THE EFFECT OF MARTEMPERING ON THE ENDURANCE LIMITS OF TWO ALLOY MACHINE STEELS

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By

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INTRODUCTION

The process called martempering was developed by B. F. Shepherd and was described in the metallurgical literature for the first time early in 1943.[1] Fundamentally the treatment is an interrupted quenching procedure applied to the hardening of steels. As described by Shepherd, the first stage of the treatment is identical with normal steel hardening practice. The material is heated to some suitable temperature above the upper critical and held at this temperature long enough to permit a reasonably complete and uniform austenitic structure to form. Where common practice consists of quenching from the austenitizing temperature directly into a cooling medium at approximately room temperature, martempering requires that the steel be cooled in two distinct steps. The first step in the cooling procedure for martempering consists of quenching the steel into some medium (usually molten salt) which is maintained at a temperature slightly above that at which martensite begins to form (the so-called M_s temperature.) The steel is held in this quenching medium until the temperature is approximately uniform throughout the entire mass of the piece (usually five minutes per inch

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[1] Shepherd, B. F., Martempering, Iron Age, Jan. 28, 1943, pp 50-52, Feb. 4, 1943, pp 45-48.

of section.)[2] The formation of martensite is then permitted to take place by removing the piece and allowing it to cool in any convenient manner to room temperature. The usual procedure is to cool the piece slowly in air.

In the past, the term martempering was used in connection with interrupted quenching procedures for which the quenching medium is held at about 400°F with no regard for whether this was below the M_s temperature. This was followed by holding and cooling as previously described. At this time the term martempering is generally accepted to imply cooling quickly to the M_s temperature, holding until a uniform temperature is attained, then cooling to room temperature to form martensite. However, practical considerations in cooling the steel and the present state of our knowledge of the temperatures at which the austenite to martensite reaction is initiated are such that a great many of the practical heat treatment procedures described as martempering processes probably involve quenching into a medium being held at a temperature somewhat below the true M_s temperature.[3]

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2. Three Keys to Satisfaction, Climax Molybdenum Co.
3. An examination of isothermal transformation diagrams for an SAE 4140 steel appearing in Republic Steel Corporation's "Atlas of Isothermal Transformation Diagrams" and in Climax Molybdenum Company's book "Molybdenum Steels Iron Alloys" revealed that the diagrams are not in agreement. That indicates that our knowledge of M_s temperatures is probably not reliable. And in addition to that fact, it is known that the austenitizing temperature chemical composition, prior austenite grain size and homogeneity, undissolved carbides and nonmetallic inclusions all exert an influence on the transformation temperatures.

It is a fortunate circumstance that the percentage of transformation that occurs after cooling below the M_s temperature is usually small for the first rather large increments of temperature drop.[4,5] Indications are that comparable advantages are realized from the procedure regardless of whether the quenching medium is slightly above or below the M_s temperature.

The one attractive advantage claimed by Shepherd for martempering over the customary steel hardening technique was an appreciable improvement in the dimensional stability of the part being hardened. So many investigators have verified Shepherd's claim that it is accepted as fact.

THEORY OF MARTEMPERING

The explanation of the reduction in warping and quench cracking that is realized by using the martempering treatment lies in the time relations between the formation of martensite in the center and outside portions of the piece. Figures 1 and 2 illustrate these relations for martempering and normal quenching practice. By quenching steel directly into some medium at room temperature, a large temperature gradient exists across the section of the piece

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4. Boyer, Howard E., The Interrupted Quench and Its Practical Aspects, ASM Transactions, 1947, Vol. 38, p. 209.
5. Archer, R. S., Briggs, J. Z., and Loeb, C. M., Jr., Molybdenum Steels Irons Alloys, New York, Climax Molybdenum Company, 1948, pp 19-34.

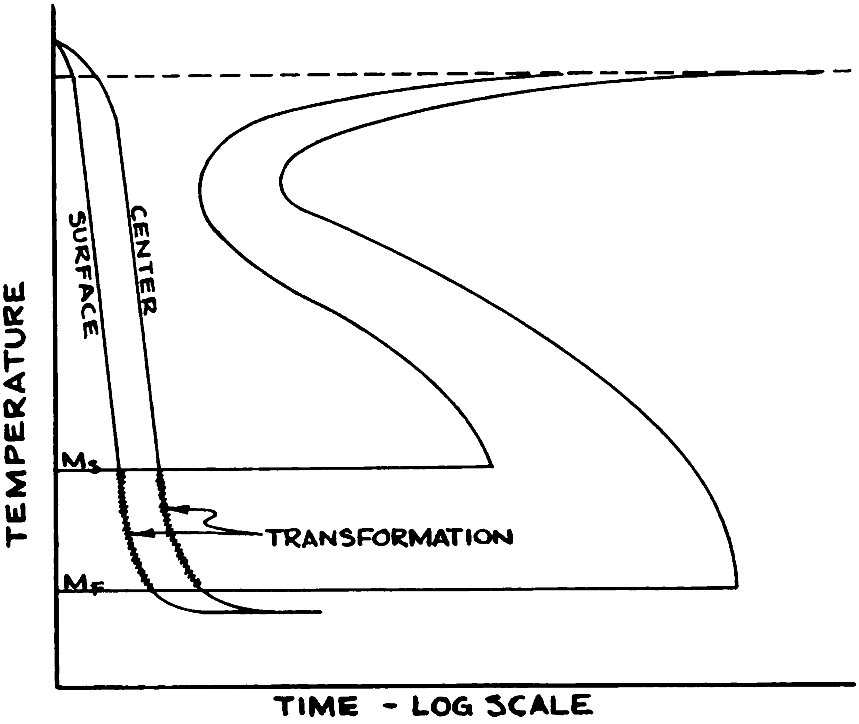

FIGURE 1. Schematic Representation of Transformation for Normal Hardening Practice.

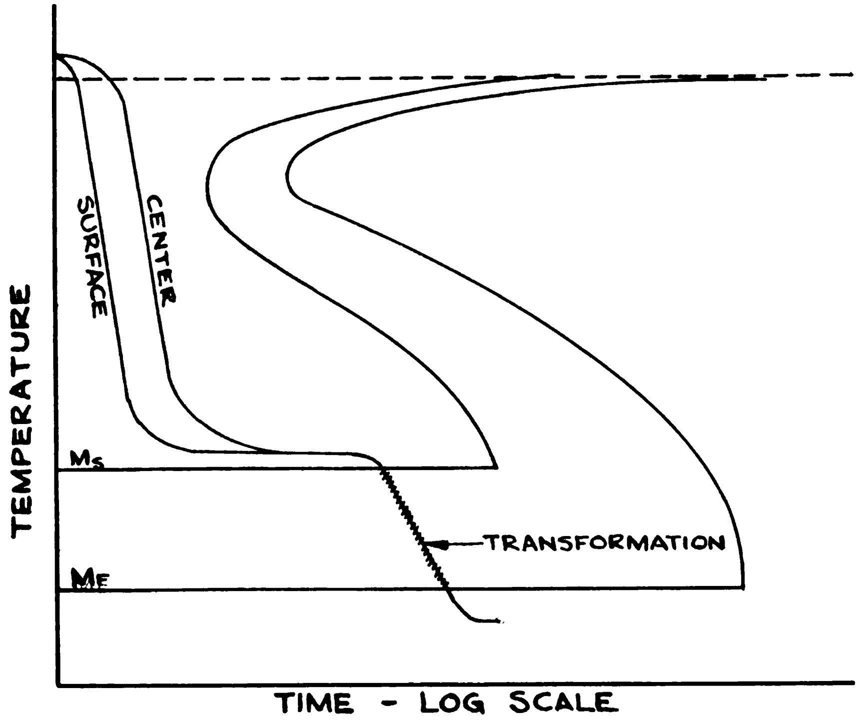

FIGURE 2. Schematic Representation of Transformation for Martempering.

