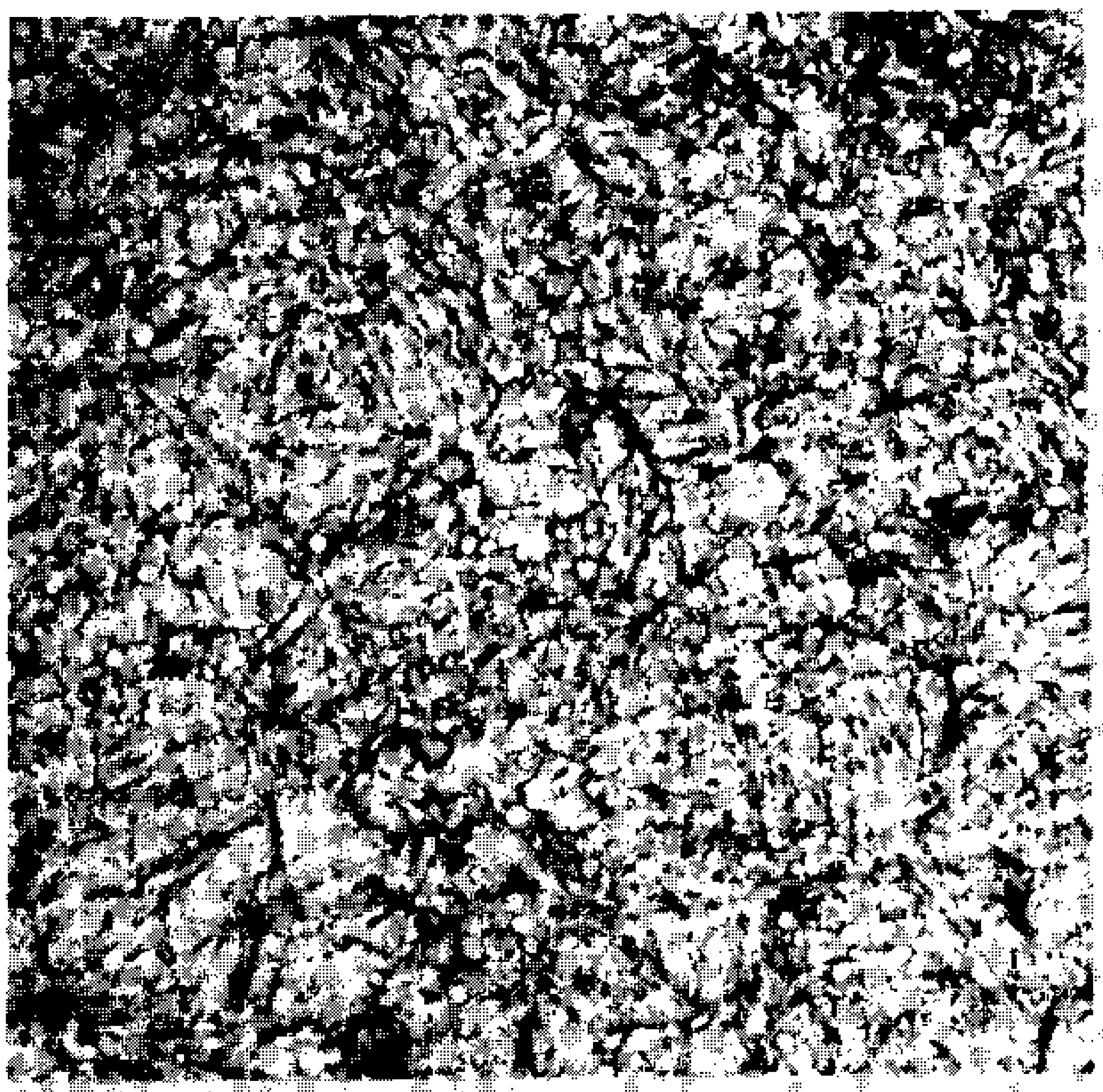


Fig. 68 .9C Halmo, austenitized 2050 F, 25 min. oil quench, tempered 1075 F 2 plus 2 hours.

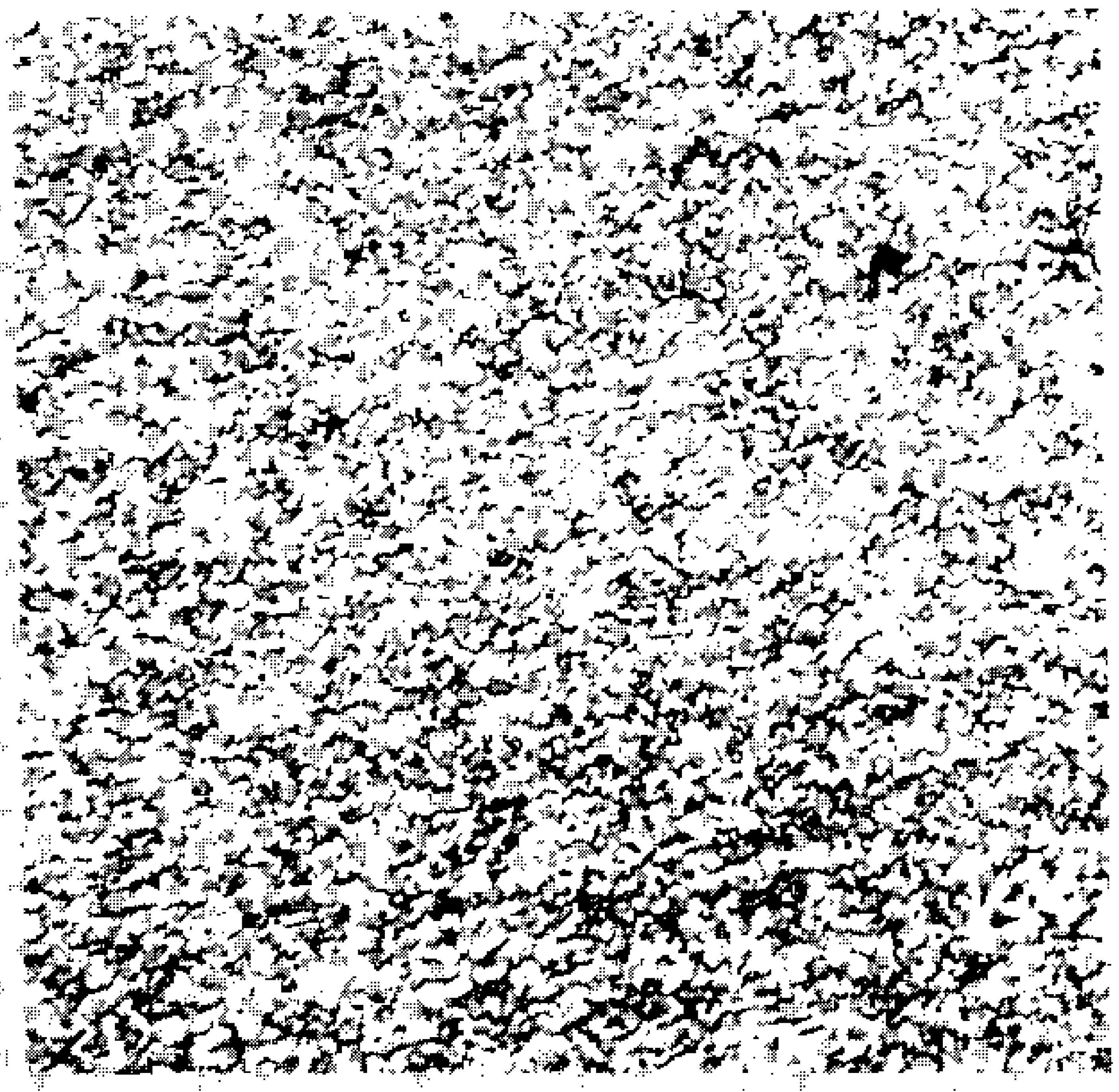


Fig. 69 52100, austenitized 1550 F, 1 hr., oil quench, tempered 400 F 2 hours.

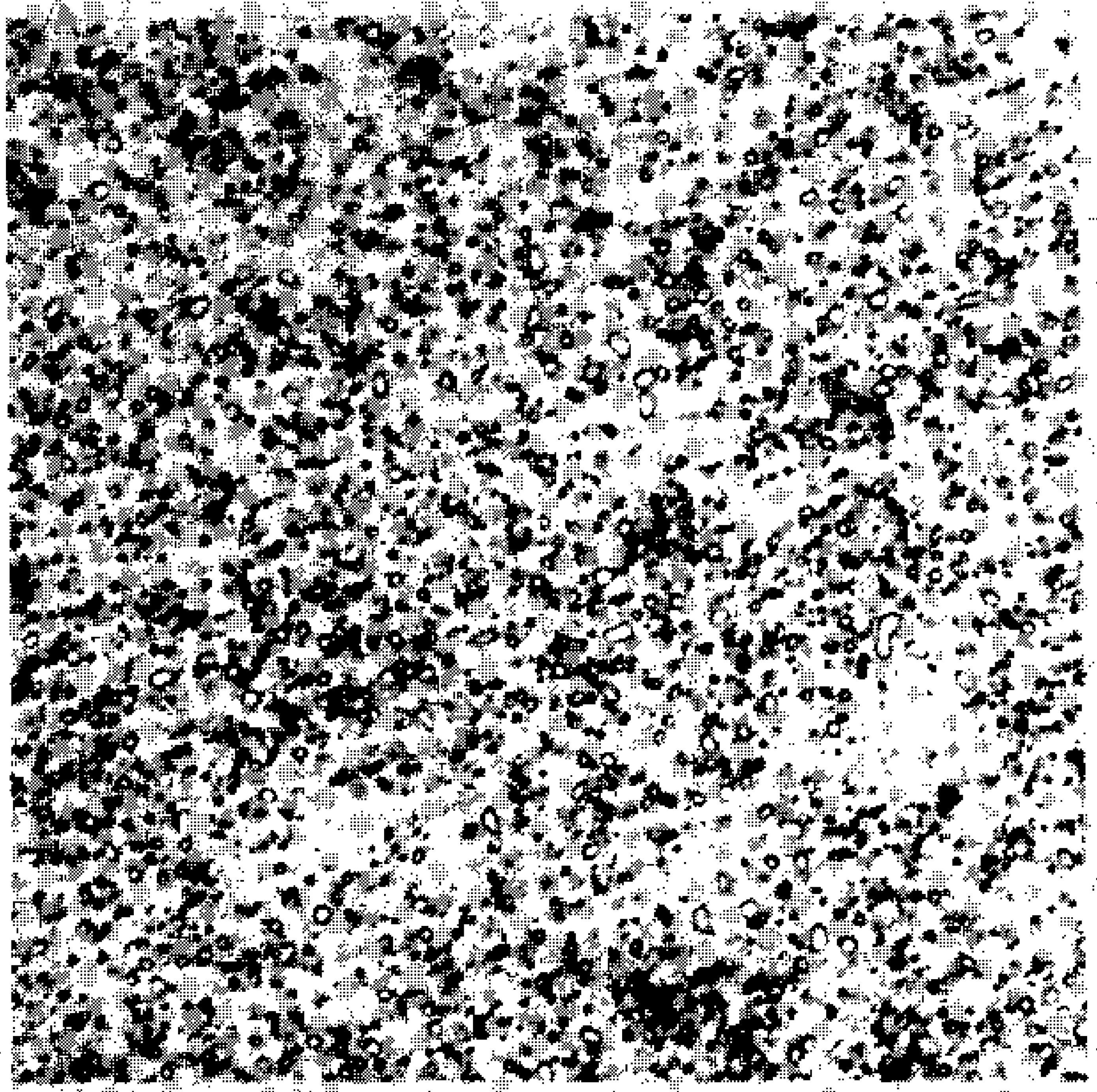


Fig. 70 Ferrovac 52100, austenitized, 1550 F, 1 hr., oil quench, tempered 400 F, 2 hours.

