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THE RELATION OF HEAT TREATMENT TO THE DYNAMIC PROPERTIES OF SOME CARBON STEELS

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ABSTRACT

In order to evaluate the effects of heat treatment upon the dynamic mechanical properties of steels, SAE 1035 and 1045 specimens that had been annealed or quenched and tempered were subjected to static or dynamic axial loads.

The dynamic yield stress was a maximum for specimens tempered in the range from 800° to 1100° F. The ductility is generally higher for the dynamic tests than for the static tests. The ratio of dynamic yield stress to static yield stress is smaller at the lower tempering temperatures. A possible mechanism for describing the influence of heat treatment upon the yield and flow characteristics is discussed.

PROBLEM STATUS

This is an interim report; work on this problem is continuing.

AUTHORIZATION

NRL Problem F01-02
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THE RELATION OF HEAT TREATMENT TO THE DYNAMIC PROPERTIES OF SOME CARBON STEELS

INTRODUCTION

Mechanical properties of materials subjected to rapidly applied loads have been under investigation for almost a century, with information being obtained by present day investigators at a greatly accelerated rate. The present investigation was undertaken because of a phenomenon observed in earlier studies, in which several different types of steel had been tested in an adaptation of the Taft-Pierce Shock Machine for Electronic Devices (1). The results indicated that whereas the yield point of annealed low-carbon steels was increased by 100 to 150 percent for rapidly applied loads, materials which had been cold-worked or heat-treated to obtain better tensile strength showed much less improvement of dynamic over static strengths.

In order to understand this behavior better, a systematic investigation was undertaken to determine the effects of heat treatment on the dynamic properties of steels. Two steels were chosen, and these were heated above the critical temperature and then were either furnace-cooled or were quenched and then tempered at various temperatures.

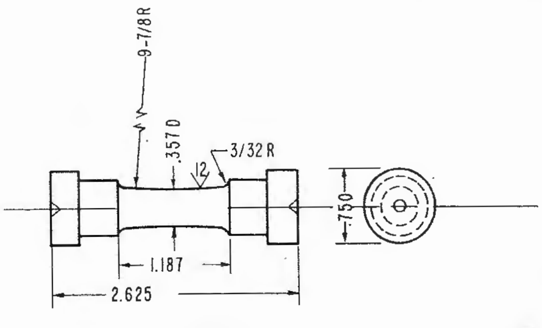
MATERIALS

The two carbon steels chosen were SAE 1035 and 1045. The chemical analysis of these is given in Table 1. From a 7/8-inch diameter bar of the 1035 steel, seven pairs of 13-inch lengths were cut and were heated at 1500°F in a salt bath for one hour. One pair was then furnace-cooled, and the other six pairs were oil-quenched and then tempered for two hours at 800°, 900°, 1000°, 1100°, 1200°, and 1300°F, respectively. Type 2 and type 3 specimens (Fig. 1) were machined from each of these pairs.

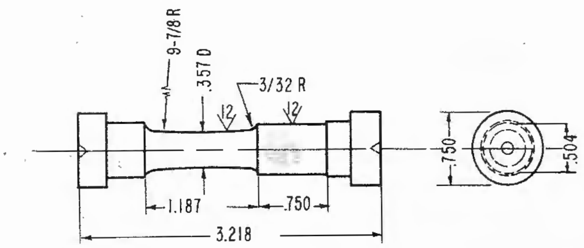
TABLE 1
Chemical Analysis of the Two Steels Chosen as Test Materials

SAE Number	Percentage of Alloying Constituents					
	C	Si	Mn	Ni	S	P
1035	0.33	0.10	1.08	0.02	0.014	0.016
1045	0.43	0.04	0.74	0.07	0.022	0.016

From the 7/8-inch diameter 1045 bar, seven pairs of 10-inch lengths were cut and were heated at 1550°F in a salt bath for one hour. One pair was then furnace-cooled, one pair was oil-quenched and left untempered, and five pairs were oil-quenched and then tempered for two hours at 200°, 500°, 800°, 1100°, and 1300°F, respectively. Again, type 2 and type 3 specimens were machined from each pair. Samples were cut from each of the fourteen pairs and photomicrographs at 500× were prepared (Figs. 2 and 3).



TYPE 2



TYPE 3

Fig. 1 - Test specimens

TEST EQUIPMENT

The adaptation of the Taft-Pierce Machine to the dynamic testing of materials in the manner described in Ref. 1 is limited by the amount of energy available, and subjects the specimen to alternating compression and tension following the initial tension load. In order to have more energy available and to eliminate the alternate cycles of loading, the machine shown in Fig. 4 was constructed.