during the entire cooling period. As a result of this temperature gradient, martensite does not form simultaneously throughout the piece, but forms at different times depending on its location. Since the outer layers of material have the more rapid cooling rate, martensite forms there while the core is still austenitic. In most cases the difference in cooling rates between the inner and outer fibers is so great that virtually complete transformation of the outer fibers to martensite has occurred before the inner fibers have cooled to the M_s. Thus, an extremely hard shell of martensite locks in the untransformed austenite at the core.

Accompanying the austenite to martensite reaction is a decrease in the density of the transformation product. Since austenite is somewhat plastic, it cushions the shock of transformation and helps to avoid the building up of high internal stresses. However, after the first stages of transformation in the conventional quenching procedure a condition is reached such that all of the remaining austenite is located in the core of the piece. When this core of austenite cools below the M_s temperature, it attempts to expand as transformation occurs. But the hard, confining shell of martensite does not readily yield plastically and extremely high internal stresses are created within the material. Unfortunately, the resulting stresses on the outer fibers are tensile in sense[6] and are manifested by warpage and quench cracking.

In the martempering process the cooling proceeds rapidly at first with great disparity between interior and surface temperatures. But the coolant is at some temperature above the M_s; consequently, the cooling process is arrested long enough to permit the temperature to become equalized throughout the mass before any martensite forms. Subsequent cooling is such that only a very small temperature differential exists between inner and outer fibers. Therefore, the formation of martensite occurs throughout the entire piece at virtually the same rate. By avoiding the formation of a non-yielding martensitic shell on the outside of the piece, expansion of the steel upon transformation is less restricted. The unconfined matrix of austenite is relatively plastic and cushions the transformation resulting in a lower intensity of internal stress and avoidance of warping and cracking.

There are certain disadvantages attendant upon the use of the martempering treatment. All other things being equal, you cannot obtain through martensitic hardness in as large a bar by martempering as you can by oil or water quenching because of the relative slowness of

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6. Compressive stresses in the outer fibers could prove beneficial to fatigue strength. Shot peening, rolling, pressing an d tumbling are used to obtain superior fatigue properties by inducing such beneficial surface compressive stresses.

cooling rate in a hot bath. This disadvantage may become even more pronounced in the future in view of the fact that new data on M_s temperatures places them at higher temperatures than previous data. In addition, a more closely controlled heat treating procedure requiring more expensive equipment and a more precise knowledge of the properties of the steel being treated are required than for the conventional hardening practice, However, in many applications, these disadvantages are outweighed by the prospect of lower spoilage and less finish machining. And the literature gives hints of other advantages not fully exploited at this time.

PURPOSE AND SCOPE OF INVESTIGATION

The manifold uses of metals for applications where high operating speeds and low weight are requisites have focused attention on their fatigue properties. Many investigations have been made and volumes have been written about the nature and causes of fatigue failures so that designers can now utilize this hard-won knowledge to predict and avoid fatigue failures in service.

It has been conclusively shown that the underlying cause of all fatigue failures is a highly unfavorable local stress condition which produces a minute rupture.[7]

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[7] Battelle Staff, Prevention of The Failure of Metals Under Repeated Stress, New York, John Wiley & Sons, Inc., 1941.

This first tiny fracture acts as stress raiser to further propogate the rupture with each application of the load. Ultimately, the rupture will have spread, in the form of a crack, to such an extent that the portion of the piece still intact will be unable to support the load and gross failure occurs. Notches, scratches, abrupt changes in section tend to reduce the nominal stress at which this type of failure occurs, because high local stresses accompany them. Where favorable stresses are induced and stress raisers avoided an improved fatigue resistance results. These facts logically lead to the conclusion that if two materials are alike in every respect except that one is martempered and the other quenched and tempered, the martempered specimen will exhibit superior fatigue properties by virtue of having a less unfavorable distribution of residual stresses.

The first work substantiating the premise that martempering gave improved fatigue strength over the normal quenching procedure appeared in 1948.[8] Forsythe and Carreker presented data on an SAE 1095 steel showing an improvement in endurance limit of over twenty-five percent resulting from martempering. These data demonstrated conclusively that martempering does enhance fatigue properties. But in view of the fact that SAE 1095 is extremely sensitive to quench cracking and that

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[8] Forsythe, A. C. and Carreker, R. A., <u>Fatigue Limit of S.A.E. 1095 After Various Heat Treatments</u>, Metal Progress, November, 1948, pp. 683-685.

Forsythe and Carreker used a low draw temperature in their experiments, much doubt remained as to whether the improvement achieved would be appreciable for steels drawn to lower hardness values. It was felt that data on some alloy machine steels drawn at higher temperatures would be more significant.

For this study SAE 4140 and SAE 6140 were selected. The basis for choosing these was that both were on hand, and that they enjoyed reasonably wide popularity in applications where medium high strength and ductility were required. Information on these steels revealed them to have been used in the oil quenched and tempered condition for a great variety of applications where the tensile strengths were in the range 100,000 to 200,000 PSI.[9]

It was decided that the steels used would be drawn to a hardness of about Rockwell 35C. This would result in a tensile strength well within the range of strengths commonly used. It was anticipated that the improvement in fatigue strength resulting from martempering in this study would be smaller than in Forsythe's and Carreker's study for two reasons:

1. The higher draw temperature would effect a greater relief of the residual stresses, and
2. The comparison would be made with an oil quenched steel instead of a water quenched steel.

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[9] U.S.S. Carriloy Steels Alloy Steels for the Special Jobs of Industry, Carnegie-Illinois Steel Co., Pittsburgh and Chicago, 1948.

To determine whether the magnitude of the improvement at a low hardness level gave promise of making the more costly martempering treatment economically attractive was the objective of this work.

PREPARATION OF SPECIMENS

The SAE 4140 and SAE 6140 steels were obtained in the form of one-half inch round hot rolled bar stock. All specimens of like material were machined from the same bar. The specimens were machined all over before the heat treatment, but the tapered ends were left oversize to permit a post tempering finish grind. After heat treatment the test sections of the specimens were polished in successive stages using graded abrasives through a 00 paper. The final polish was longitudinal using a soft cloth dipped in oil and a 600 grade aluminum oxide abrasive powder. This series of polishing operations removed about three-thousandths of an inch from the diameter of the test section. It is held that not only the scratches due to machining, but that any cracks and sore spots in the surface layers of material that might have resulted from the action of the quenching medium were removed by the polishing. The taper ends were then ground between centers using a tool post grinder so that the final form of the specimens was that illustrated in Figure 3.