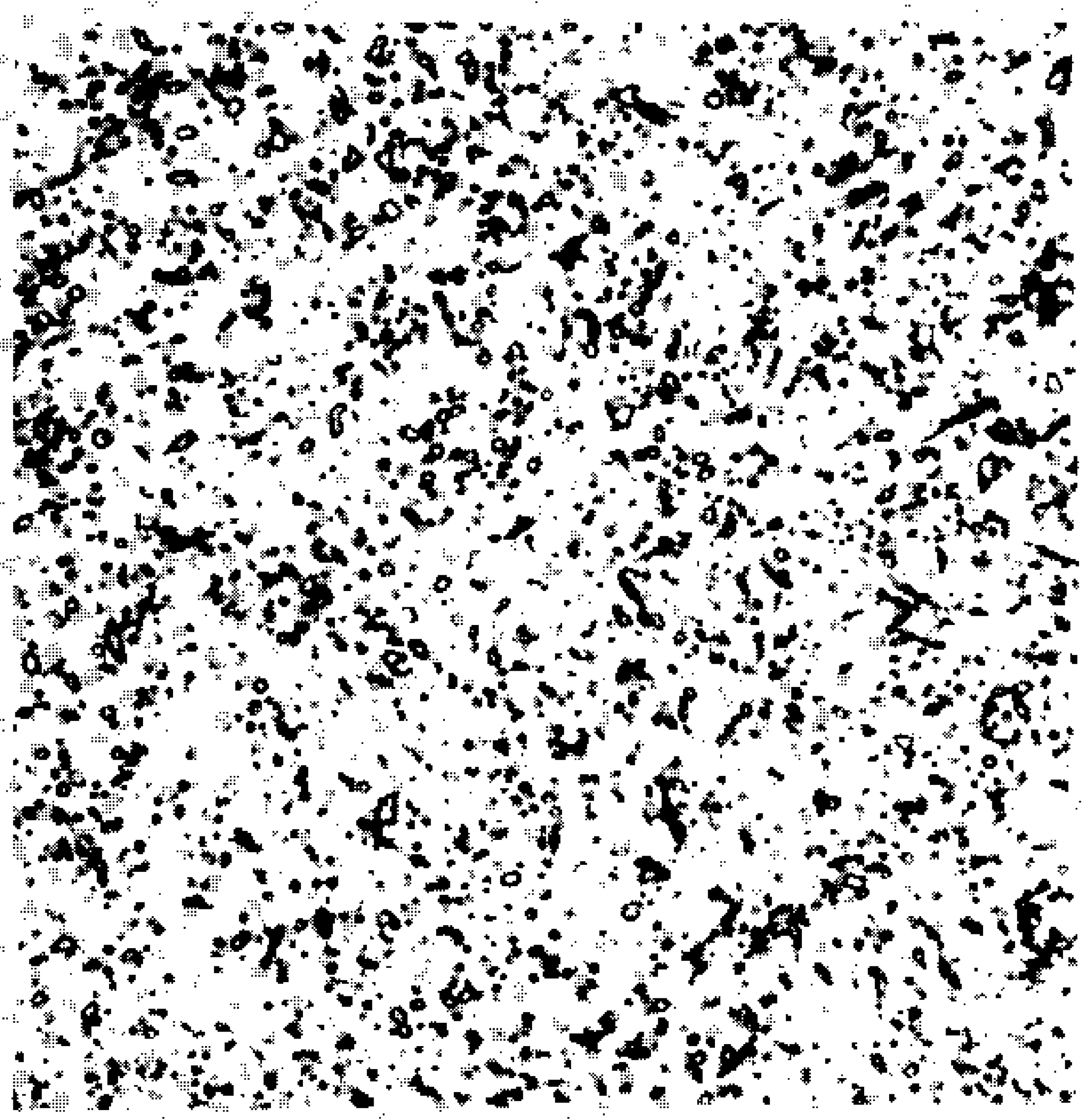


Fig. 71 MHT, austenitized 1550 F, 1 hour, oil quench, tempered, 400 F, 2 hours.

FIGURES 68 to 71 MICROSTRUCTURES SHOWING CARBIDE SIZE AND DISTRIBUTION IN BEARING STEELS.

Picral + 0.1% HCl Etch　　　Magnification X 750

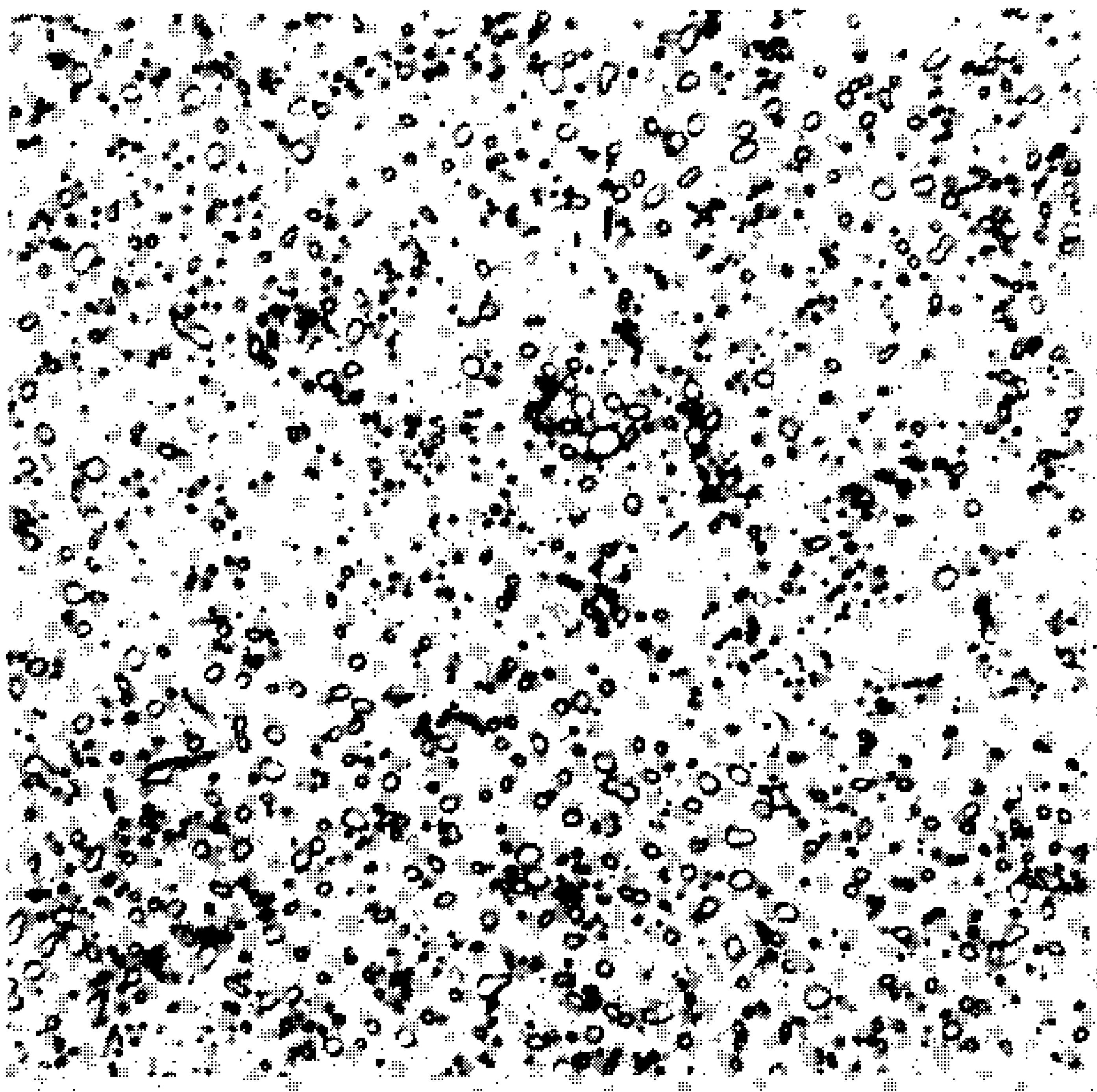


Fig. 72 Ferrovac MHT, austenitized 1550 F, 1 hour, oil quench, tempered 400 F, 2 hours
Picral + 0.1% HCl Etch

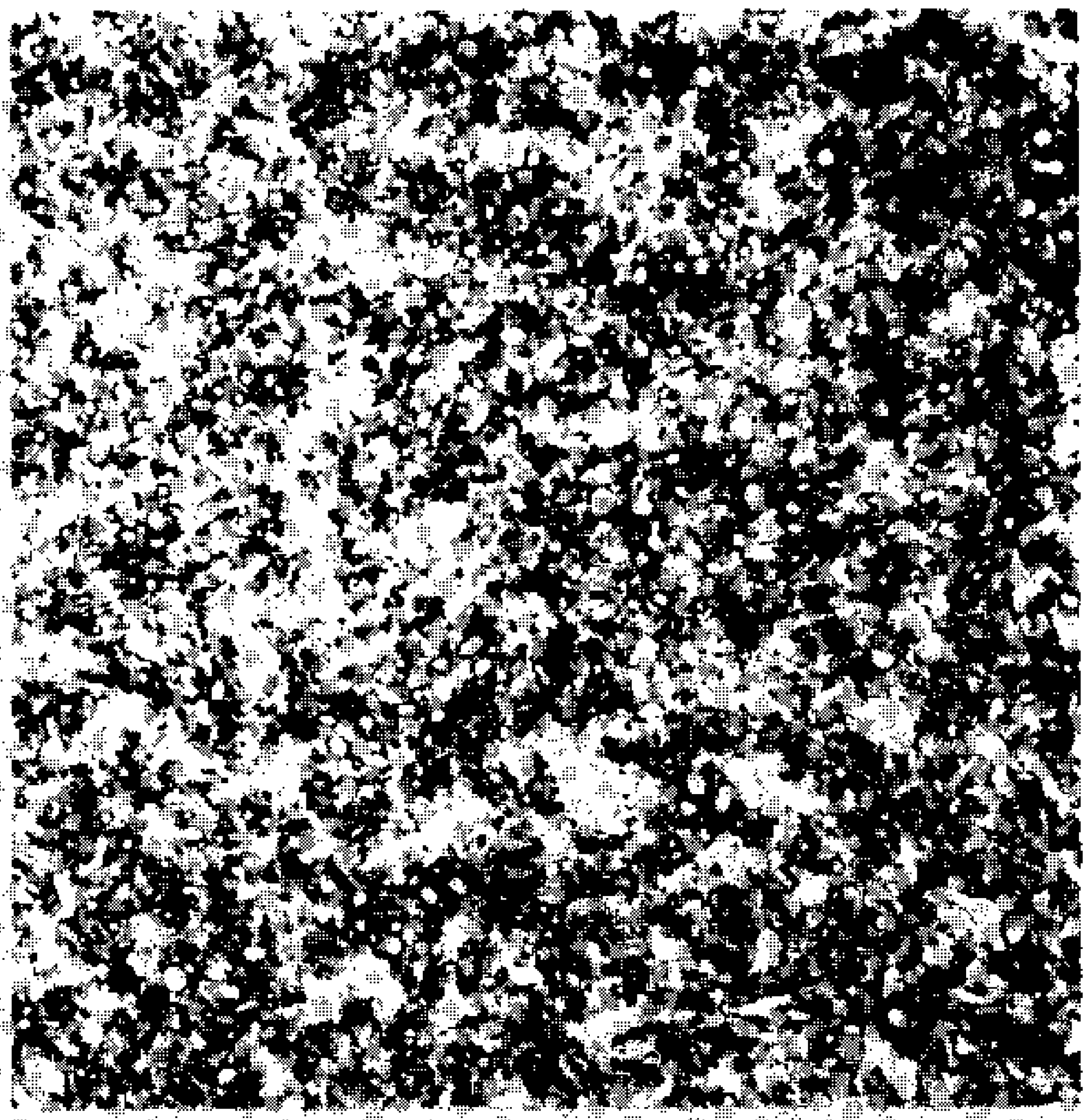


Fig. 73 MHT plus Si, austenitized 1600 F, 1 hour, oil quench, tempered 400 F, 2 hours

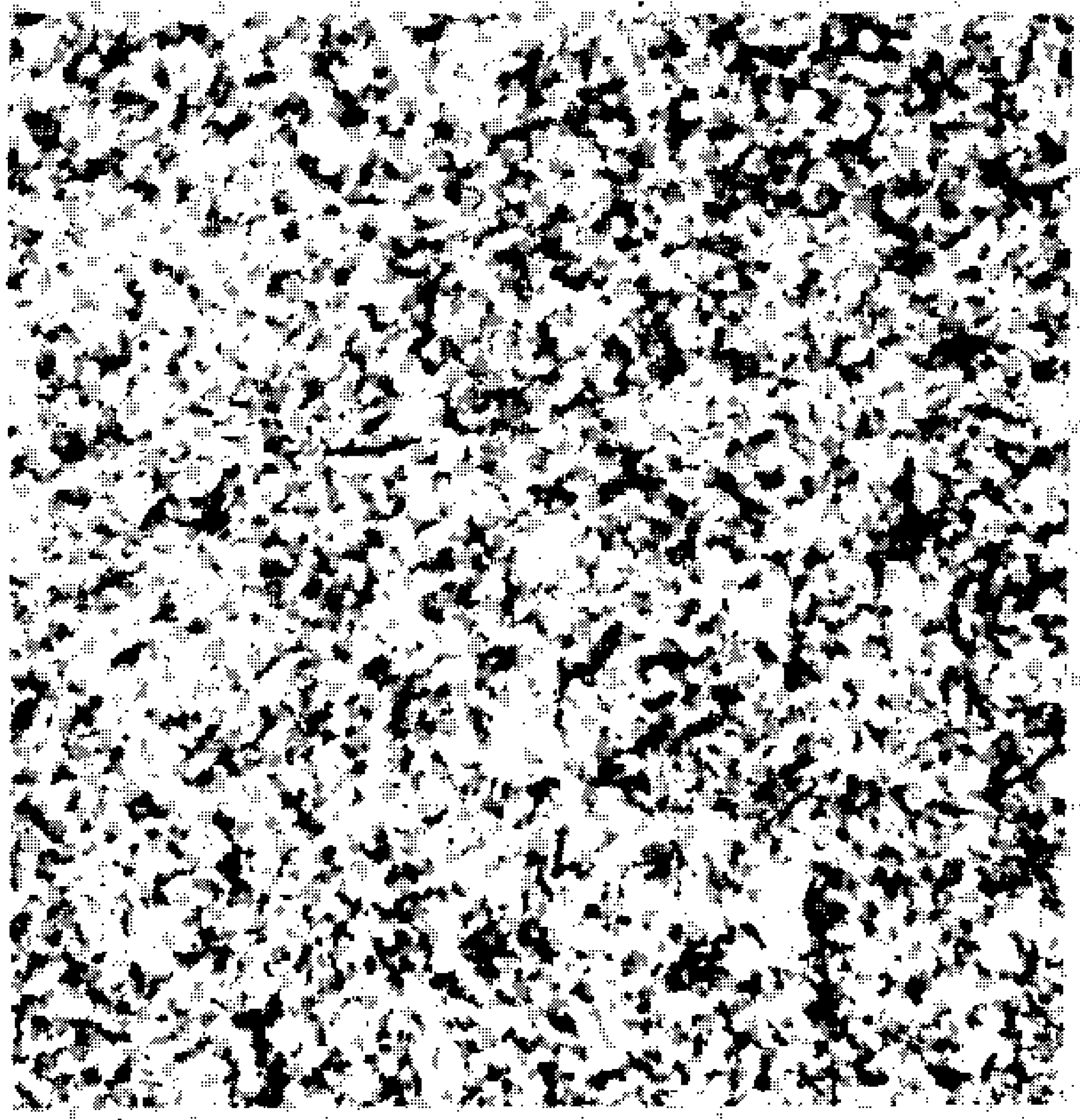


Fig. 74 440 C, austenitized 1950 F, 1 hour, oil quench, heated to 350 F 1 hour, refrigerated and tempered 900 F, 2 plus 2 hours.