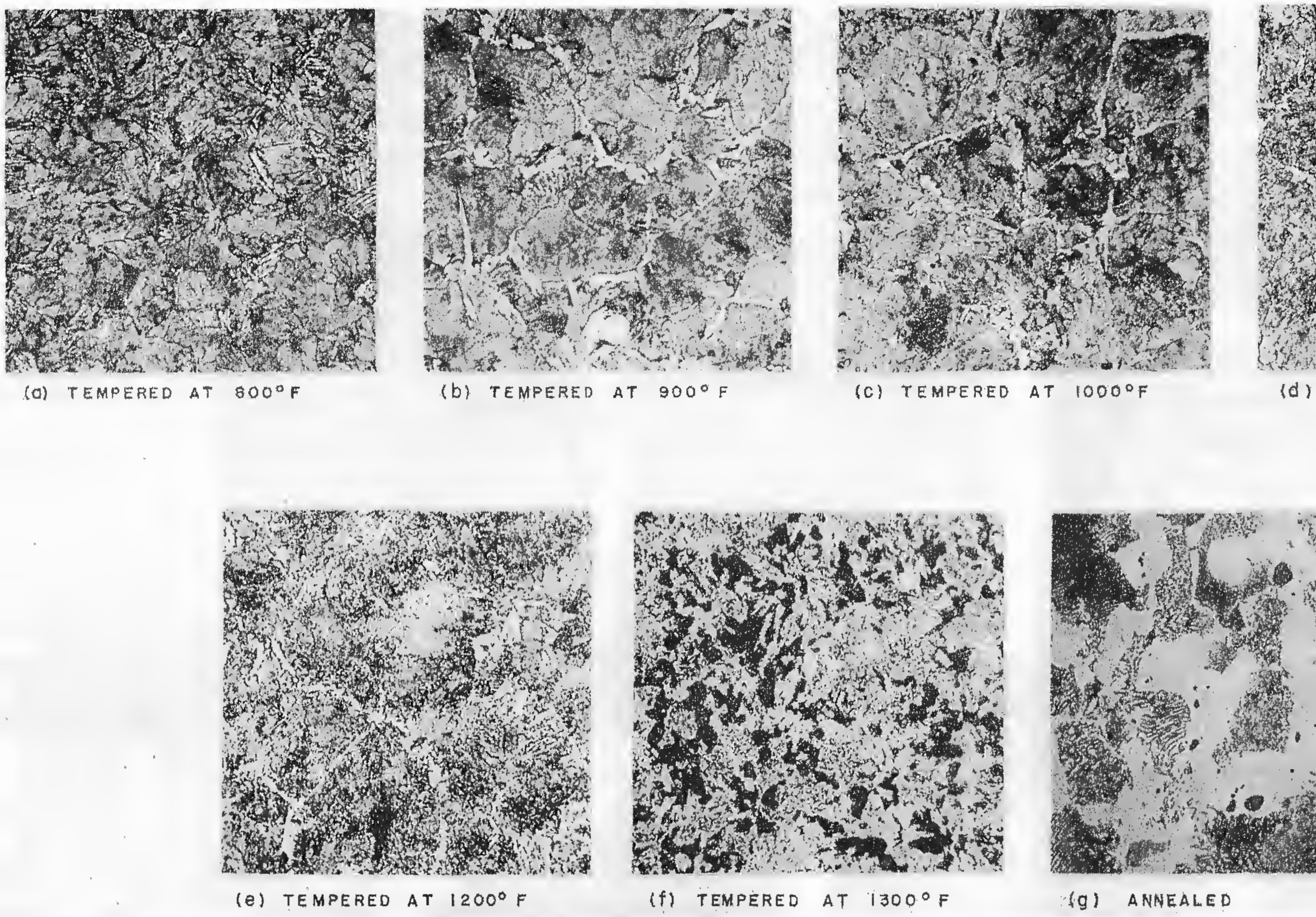
The specimen is drawn tight against the ground surfaces of the specimen holder by means of split rings and clamping nuts. This type of arrangement is employed because of its previous success in securing the best specimen alignment. The mas weighing 50 pounds, suspended from the lower specimen holder, is free to move vertically along the same guides which direct the motion of the hammer. After the hammer strikes and the mass reaches the limit of its travel (as determined by the extension of the specimen), a sliding fit between the mass and the lower specimen holder permits the mass to rebound without subjecting the specimen to a compressive stress.

The hammer is raised by means of the crank and is held at the desired height by tighte ing the band on the cable drum. The release mechanism is actuated by energizing a solenoi Two copper wires, 0.04 inches in diameter and bent into semicircular form, are placed on top of the mass to cushion the hammer blow and thereby govern the rate of application of the load to the specimen. This eliminates disturbing high-frequency oscillations and assures that the stresses are uniform throughout the length of the specimen.