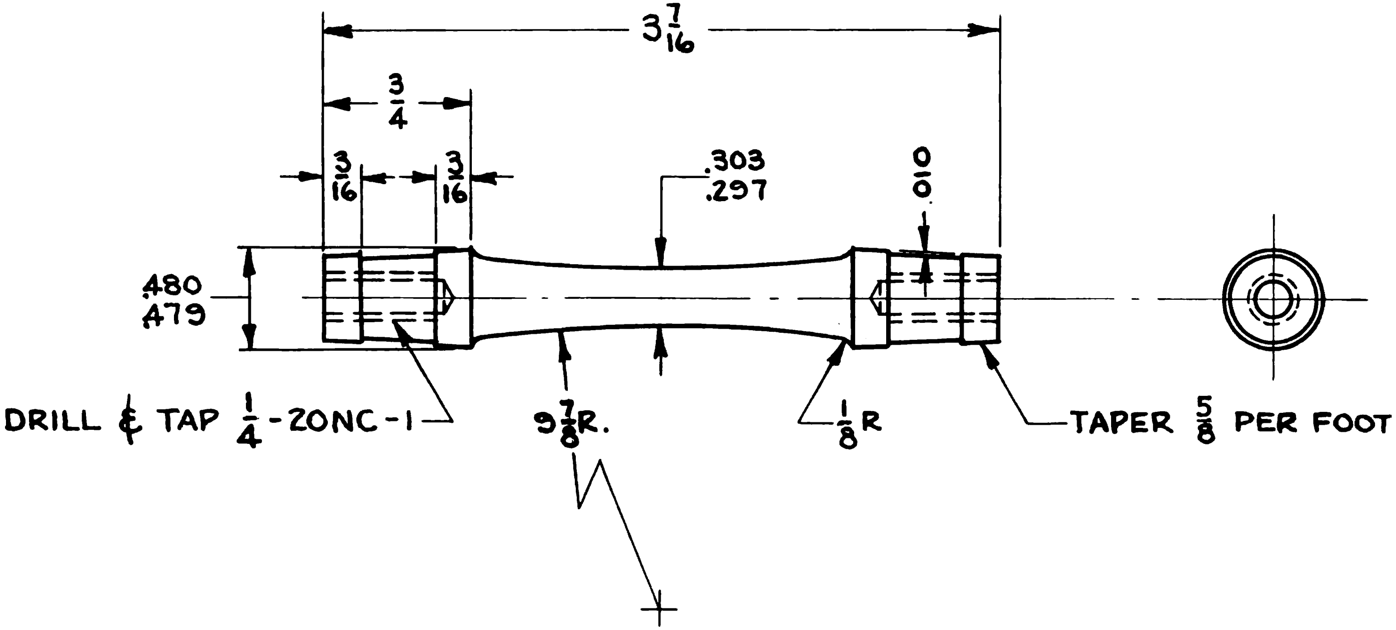

FIGURE 3 R.R. MOORE FATIGUE SPECIMEN

HEAT TREATMENT

A quenching fixture like that shown in Figure 4 was used for mounting all specimens. Its use made it possible to quench all specimens simultaneously and to minimize distortion by holding them vertical during their entry into the quenching bath.

A Leeds and Northrup, 15 KW, Vapo-Carb furnace was used for austenitizing all specimens. The furnace was permitted to come up to 1100°F at which time the specimens were inserted. Upon placing the specimens in the furnace the flow of cracked hydro-carbon fluid through the furnace was adjusted to produce an atmosphere previously established as being inert with respect to the steel being used. One hour was required for the furnace to come to the austenitizing temperature of 1575°F. Following a one hour soaking period, half of the specimens were quenched in oil. At the same time the remaining half of the specimens were cooled in a Hoskins electric salt pot being maintained at a temperature of 500°F. During cooling, the specimens were vigorously agitated in the cooling medium. The oil quenched specimens were permitted to cool to room temperature in the oil. The other specimens were held in the 500°F salt for one minute and then removed and cooled in air.

All specimens were drawn for one hour at approximately 1100°F in an electric Lindberg draw furnace to a hardness of about Rockwell 35C.

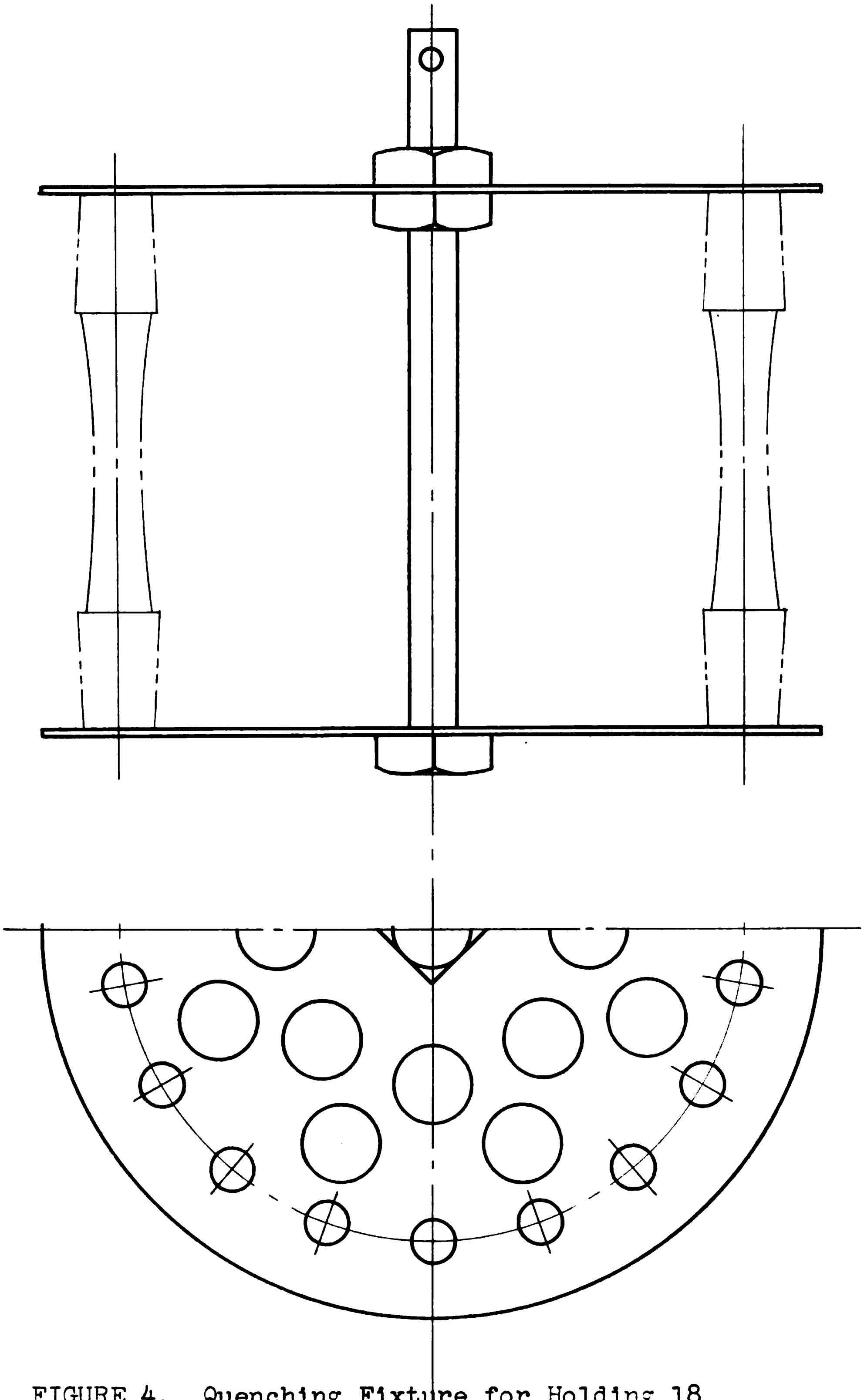

FIGURE 4. Quenching Fixture for Holding 18 Fatigue Specimens

After finishing the specimens as previously described, S-N curves were determined for each of the four groups of specimens.