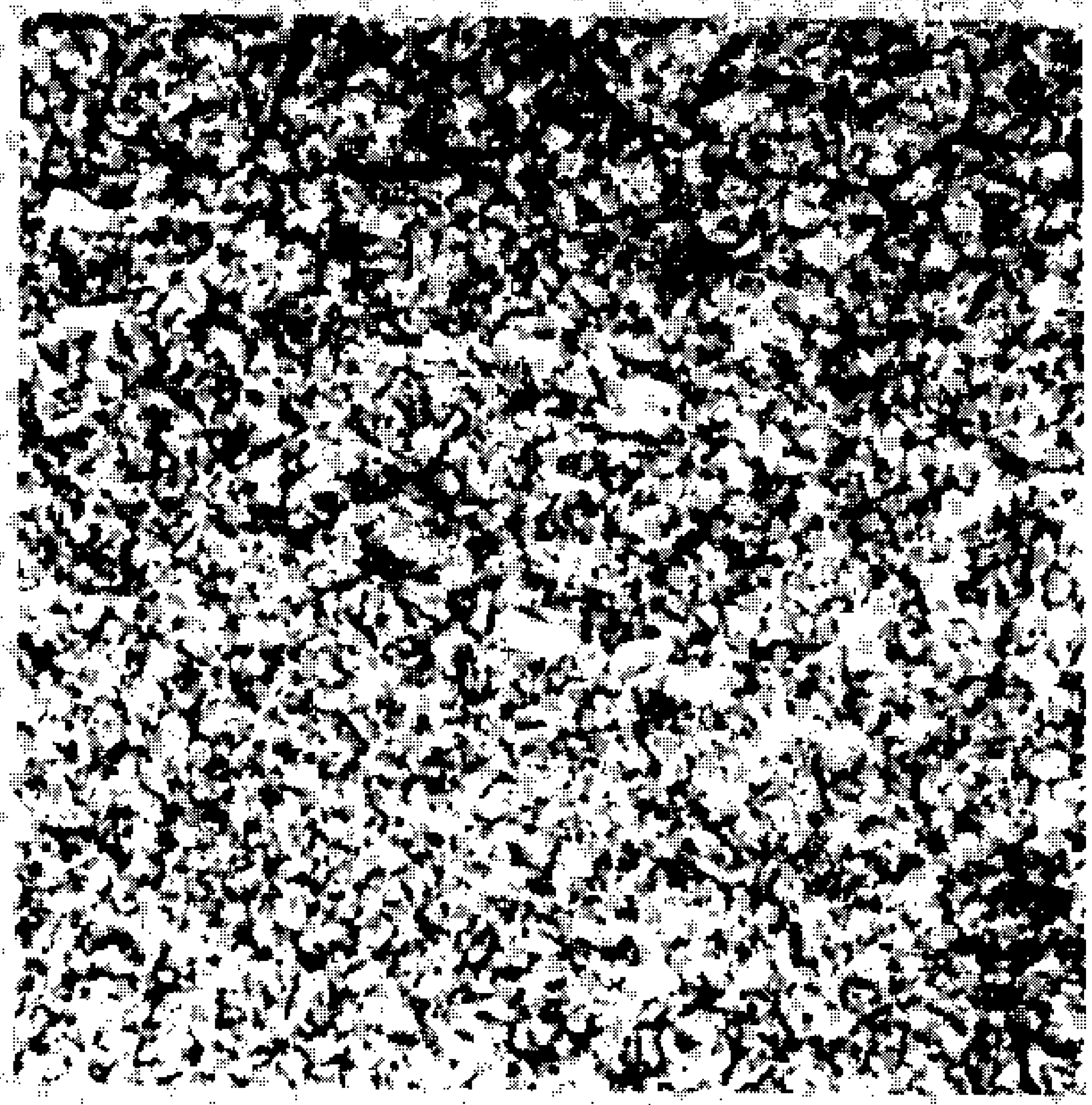


Fig. 75 440 BM, austenitized 1950 F, 1 hour, oil quench, heated to 350 F 1 hour, refrigerated and tempered 900 F, 2 plus 2 hours.

FIGURES 72 to 75 MICROSTRUCTURES SHOWING CARBIDE SIZE AND DISTRIBUTION IN BEARING STEELS

Alcoholic 10% HCl Etch (440C and 440BM) Magnification X 750

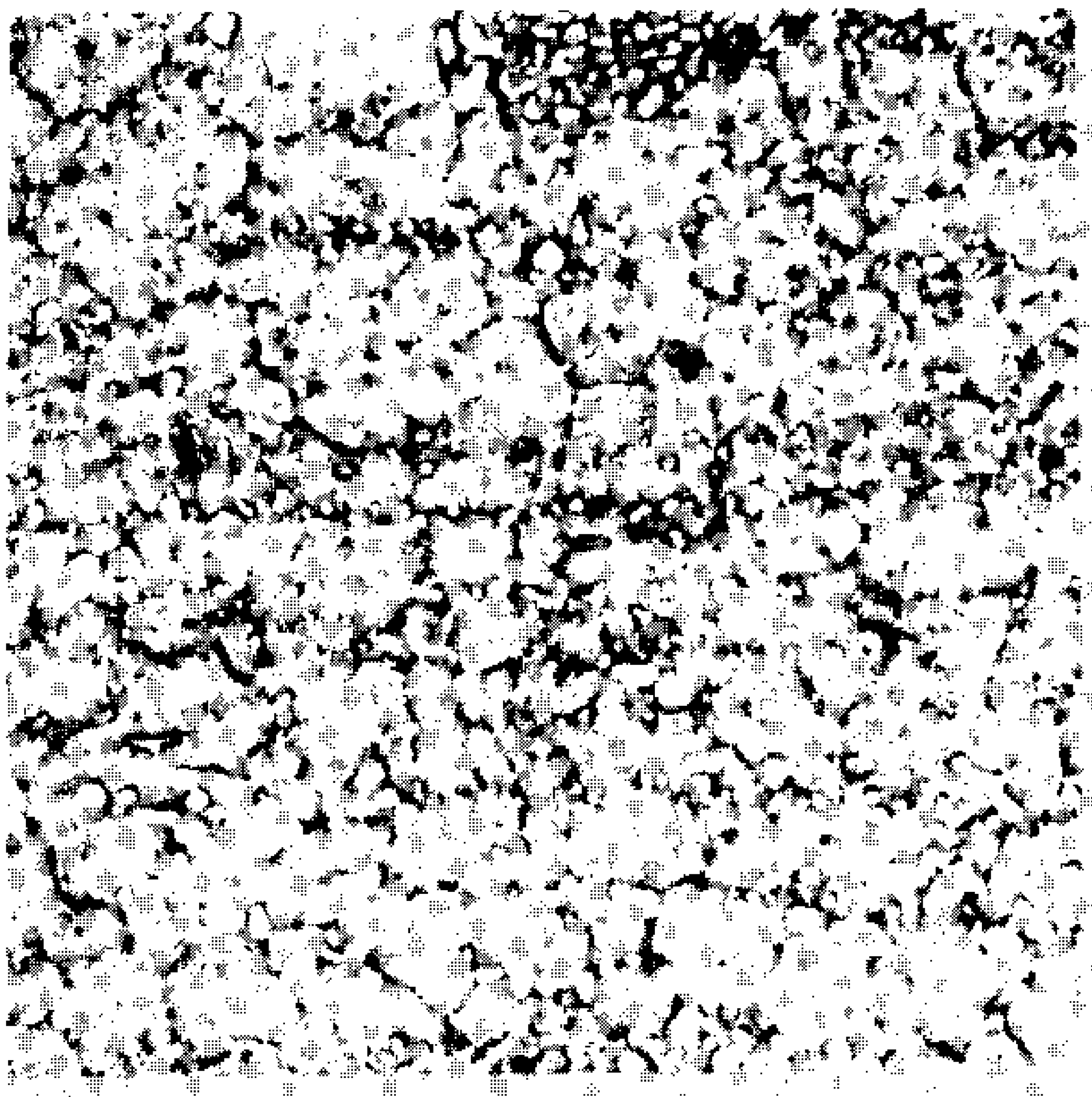


Fig. 76 T1, austenitized 2350 F, 5 min. oil quench, tempered 1050 F 2 plus 2 hours

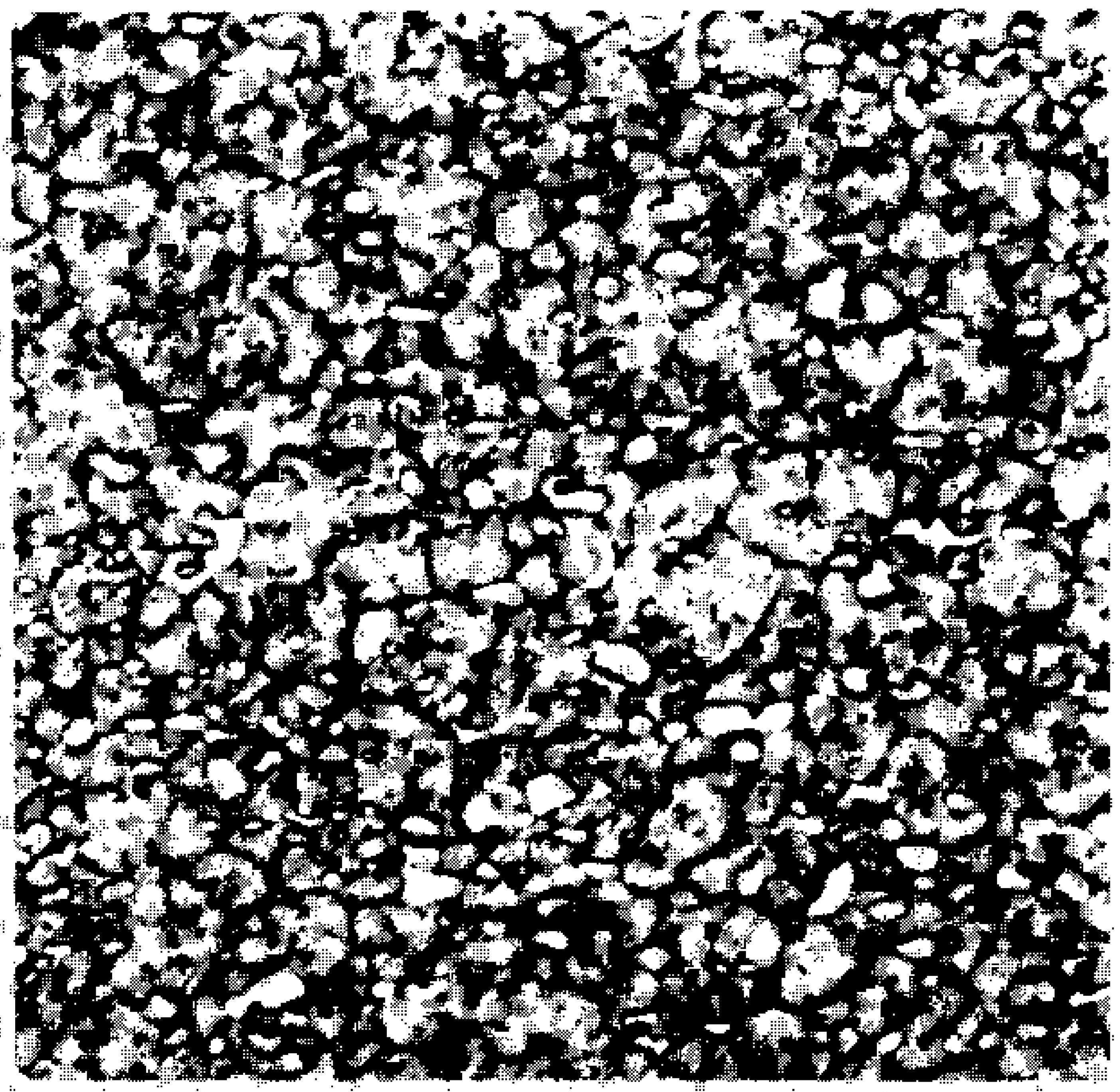


Fig. 77 T5, austenitized 2300 F, 5 min. oil quench, tempered 1000 F 2 plus 2 hours.