The recording apparatus is described in Ref. 1, hence only a brief description is given here. A sequencing device operates the hammer trip solenoid switch, starts the oscillograph camera motor, releases the film brake, and reapplies the brake in proper sequence. The still camera shutter is also operated by means of a solenoid actuated by the same device. The camera film speed is greater than 15 feet per second, but by proper spacing of the cams on the sequencer, the entire record can be obtained on about 6 feet of film. Records of stress and strain versus time and of stress versus strain are obtained by means of wire resistance gages cemented to the test section and to the weigh bar section of the type 3 specimen.

TEST PROCEDURE

The type 3 specimens were used for the dynamic tests. The hammer height was varied from 6 inches to 4 feet. Oscillographic records of stress and strain were made for at least the first and second hammer drops, or until the strain-gage failed. Each specimen was given repeated blows until rupture occurred, after which the total elongation and reduction in area were measured.



(a) TEMPERED AT 800° F

(b) TEMPERED AT 900° F

(c) TEMPERED AT 1000° F

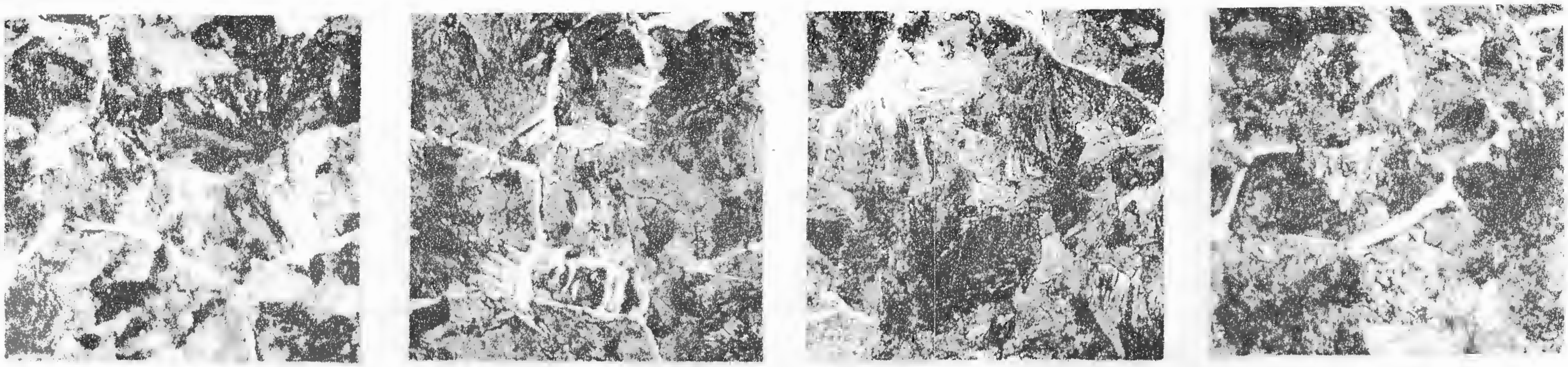
(d)