TESTING PROCEDURE

A Baldwin-Southwark, R. R. Moore high speed rotating beam fatigue testing machine was used to test each specimen. This machine produced a uniform bending moment on the specimen while it rotated the specimen at a normal speed of 10,000 RPM. Because of variations in the supply line voltage, the speed of the machine was observed to vary between 9,000 RPM and 11,000 RPM during the progress of the tests. It is held that these speed variations were not sufficiently great to have materially affected the significance of the results obtained. Investigations by Oberg and Johnson,[10] Krouse,[11] and Roos, Lemmon, and Ransom[12] on the effect of speed in fatigue testing substantiate this point of view.

After each test the hardness and microstructure of each specimen were observed to insure uniformity. The

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[10] Oberg, T. T. and Johnson, J. B., Fatigue Properties of Metals Used in Aircraft Construction at 3450 and 10600 Cycles, Proc. Am.Soc.Test.Mat., 1937, Vol. 37, part II, pp 195-205.

[11] Krouse, G. H., A High Speed Fatigue Testing Machine and Some Tests of Speed Effect on Endurance Limit, Proc. Am.Soc.Test.Mat., 1934, Vol. 34, part II, pp 156-164.

[12] Roos, P. K., Lemmon, D. C., and Ransom, J. T., Influence of Type of Machine, Range of Speed, and Specimen Shape on Fatigue Test Data, Am. Soc. Test. Mat., Bulletin No. 158, May, 1949, pp 63-65.

average hardness values for each specimen are given in Table I. These represent the average of five hardness checks at selected points across the section of the piece. It was found that all pieces were hardened uniformly throughout and that all specimens within any one group exhibited an average hardness of within 1.5 Rockwell C of the average of the entire group. The maximum hardness variation observed for any one specimen was 2 Rockwell C. Examination of the microstructures revealed a uniform, tempered martensitic structure probably containing some tempered bainite. There was no evidence of carburization or decarburization during heat treatment. Figures 5 to 8 are typical of the final structures that were obtained.

DISCUSSION OF RESULTS

As was anticipated, the endurance limits of the SAE 4140 and SAE 6140 steels in the martempered and drawn condition were greater than the endurance limits of the same steels in the oil quenched condition when drawn to the same hardness. The increase in endurance limit, shown in Figures 9 and 10, was approximately 3% and 13% for the SAE 4140 and SAE 6140 steels respectively.

It may be argued that the difference in endurance limits found could be attributed to variations in hardness of the specimens, since all specimens in the groups

SAE 4140

Oil Quenched & Drawn		Martempered & Drawn	
Specimen Number	Rockwell C Hardness	Specimen Number	Rockwell C Hardness
4-1	35.0	4-11	35.0
4-2	35.0	4-12	34.5
4-3	34.5	4-13	36.0
4-4	34.5	4-14	36.0
4-5	34.5	4-15	36.0
4-6	35.5	4-16	35.5
4-7	35.0	4-17	35.0
4-8	34.5	4-18	35.5
Average	35.0	Average	35.5

SAE 6140

Oil Quenched & Drawn		Martempered & Drawn	
Specimen Number	Rockwell C Hardness	Specimen Number	Rockwell C Hardness
6-1	34.0	6-11	35.0
6-2	34.0	6-12	35.0
6-3	34.0	6-13	35.0
6-4	35.0	6-14	35.0
6-5	34.0	6-15	34.5
6-6	34.0	6-16	35.0
6-7	35.0	6-17	35.5
6-8	36.0	6-18	35.5
Average	34.5	Average	35.0

TABLE I: Final Hardness Values for Fatigue Specimens

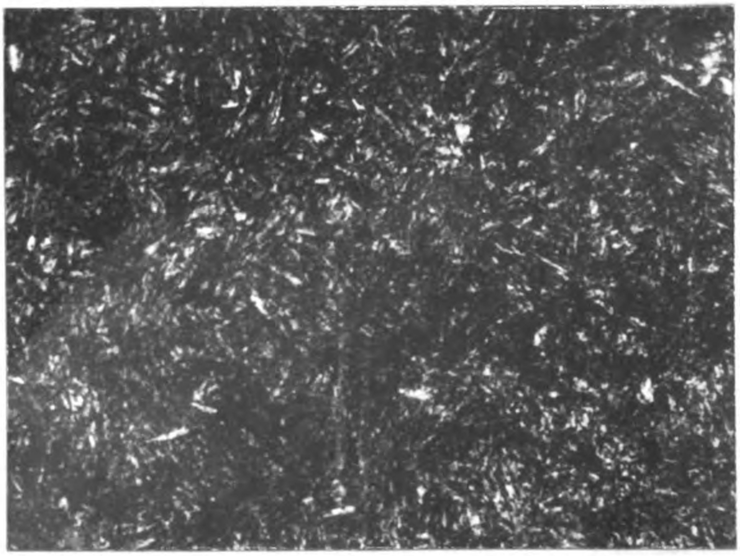
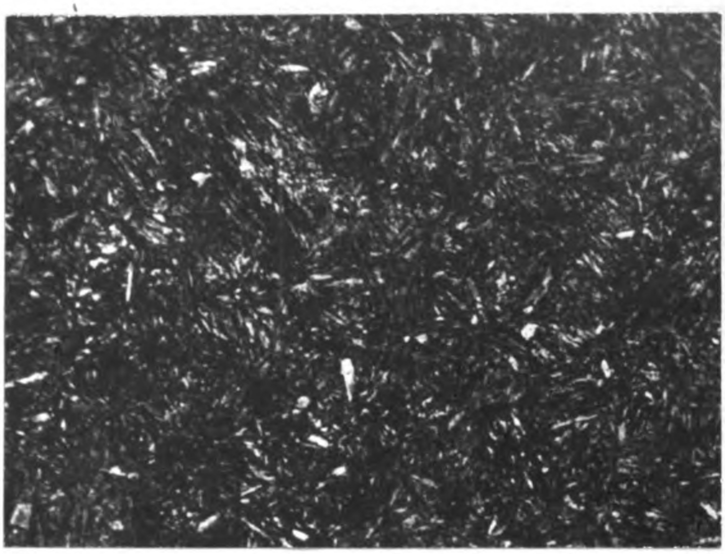