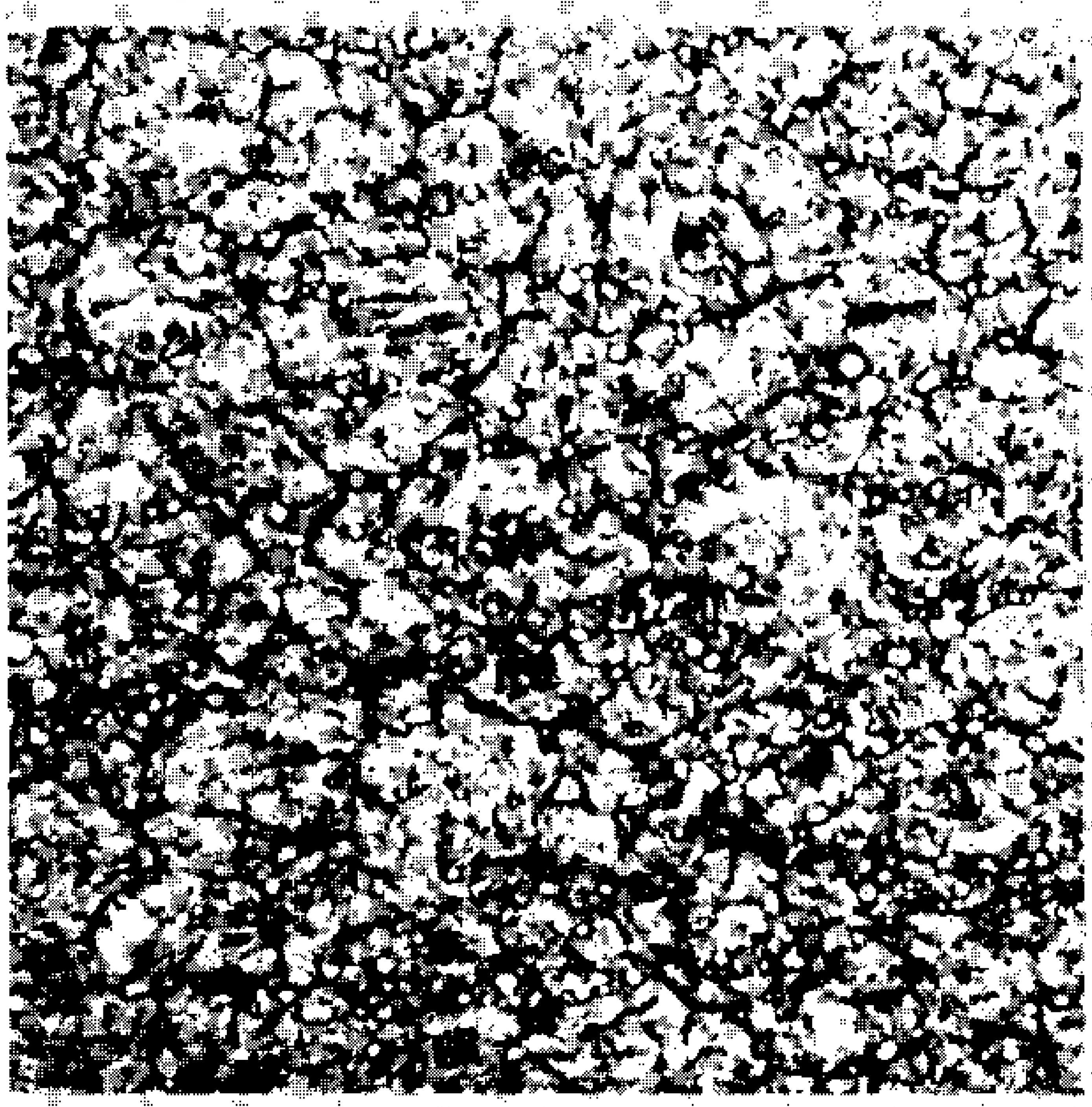


Fig. 78 M2, austenitized 2250 F, 10 min. oil quench, tempered 1050 F, 2 plus 2 hours.

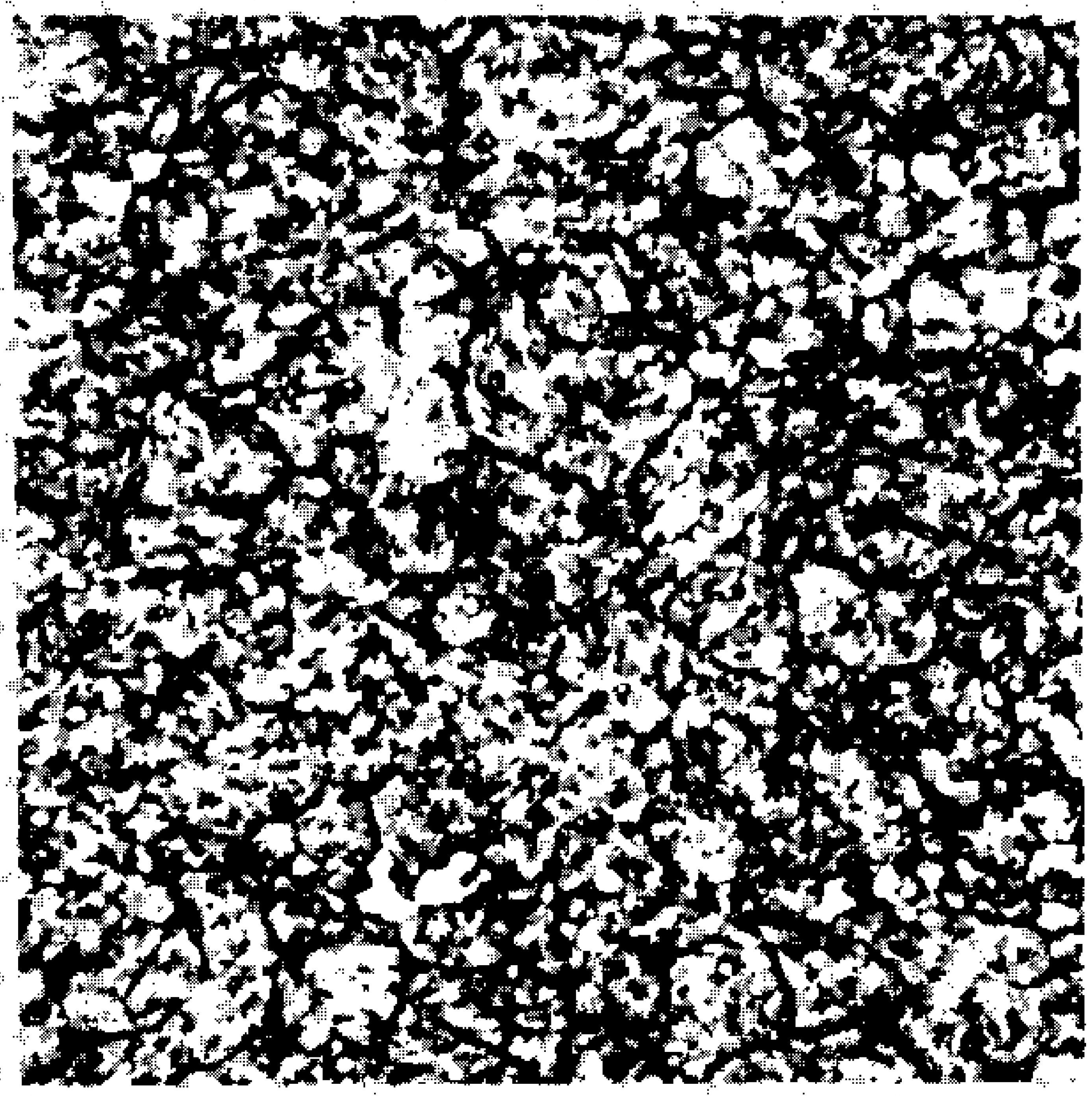


Fig. 79 Ferrovac-M2, austenitized 2250 F, 10 min. oil quench, tempered 1050 F, 2 plus 2 hours.

FIGURES 76 to 79 MICROSTRUCTURES SHOWING CARBIDE SIZE AND DISTRIBUTION IN BEARING STEELS.

Picral + 0.1% HCl Etch Magnification X 750

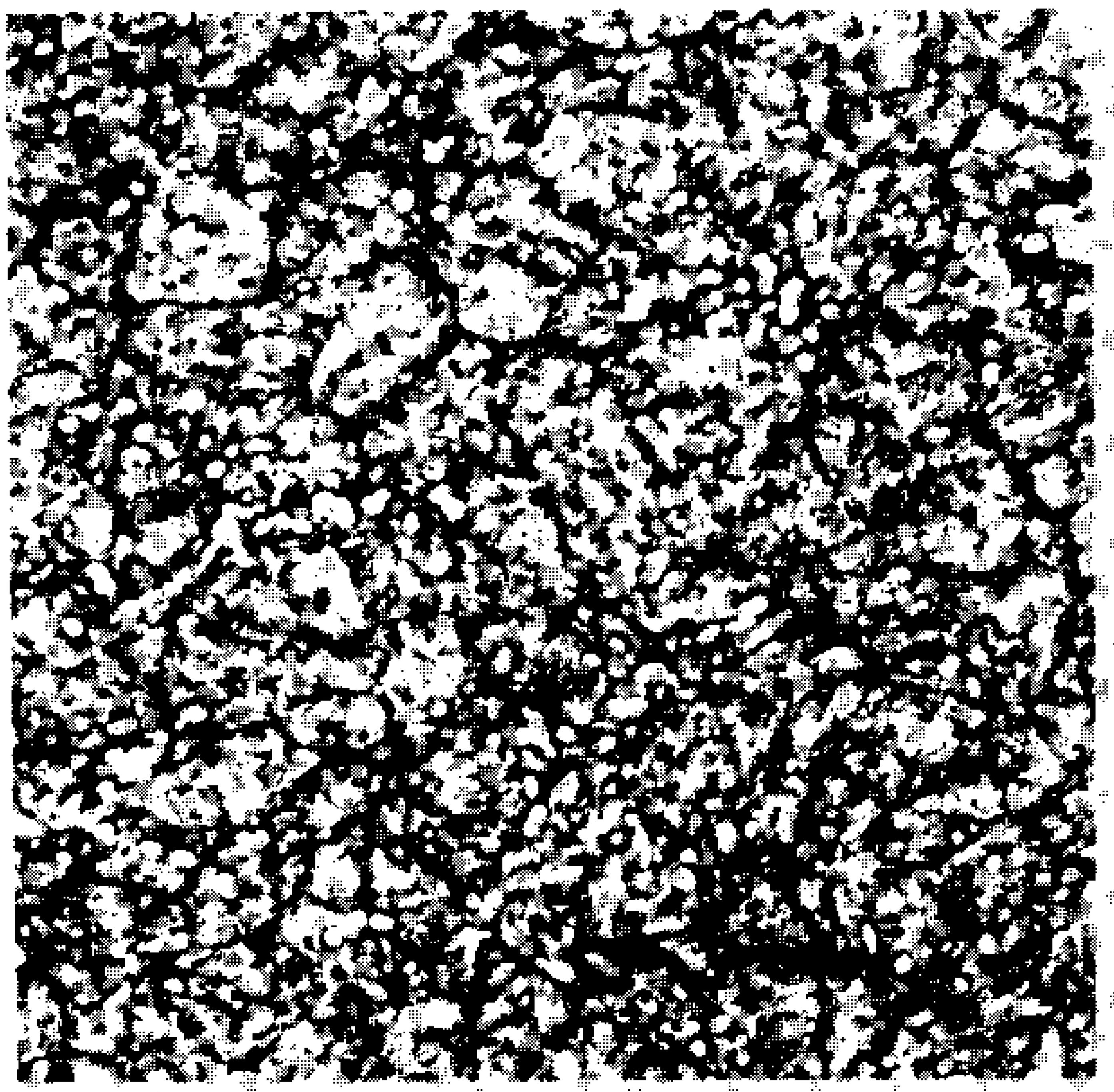


Fig. 80 M1, austentized 2200 F, 15 min. oil quench, tempered 1050 F, 2 plus 2 hours.

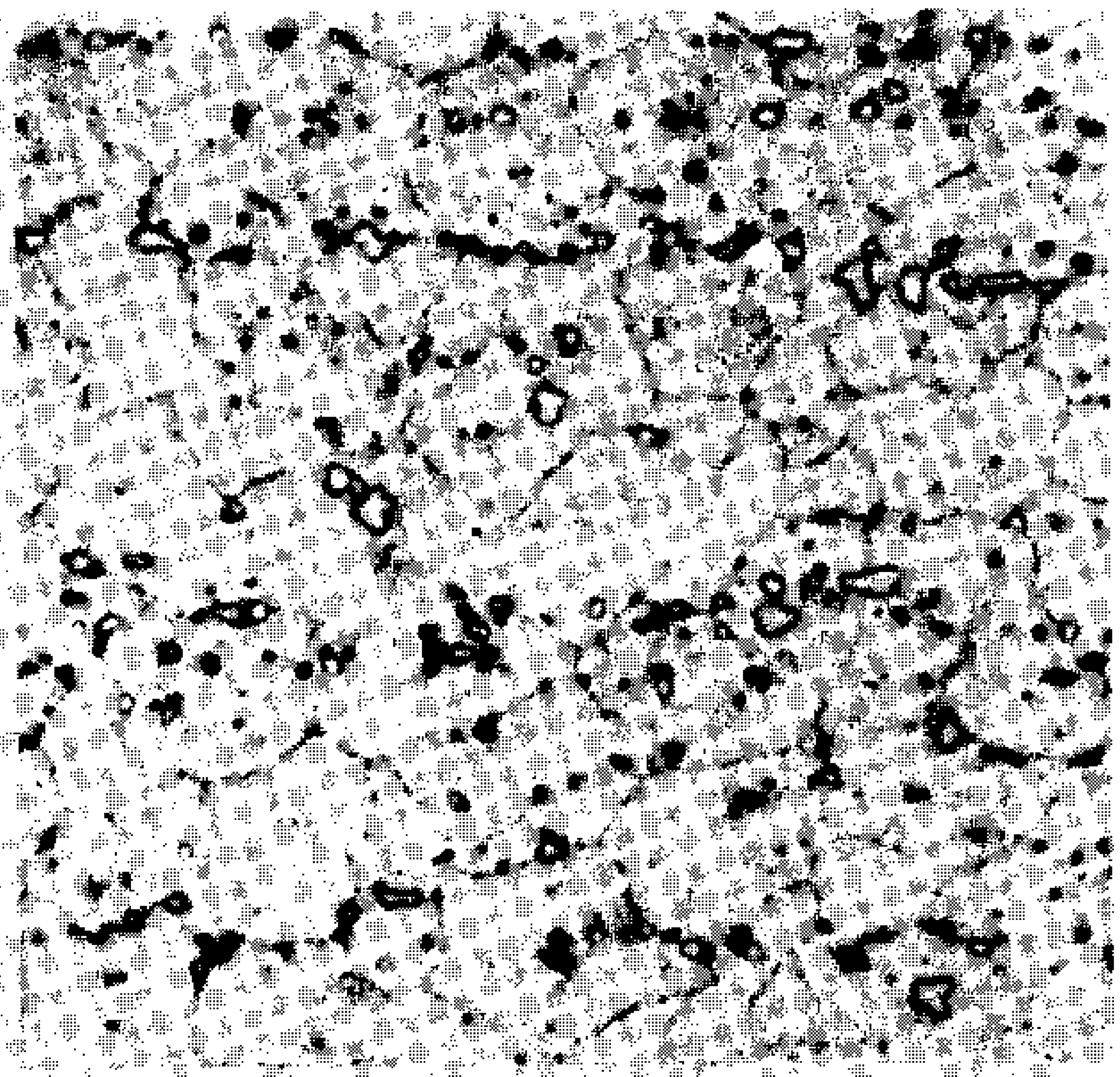


Fig. 81 M10, austenitized 2200 F 15 min. oil quench, tempered 1050 F, 2 plus 2 hours.

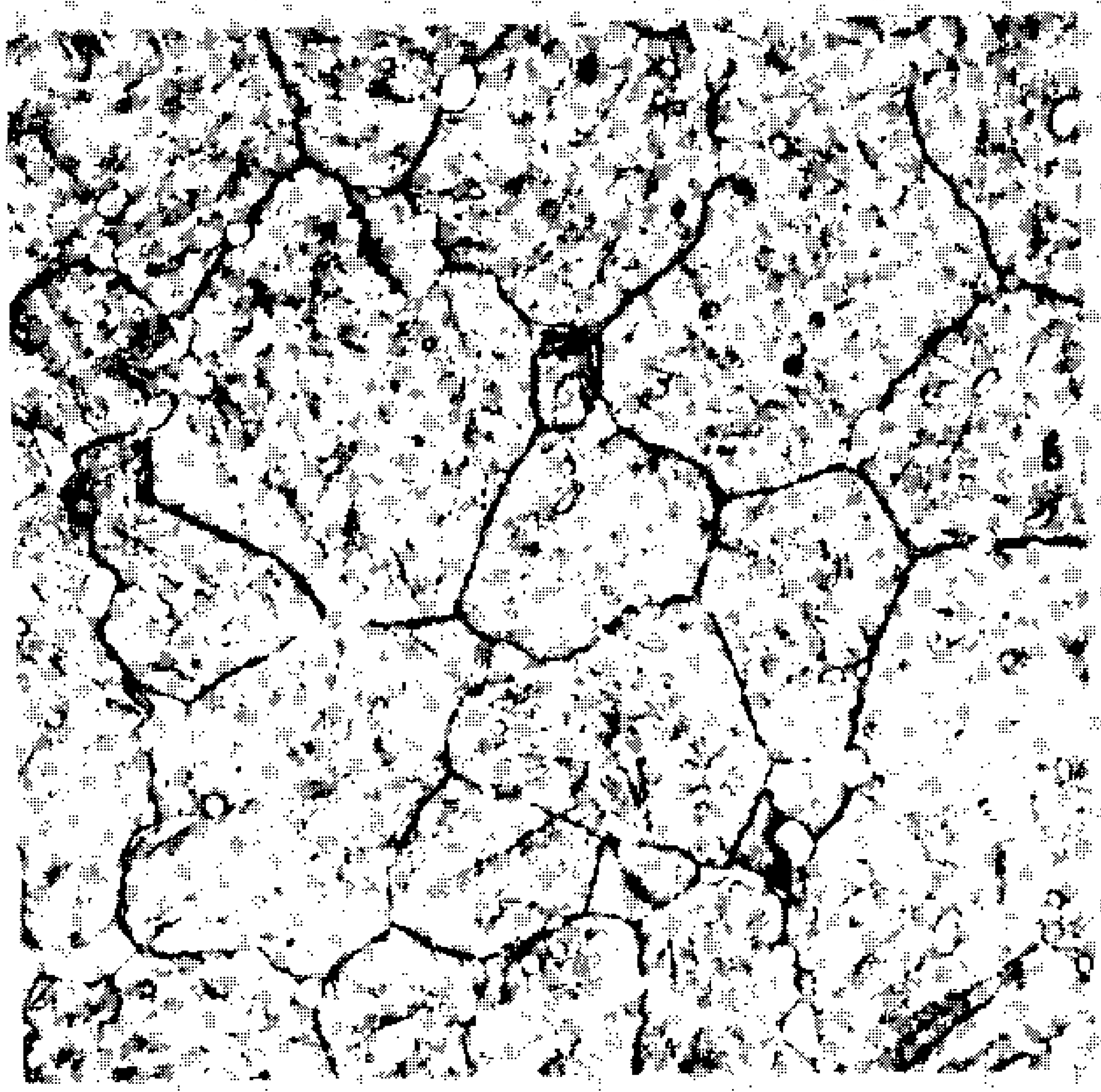


Fig. 82 HiC-M10, austenitized 2200 F, 15 min. oil quench, tempered 1050 F, 2 plus 2 hours.

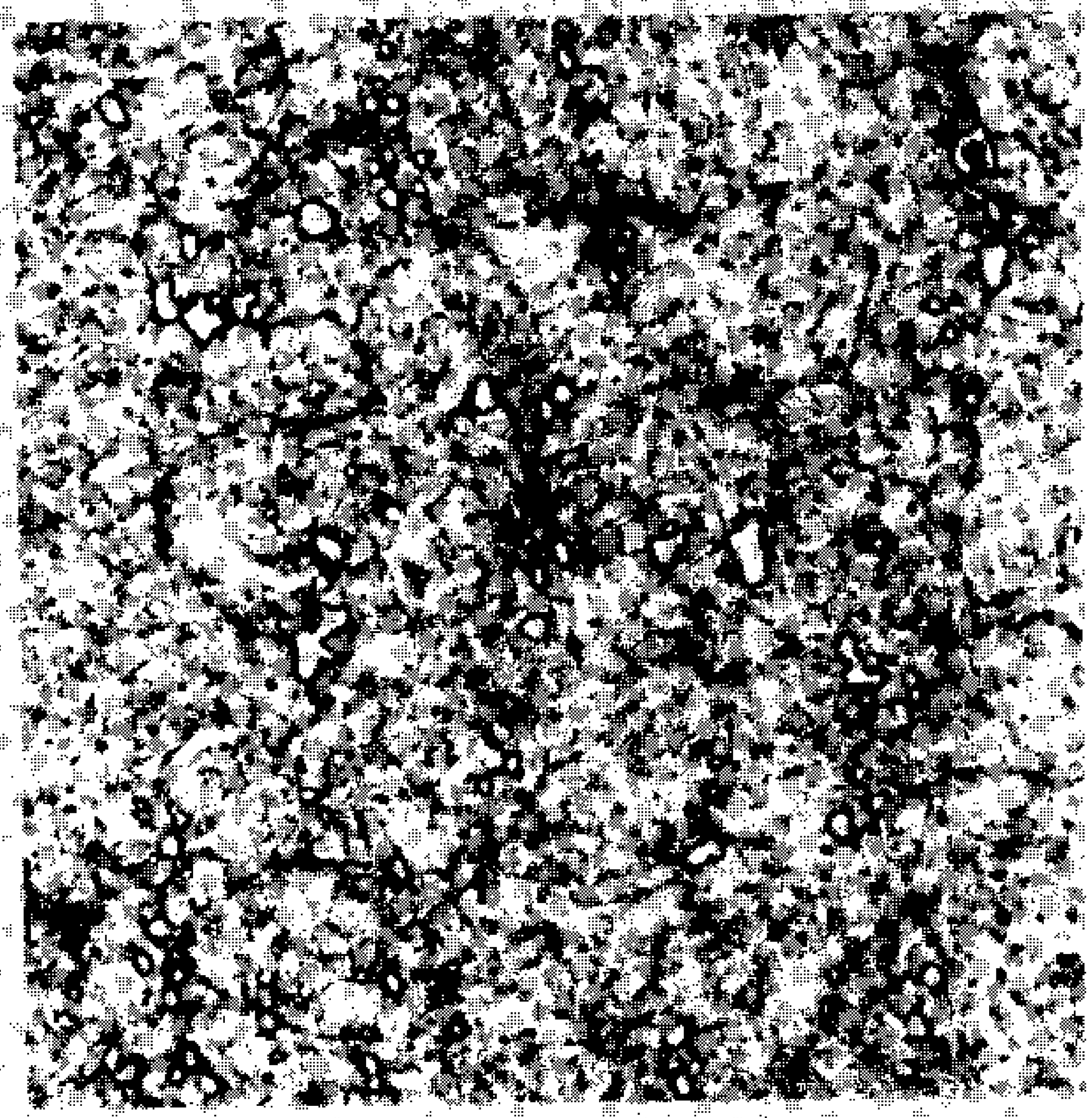


Fig. 83 VSM, austenitized 2050 F 20 min. oil quench, tempered 1000 F, 2 plus 2 hours.

FIGURES 80 to 83 MICROSTRUCTURES SHOWING CARBIDE SIZE AND DISTRIBUTION IN BEARING STEELS.