FIGURE 5. Microstructure of SAE 4140

Treatment: Oil quench and tempered

Hardness: Rockwell 35 C

Magnification: 500 X

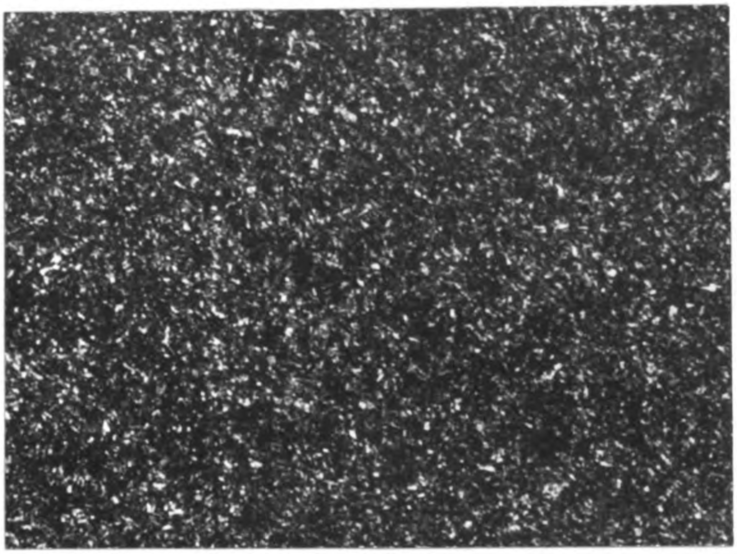


<u>FIGURE</u> 6. Microstructure of SAE 4140

<u>Treatment</u>: Quenched in salt at 500°F, held for one minute, air cooled, and tempered.

<u>Hardness</u>: Rockwell 35.5C

<u>Magnification</u>: 500 X



<u>FIGURE</u> 7. Microstructure of SAE 6140

<u>Treatment</u>: Oil quenched and tempered

<u>Hardness</u>: Rockwell 35 C

<u>Magnification</u>: 500 X

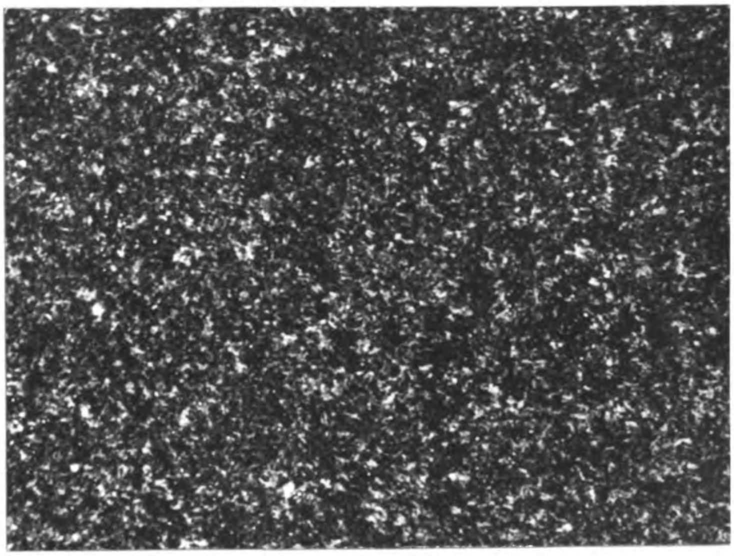
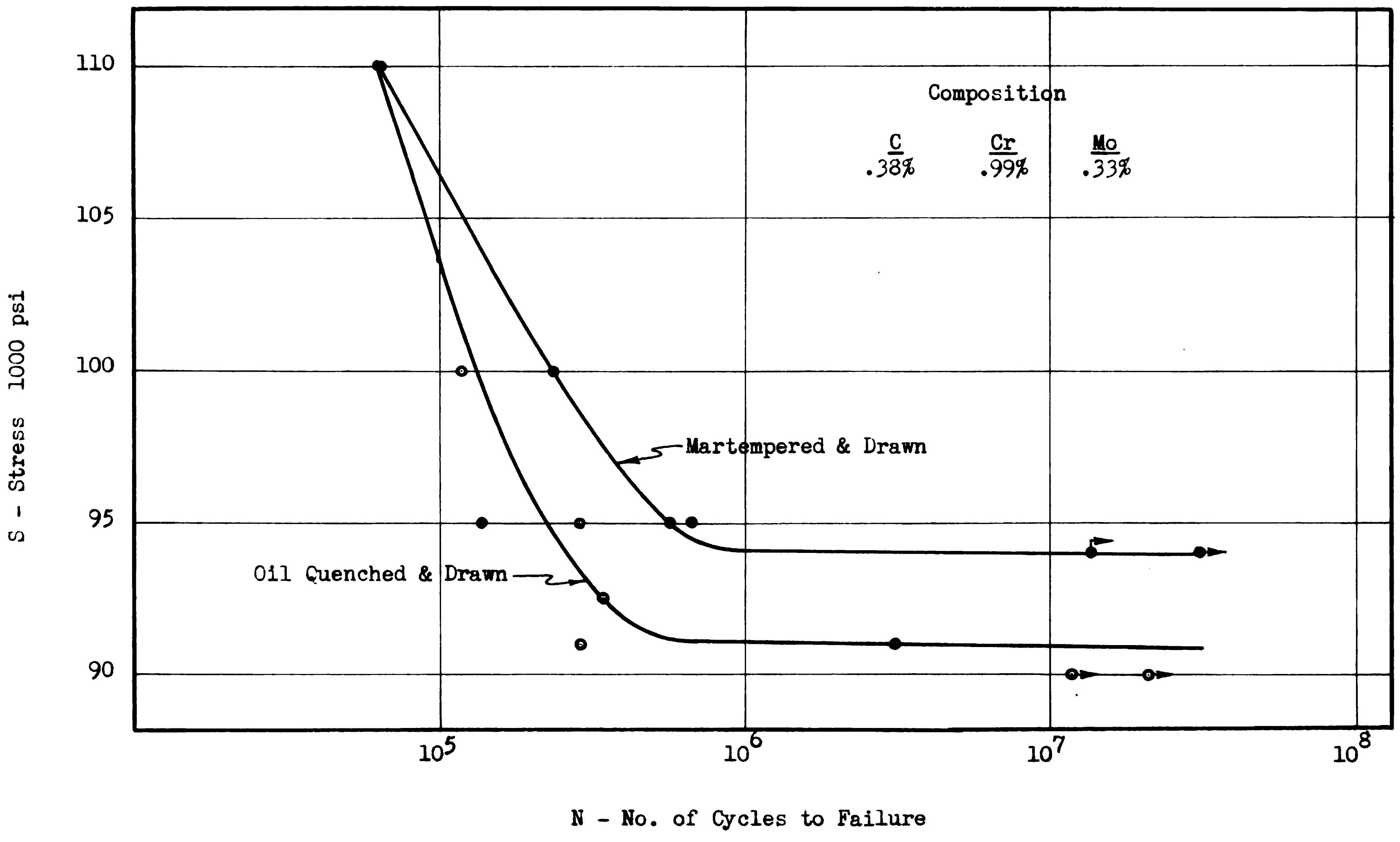