Picral + 0.2% HCl Etch Magnification X 750

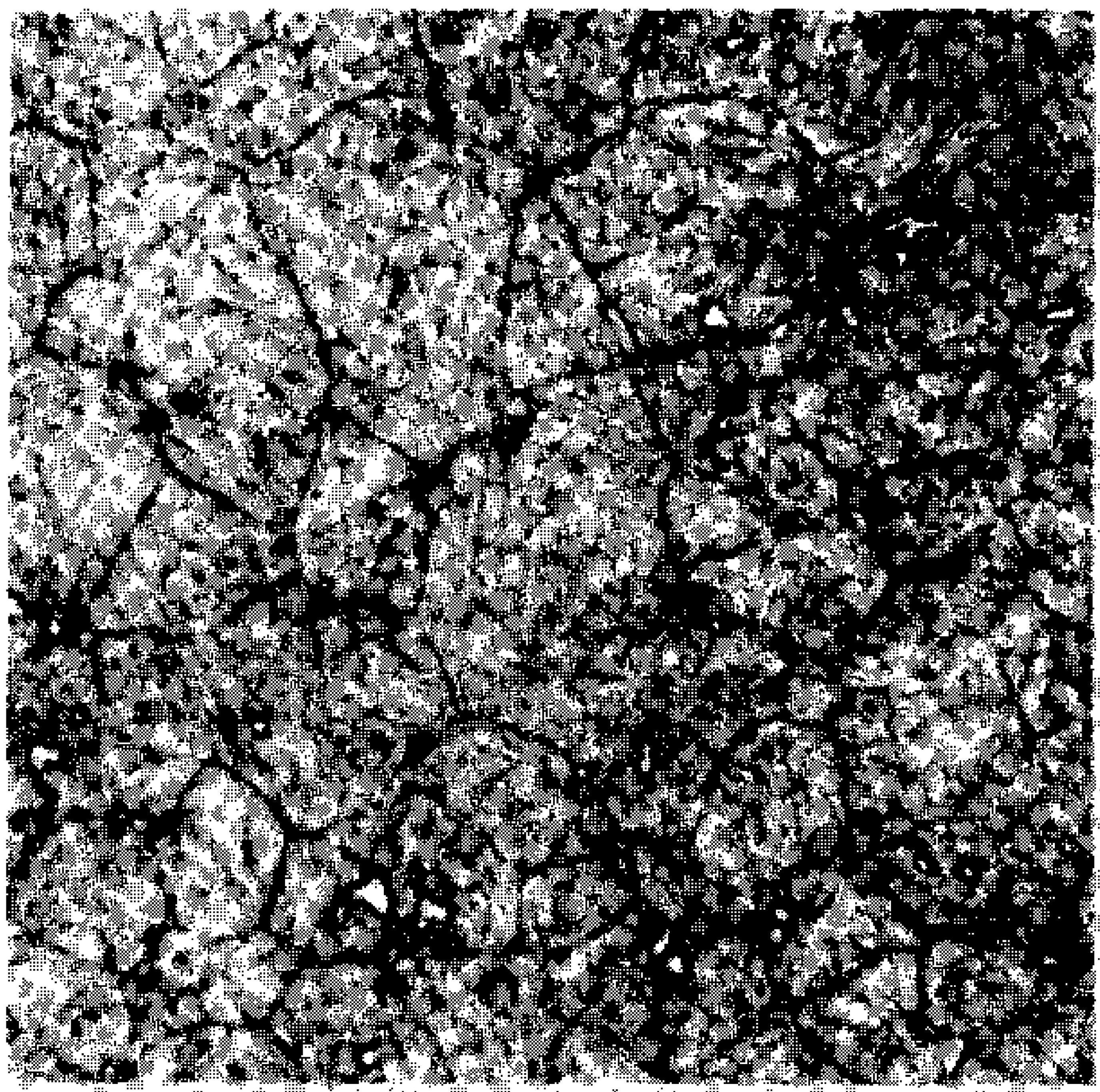


Fig. 84 M50, austenitized 2100 F, 20 min., oil quench, tempered 1050 F, 2 plus 2 hours.

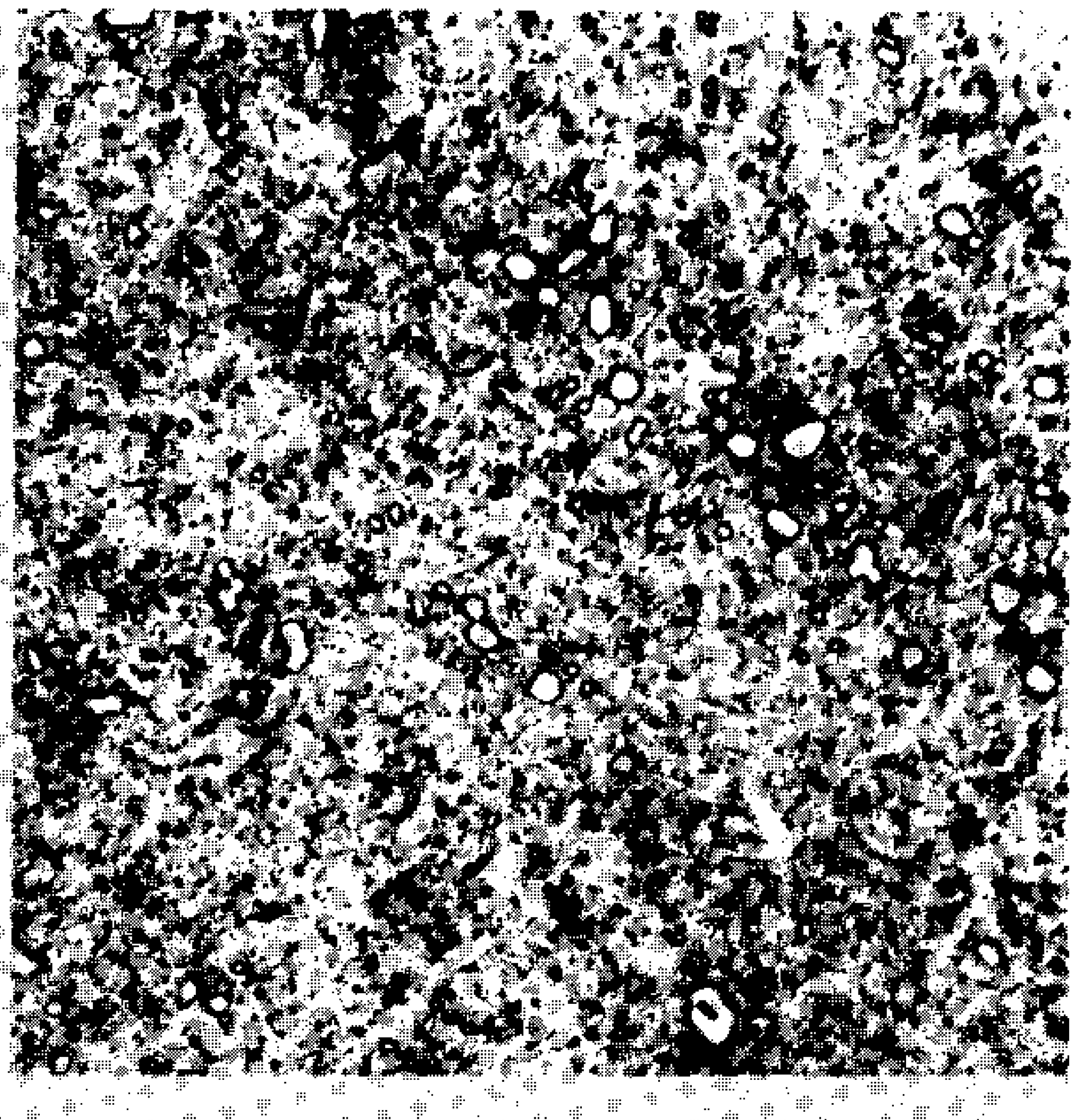


Fig. 85 UC, austenitized 1950 F, 45 min., oil quench, tempered 1000 F, 2 plus 2 hours.

FIGURES 84 and 85 MICROSTRUCTURES SHOWING CARBIDE SIZE AND DISTRIBUTION IN BEARING STEELS.

Picral + 0.2% HCl Etch Magnification X 750

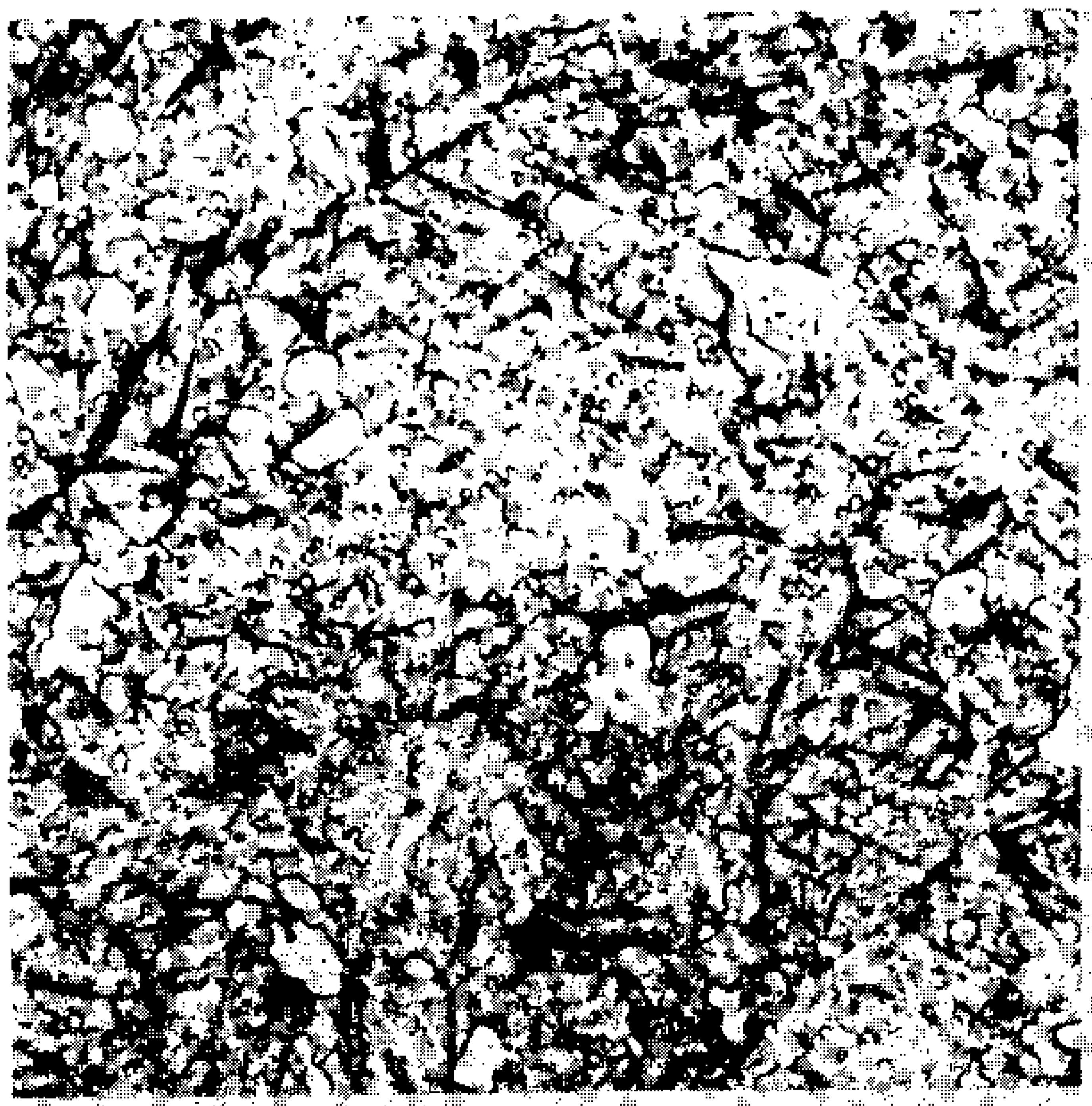


Fig. 86 Steel-A, austenitized 2000 F, 30 min. oil quench, tempered 1000 F 2 plus 2 hours. Alcoholic 10% HCl Etch

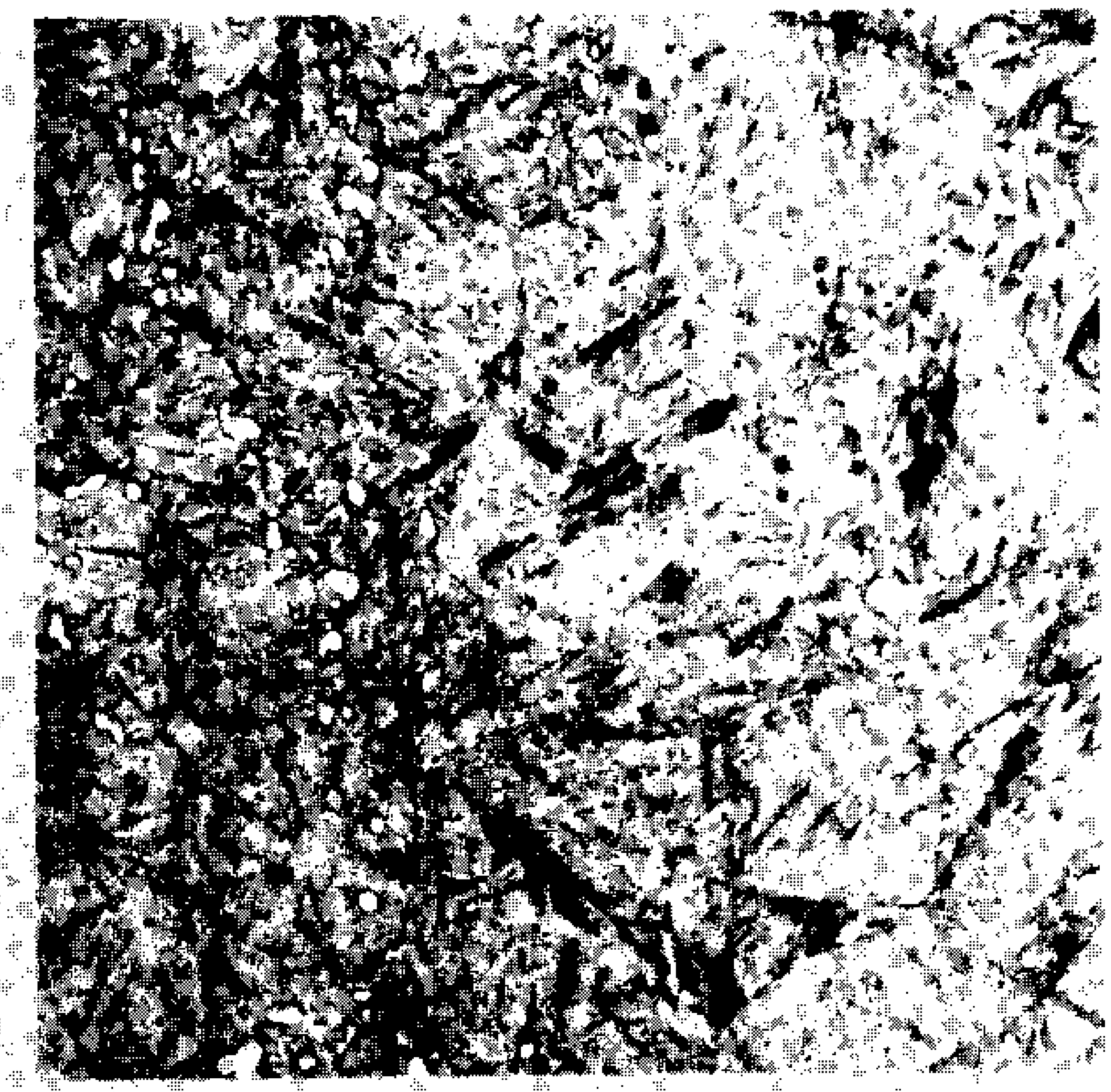


Fig. 87 Steel-B, austenitized 2150 F, 15 min. oil quench, tempered 1000 F 2 plus 2 hours. Alcoholic 10% HCl Etch