FIGURE 8. Microstructure of SAE 6140

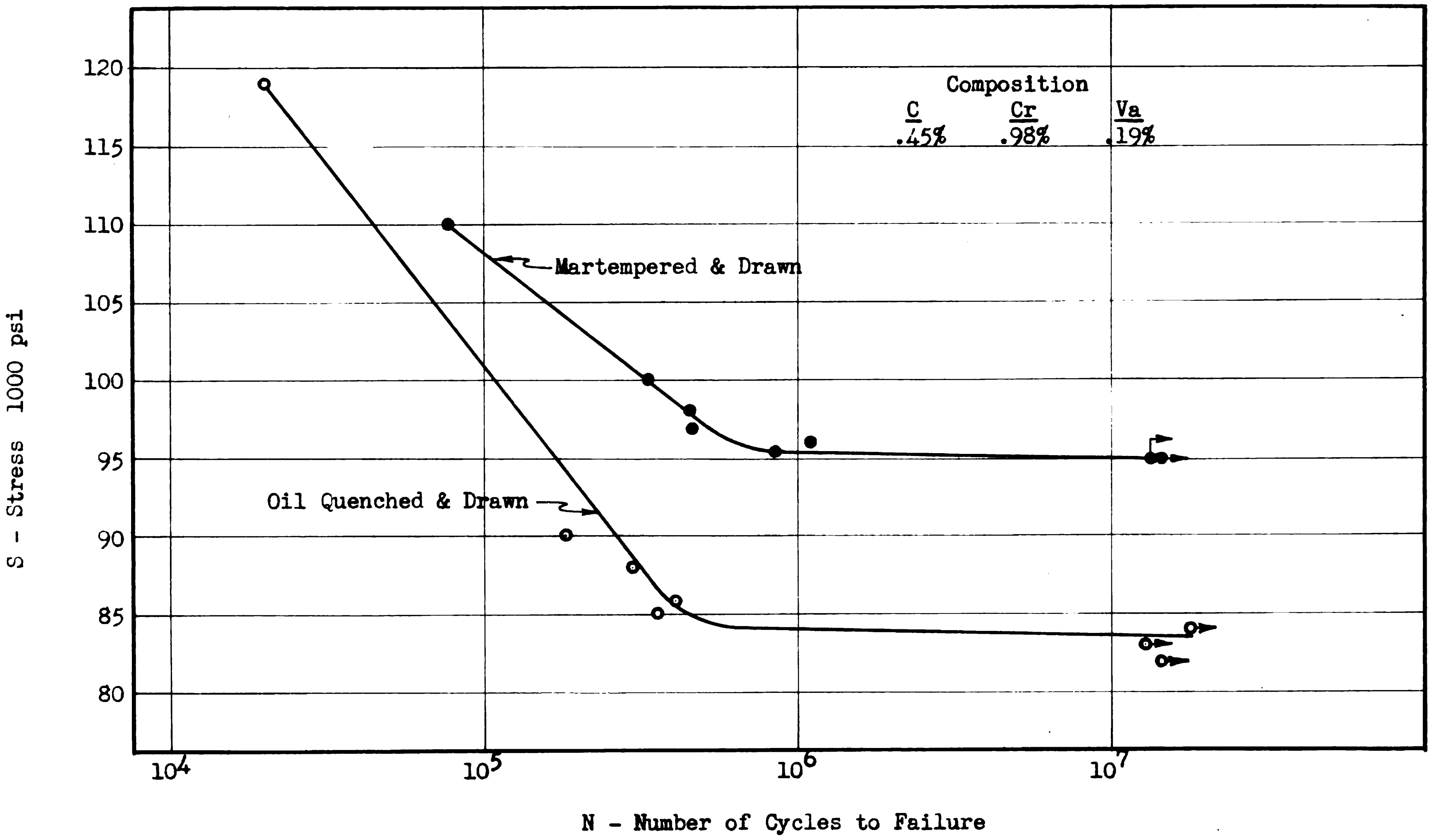
Treatment: Quenched in salt at 500°F, held for one minute, air cooled, and tempered.

Hardness: Rockwell 35 C

Magnification: 500 X



<u>FIGURE</u> 9 S-N Curves for SAE 4140 Hardened & Drawn to Hardness of Rockwell 35C



<u>FIGURE</u> 10 S-N Curves for SAE 6140 Hardened & Drawn to Hardness of Rockwell 35C

that were compared did not exhibit exactly the same hardnesses. However, in plotting the results the individual hardnesses were considered and the curves that seemed most representative in the light of this hardness data were drawn. Data found in Hoyt[13] and in a recent issue of the SAE Journal[14] attest to the probable correctness of these curves. In the former, the tensile strengths of SAE 4140 and SAE 6140, which have been oil quenched and drawn to a hardness of 35 Rockwell C are given as 176,000 PSI and 160,000 PSI respectively. Based on this data the endurance ratios of the oil quenched specimens were both approximately 0.52, which is consistent with generally accepted values of endurance ratio. In the latter reference, an S-N curve is shown for an SAE 4140 steel which had been oil quenched and drawn to a hardness of 35 Rockwell C. The endurance limit of 90,500 PSI compares very favorably with the endurance limit reported in this paper. In view of these facts and the fact that the results were consistent and reasonable, the improvements in fatigue strengths found can undoubtedly be attributed to the lower thermal and transformational stresses that resulted from the martempering treatment. However, it would seem that the improvements in fatigue strengths

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13. Hoyt, Samuel L., Metals and Alloys Data Book, Reinhold Publishing Corp., New York, 1943, p 77 and 87.
14. Boegehold, A. L., Selection of Steel for Automobile Parts, Part IV, SAE Journal, Nov. 1949, pp39-48.

would be more nearly alike percentagewise, since both types of steel were similarly treated to approximately the same final hardness. Some insight as to a possible explanation can be gained from the results of preliminary tests made on the steels.

A series of preliminary experiments was performed in an effort to determine the salt temperature and holding time that was to be used in martempering the materials employed. Cylindrical specimens one-half inch in diameter by one-half inch in height were used. Some were quenched in water, some in oil and some in molten salt. The salt quenched specimens were held for various times, ranging from a few seconds to five minutes, in molten salt at various temperatures, ranging from 700°F to 400°F, followed by cooling in air. Typical as quenched hardness values are shown in Table II.

It was evident from a scrutiny of these data of the microstructures, and of the isothermal transformation diagrams available for these materials that the selection of a salt temperature to be used for martempering was a compromise. The use of higher temperatures yielded low hardness values, indicating that a partial isothermal transformation of austenite to bainite had occurred in the salt bath. The use of lower salt temperatures to avoid the formation of bainite made it very likely that considerable transformation of austenite to martensite had occurred before a uniform temperature in the sample

SALT QUENCHED & AIR COOLED

Time in Salt	600°F SALT		500°F SALT		400°F SALT	
	SAE 4140	SAE 6140	SAE 4140	SAE 6140	SAE 4140	SAE 6140
2 Sec.	31C	32C	32C	34C	40C	40C
5 Sec.	37C	36C	46C	47C	48C	50C
15 Sec.	44C	45C	52C	54C	53C	56C
30 Sec.	51C	51C	53C	57C	53C	57C
1 Min.	46C	48C	52C	57C	53C	57C
2 Min.	47C	48C	52C	57C	53C	57C
3 Min.	47C	48C	52C	56C	53C	57C
5 Min.	48C	48C	51C	54C	53C	57C

WATER QUENCHED

SAE 4140 - 59C SAE 6140 - 61C

OIL QUENCHED

SAE 4140 - 55C SAE 6140 - 59C

TABLE II: As-quenched Rockwell Hardness of Preliminary Test Specimens For Various Treatments.

had been obtained. This was undesirable since it was the purpose of martempering to avoid such a condition. The other alternative was to use only a very short holding time in the salt bath. Unfortunately, it was found that even with the small specimens used, the cooling rate was not sufficiently great to avoid the knee of the S-curve unless a holding time of more than fifteen seconds was used. It was decided that the best compromise was a salt temperature of 500°F and a holding time of one minute. Typical as-hardened microstructures for the group of preliminary specimens quenched into 500°F salt are shown in Figures 11 through 18.

Evidence presented by Holloman, Jaffe, McCarthy and Morton[15] and by Forsyth and Carreker[16] indicated that tempered bainitic structures and mixed structures of tempered martensite and bainite exhibit lower endurance limits than does a tempered martensitic structure. It is evident from the microstructures and hardness values in Figures 11 through 18 that neither the oil quenching or martempering treatment employed produced a structure that was free of bainite. This suggests that a smaller proportion of bainite in the SAE 6140 than in the SAE 4140 might account for the disparity between relative

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15. Hollomen, J. H., Jaffe, L. D., McCarthy, D. E., and Morton, M. R., The Effects of Microstructure on The Mechanical Properties of Steel, ASM Preprint 25, 1947.
16. Forsyth, A. C. and Carreker, R. P., Fatigue Limit of SAE 1095 After Various Heat Treatments, Metal Progress, Nov., 1948, pp 683-685.

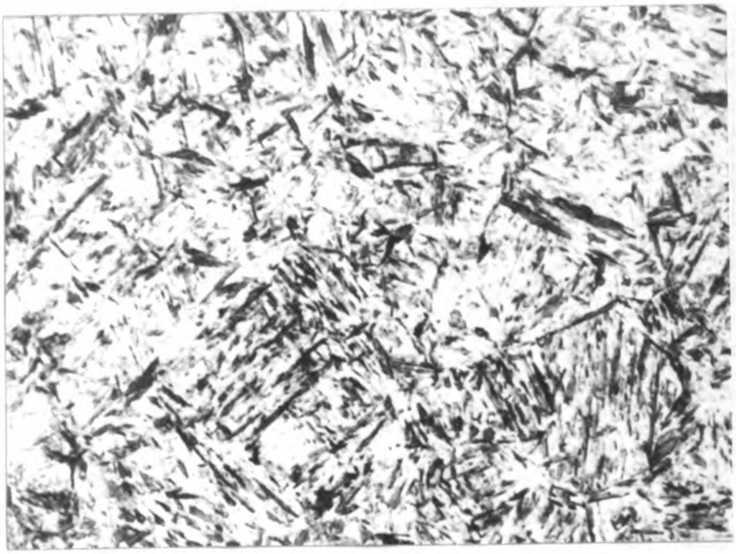

FIGURE 11. Microstructure of SAE 4140

Treatment: Water quenched from 1575°F

Hardness: Rockwell 59 C

Magnification: 500 X

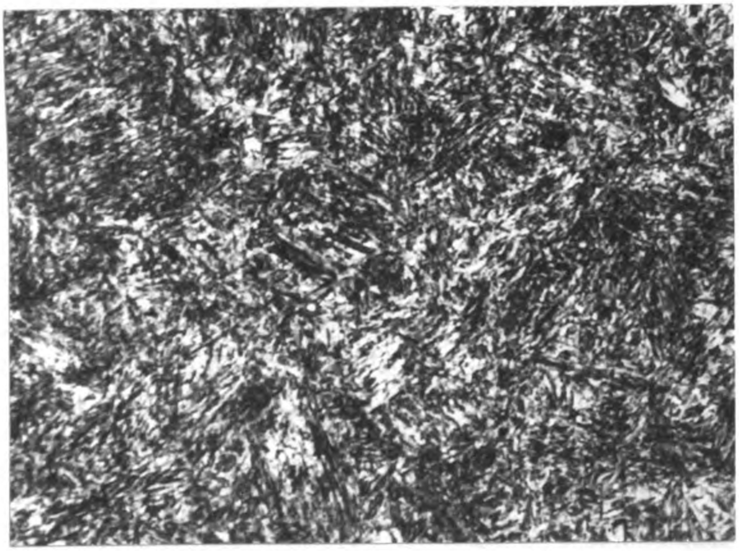

FIGURE 12. Microstructure of SAE 4140

Treatment: Oil quenched from 1575°F

Hardness: Rockwell 55 C

Magnification: 500 X

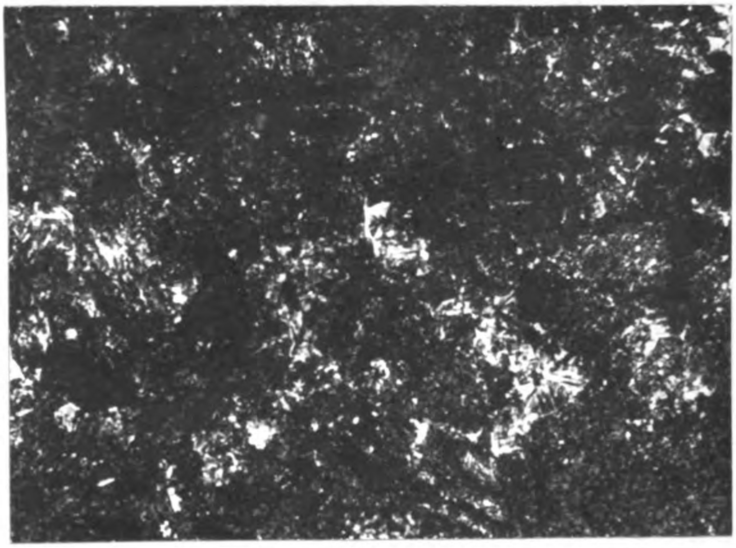

FIGURE 13. Microstructure of SAE 4140

Treatment: Quenched from 1575°F into salt at 500°F, held for two seconds, and cooled in still air.

Hardness: Rockwell 32 C

Magnification: 500 X

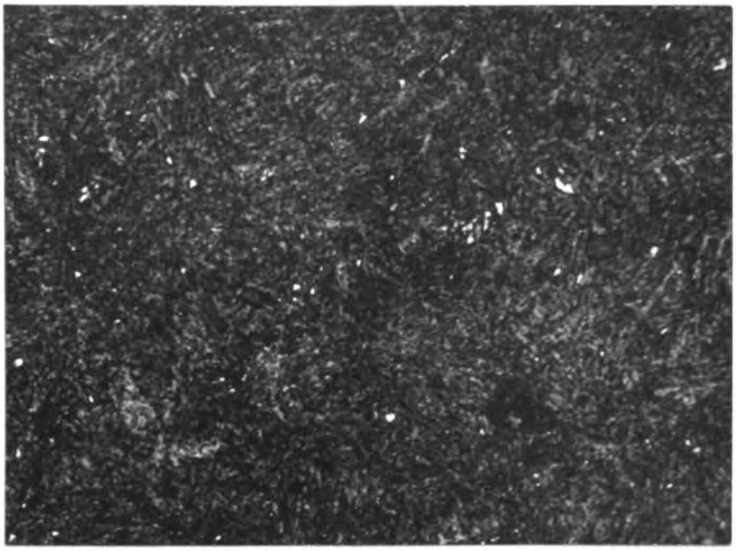

FIGURE 14. Microstructure of SAE 4140

Treatment: Quenched from 1575°F into salt at 500°F, held for five seconds and cooled in still air.