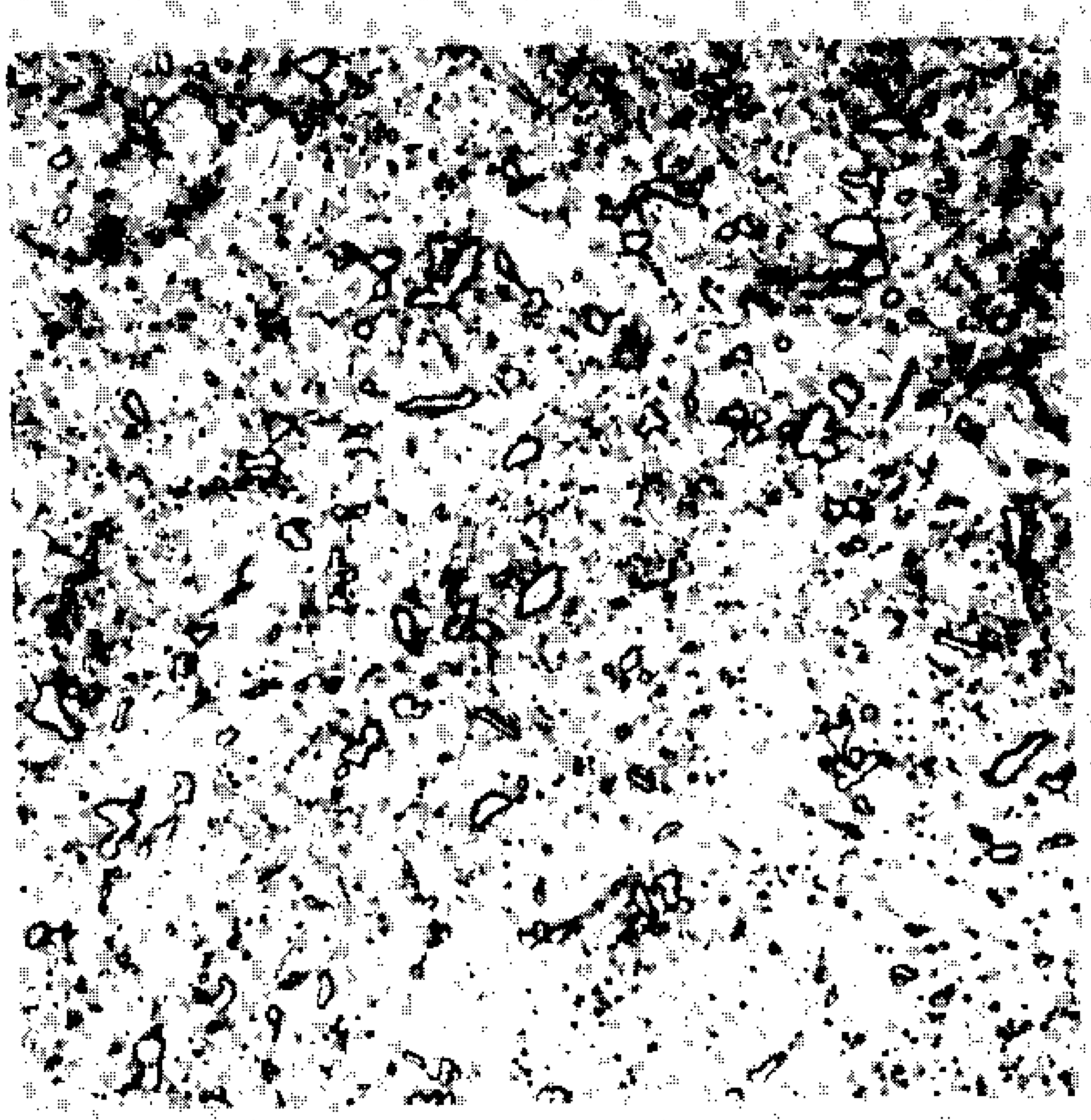


Fig. 88 Steel C, austenitized 2100 F, 20 min. oil quench, tempered 1000 F 2 plus 2 hours. Alcoholic 10% HCl Etch

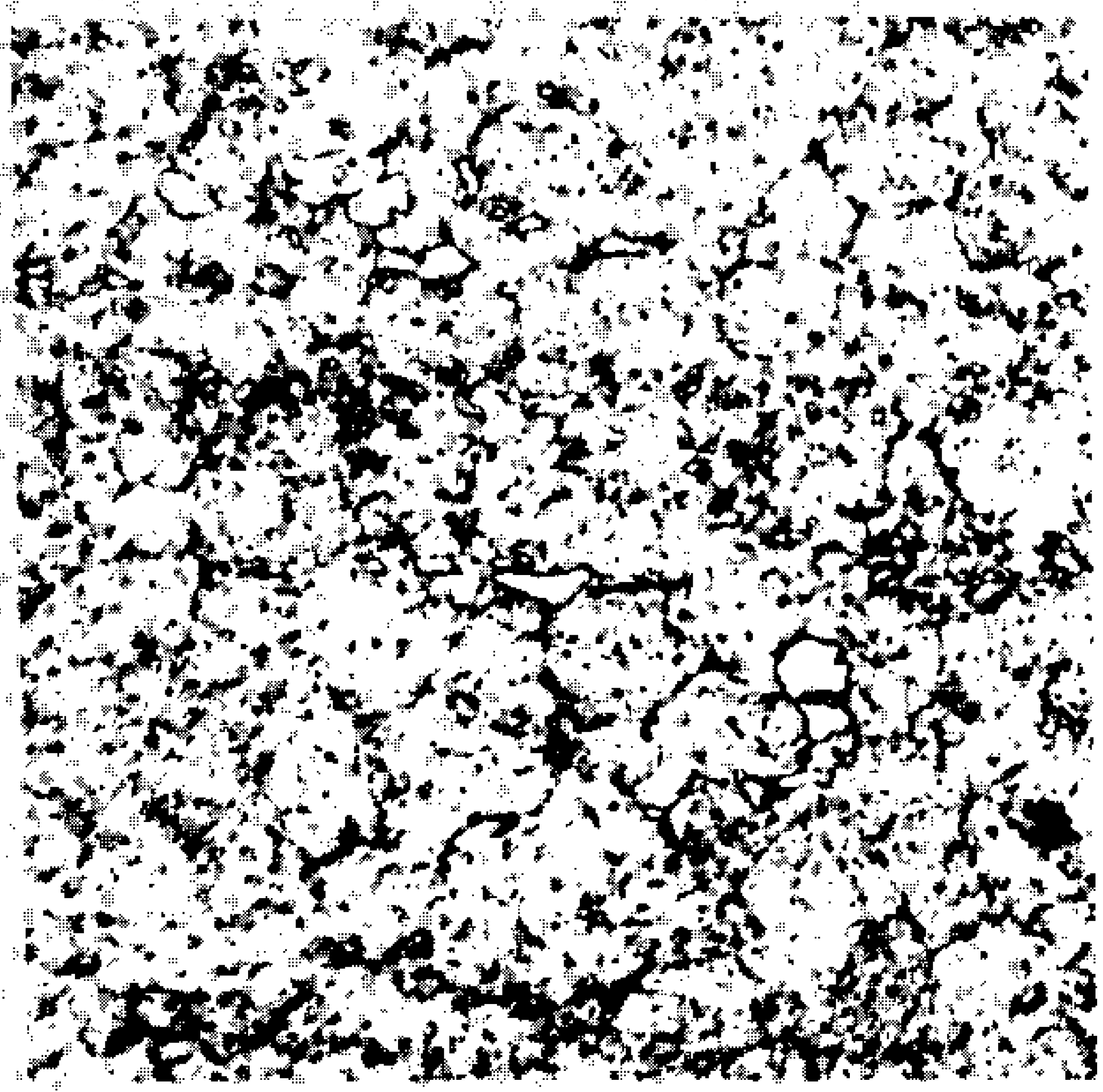


Fig. 89 Steel-D, austenitized 2200 F, 15 min. oil quench, tempered 1000 F 2 plus 2 hours. Picral Etch

FIGURES 86 to 89 MICROSTRUCTURES SHOWING CARBIDE SIZE AND DISTRIBUTION IN BEARING STEELS.

Magnification X 750

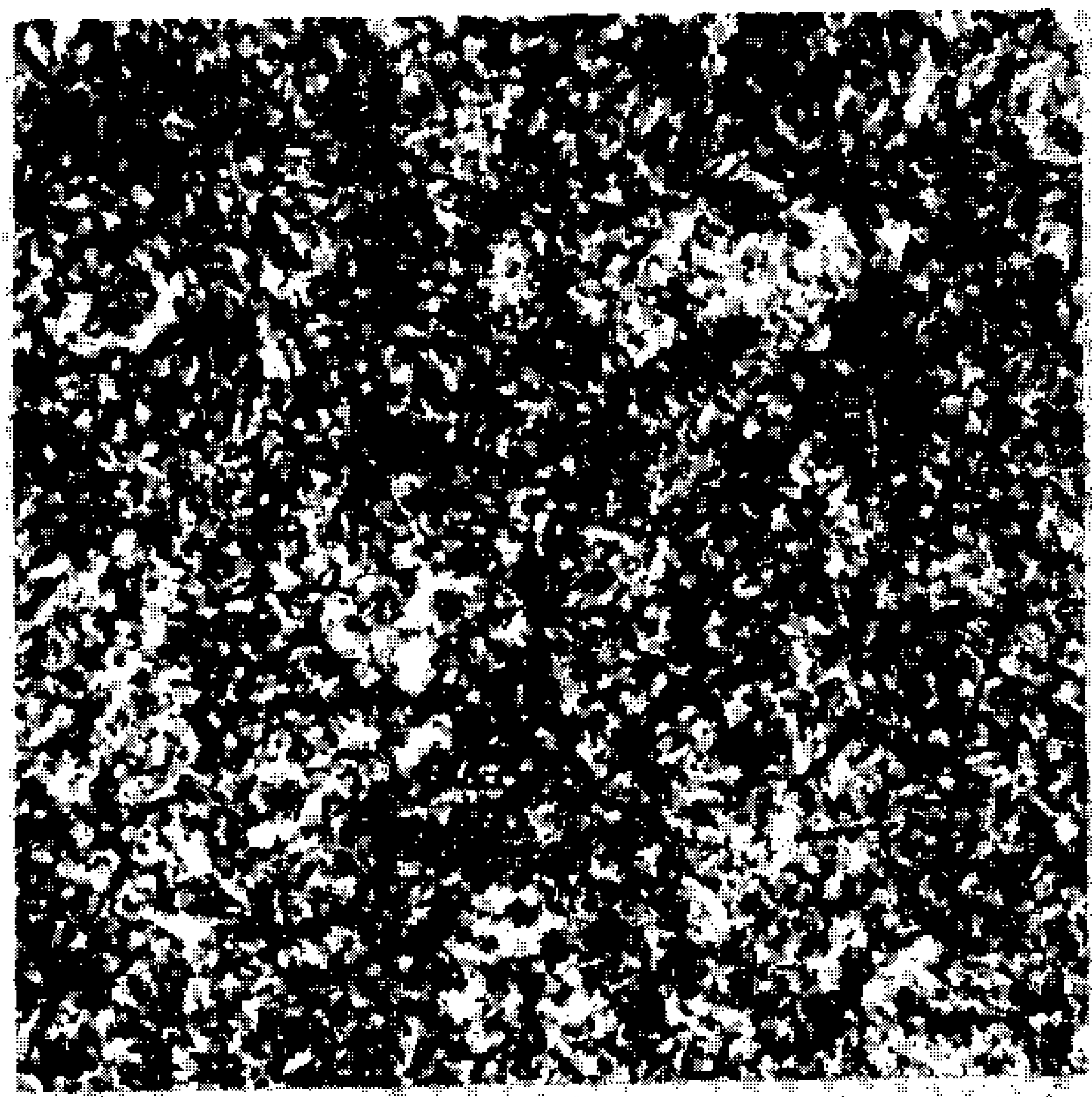


Fig. 90 Steel-E, austenitized 2100 F, 20 min. oil quench, tempered 1000 F, 2 plus 2 hours.