Hardness: Rockwell 46 C

Magnification: 500 X

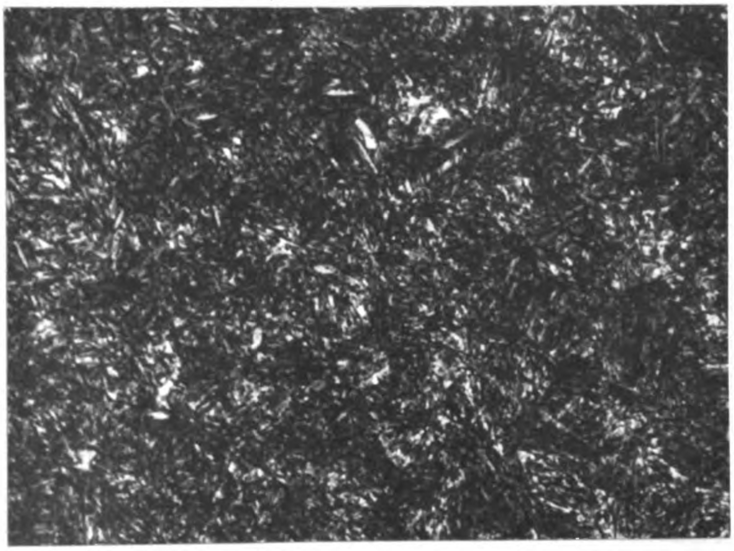

FIGURE 15. Microstructure of SAE 4140

Treatment: Quenched from 1575°F into salt at 500°F, held for thirty seconds, and cooled in still air.

Hardness: Rockwell 53 C

Magnification: 500 X

FIGURE 16: Microstructure of SAE 4140

Treatment: Quenched from 1575°F into salt at 500°F, held for one minute and cooled in still air.

Hardness: Rockwell 52 C

Magnification: 500 X

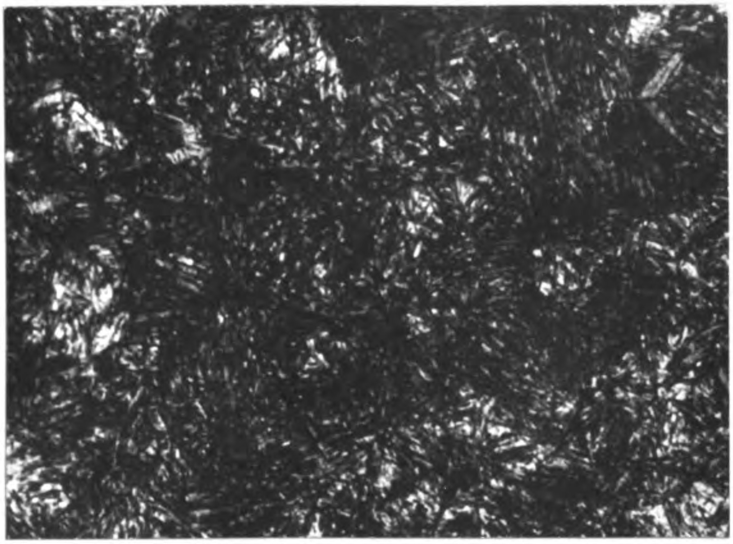

FIGURE 17. Microstructure of SAE 4140

Treatment: Quenched from 1575°F into salt at 500°F, held for three minutes, and cooled in still air.

Hardness: Rockwell 52 C

Magnification: 500 X

FIGURE 18. Microstructure of SAE 4140

Treatment: Quenched from 1575°F into salt at 500°F, held for five minutes, and cooled in still air.

Hardness: Rockwell 51 C

Magnification: 500 X

improvements of fatigue strength effected by the martemper and draw treatment. Further credence is lent to this explanation by an examination of the as-quenched hardness values for the two series of steels shown in Table II. Observe that for those specimens quenched in salt at 500°F there is a wider variation in hardness between the water quenched and oil quenched, and between the oil quenched and salt quenched specimens for the SAE 4140 group than for the SAE 6140 group. This implies that a greater proportion of tempered bainite was present in SAE 4140 specimens than was present in SAE 6140 fatigue specimens. Unfortunately, it is difficult to distinguish tempered lower bainite from tempered martensite. Because of that, no supporting evidence could be gleaned from a microstructural examination of the fatigue specimens.

The presence of bainite, as evidenced by the darker appearance of the etched structures, in the as-hardened microstructures of all except the water quenched specimens was very exasperating. It was desired that the formation of bainite be avoided in view of the inferior mechanical properties attending its presence. To avoid bainite, the use of a steel of higher hardenability suggests itself as a logical solution. It happened that the series of preliminary tests included an SAE 3340 group of steel. But even with this steel of relatively high hardenability the oil quenched and salt quenched specimens exhibited a lower hardness and a darker etching microstructure than did the water quenched specimens. The implication of these data is that only in pieces of **very** small cross section is it possible to avoid the formation of bainite by martempering or by oil quenching.

CONCLUSIONS

The primary objective of this work was to determine whether the improvement in fatigue strength realized by martempering a medium alloy machine steel over that resulting from the customary oil quenching treatment was sufficiently great to give promise of proving economically advantageous when the steel was tempered to a medium hardness. These experiments show that for the steels used and the conditions stated there was an improvement realized, and for the SAE 6140 the improvement was appreciable. Since these results were obtained with specimens that were specially prepared to avoid stress concentrations and since stress concentrations are invariably present in practical designs, it can be inferred that the use of martempering to avoid high residual stresses arising during transformation would prove even more beneficial in practical heat treatments. From this it would seem that further research in this vein will demonstrate that for certain machine steels drawn to a medium hardness the martempering process will prove economically advantageous. In addition, this work suggests the probable nature of future researches bearing on this problem.

As the presence of bainitic structures seems to be detrimental to the fatigue properties of a steel, more promise of improvement is held for steels of high hardenability than for those of lower hardenability. However, with steels of high hardenability a considerable amount of austenite might be retained. Upon tempering, this retained austenite would transform to bainite and it's possible that the beneficial effects of martempering could be completely offset.

Since stress concentrations exist in most practical designs, more significance would be attached to tests on notched specimens than would be attached to tests on unnotched specimens.

Because the improvement in fatigue resistance has been shown quite conclusively to be the result of lower residual stresses arising during heat treatment, the determination of residual stresses in the specimens used probably would yield some interesting and significant data. Possibly the X-ray diffraction technique could be used, since at this time it is the only non-destructive method of making such determinations. Unfortunately, it is a very time consuming and expensive test yielding results of doubtful accuracy.

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