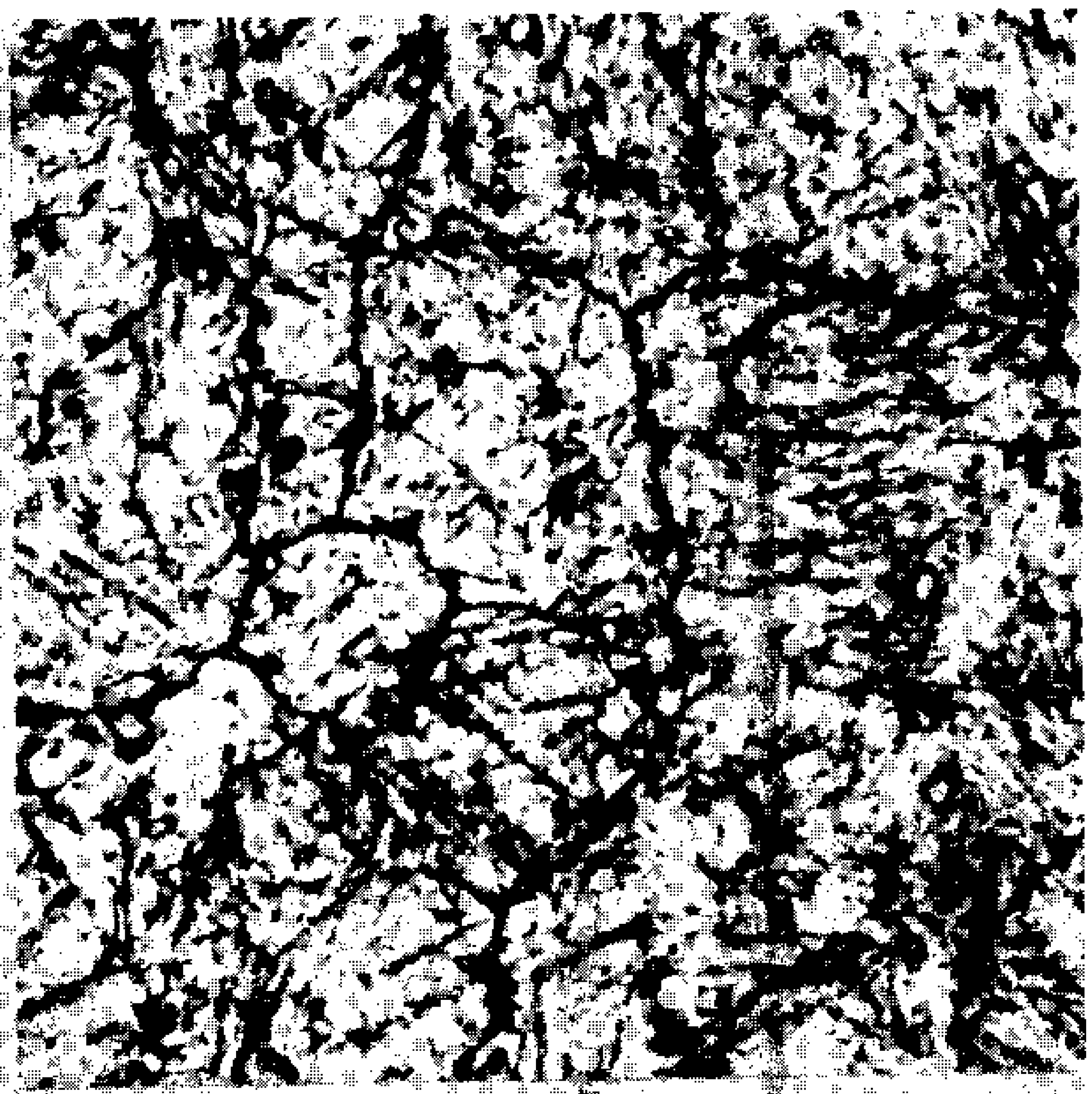


Fig. 91 Steel-F, austenitized 2200 F, 15 min. oil quench, tempered 1000 F, 2 plus 2 hours

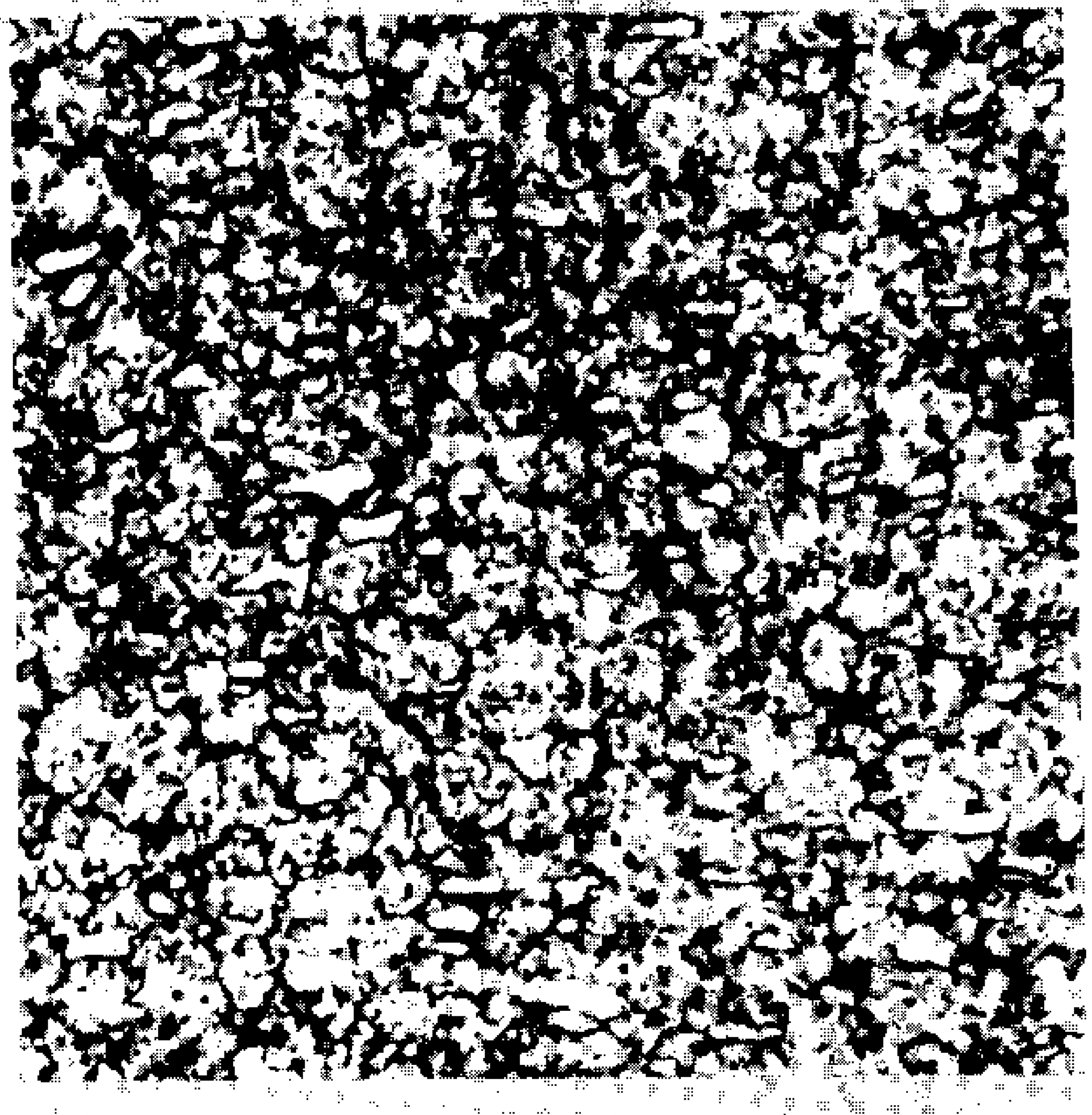


Fig. 92 Steel-G, austenitized 2200 F, 15 min., oil quench, tempered 1000 F, 2 plus 2 hours.

FIGURES 90 to 92 MICROSTRUCTURES SHOWING CARBIDE SIZE AND DISTRIBUTION IN BEARING STEELS.

Picral + 0.3% HCl Etch Magnification X 750

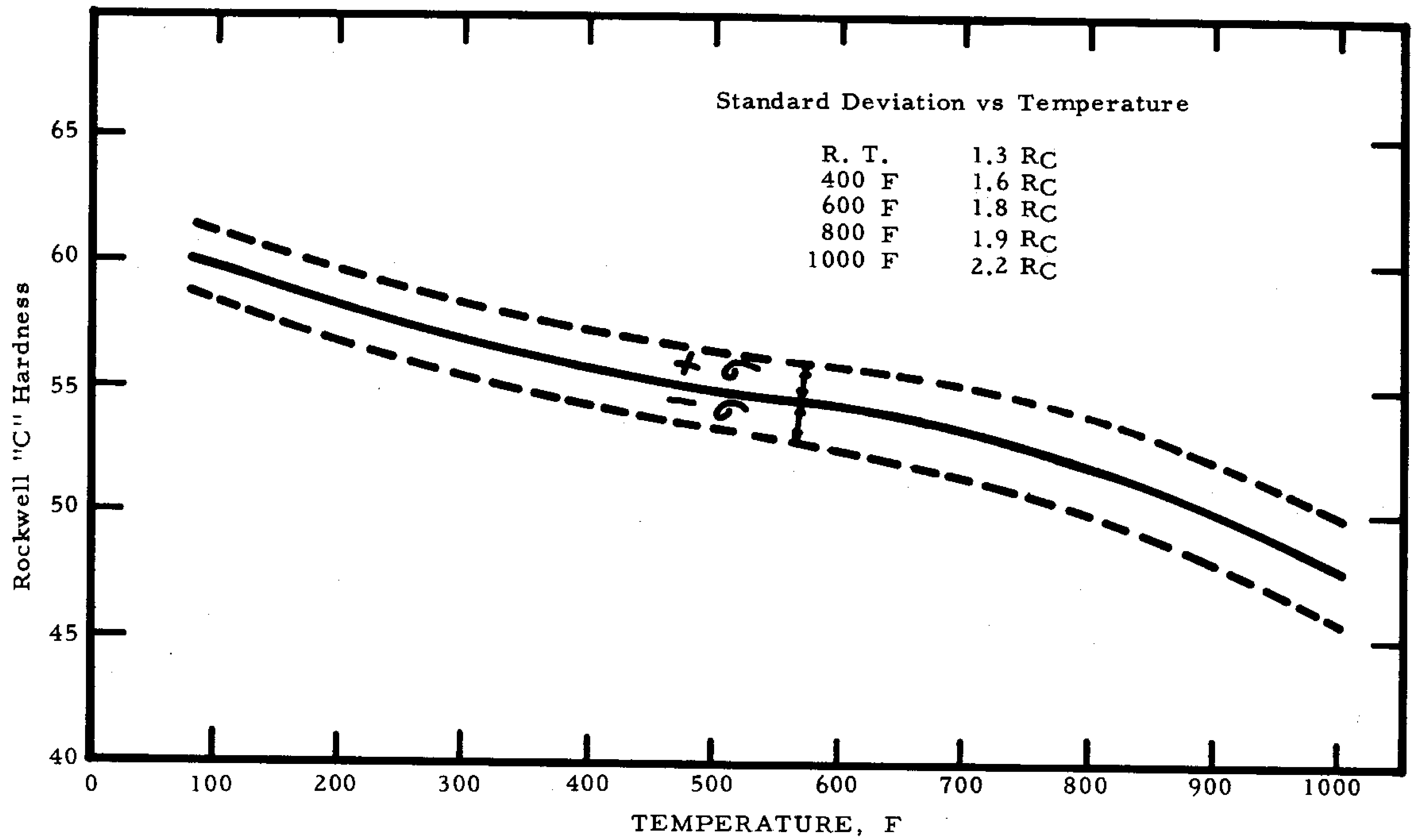


FIGURE 93. A CURVE SHOWING THE MEAN HARDNESS VALUES AND THE STANDARD DEVIATIONS FROM THE MEAN COMPUTED FOR 22 BEARING STEELS AT TEMPERATURES VARYING FROM ROOM TEMPERATURE TO 1000 F.