(e) TEMPERED AT 1200° F

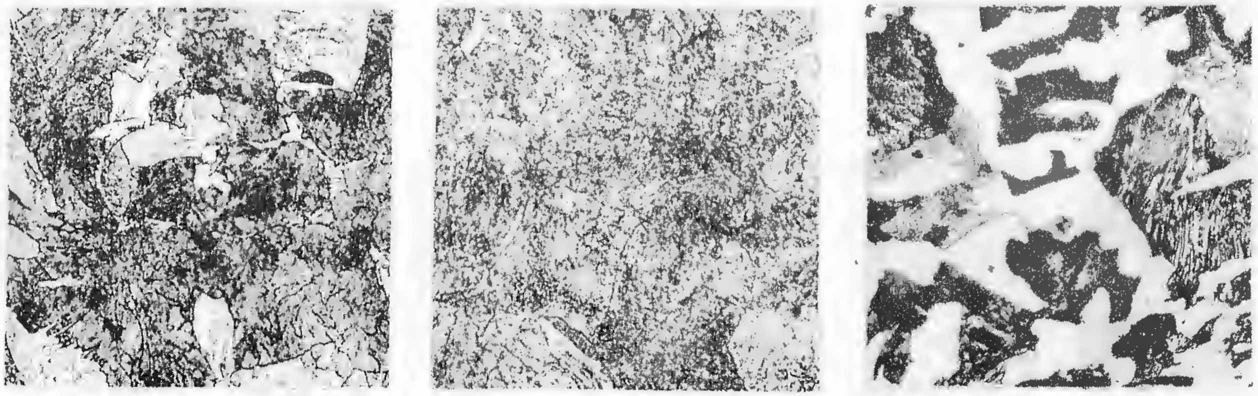
(f) TEMPERED AT 1300° F

(g) ANNEALED

Fig. 2 - Photomicrographs at 500X of samples cut from the SAE 1035 steel



(a) AS QUENCHED (b) TEMPERED AT 200°F (c) TEMPERED AT 500°F (d) TEMPERED AT 800°F



(e) TEMPERED AT 1100° F (f) TEMPERED AT 1300° F (g) ANNEALED

Fig. 3 - Photomicrographs at 500× of samples cut from the SAE 1045 steel

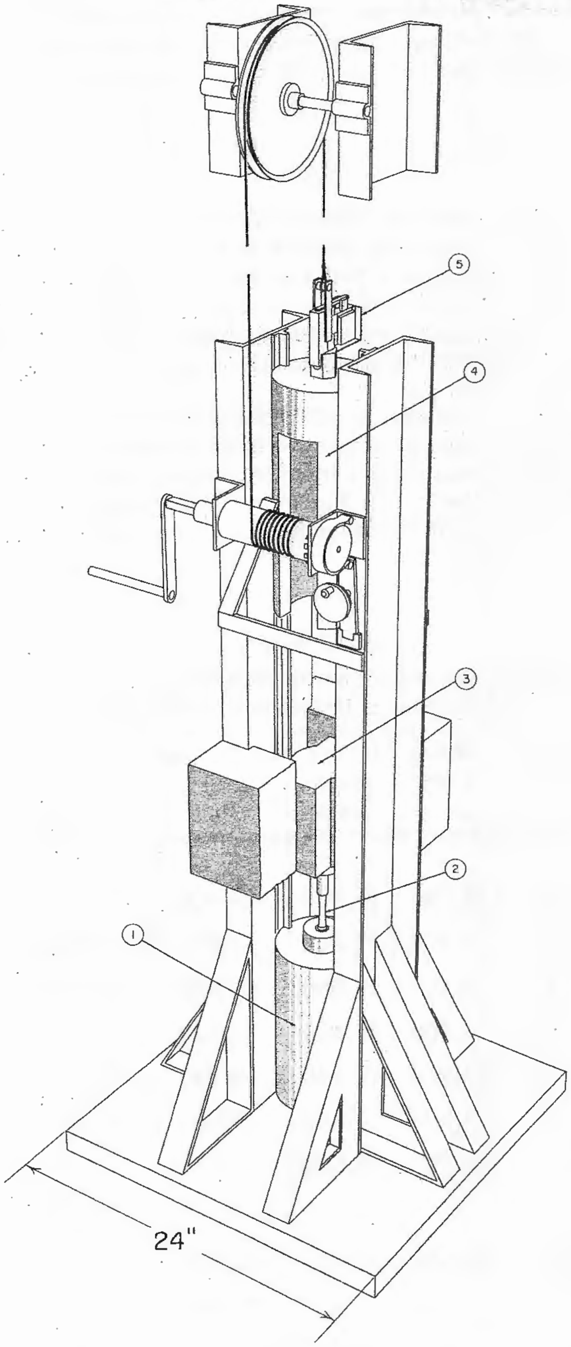


Fig. 4 - Rapid load testing machine

1 - mass weighing 50 pounds
2 - specimen
3 - specimen support
4 - 60-pound hammer, split to straddle
    the specimen and support
5 - hammer release mechanism

The type 2 specimens were pulled to failure in a static tensile testing machine. Autographic records of stress versus strain were obtained, and the final diameter and elongation were measured. Since the test sections of the two types of specimens are identical, values of dynamic and static elongation and reduction of area are comparable.

RESULTS

The static properties of the fourteen groups of specimens are presented in Table 2. The dynamic and static yield stresses are plotted in Fig. 5 for the SAE 1035 steel and in Fig. 6 for the SAE 1045 steel. The static yield points have been determined for the upper yield stress, where such exists, or for a 0.01 percent offset, which is roughly equal to the offset of the pronounced yield point. In addition the static yield point corresponding to a 0.2 percent offset is plotted. This value usually corresponds to the lower yield point.

During an impact the rate of loading gradually increases to a maximum value that remains essentially constant for values of stress between the static proportional limit and the dynamic yield stress. These maximum (constant) values of strain rate are plotted in Fig. 7 and are indicated in parentheses on Figs. 5 and 6. By means of this information the delay yield times under conditions of constant strain rate can be correlated with delay times for constant load (2).

TABLE 2
Static Properties of Specimens as Determined by Means of a Baldwin 60,000-Pound Universal Testing Machine

Specimen	Proportional Limit (psi)	Upper Yield (psi)	Lower Yield (psi)	0.2% Offset Yield (psi)	Ultimate Strength (psi)	Total Elong. (%)	Reduction of Area (%)
<u>SAE 1035 Steel</u>							
Annealed	49,400	49,400	45,000	45,000	84,800	19.4	43.6
800° T	82,000	83,800	83,200	84,300	124,600	14.5	44.9
900° T	76,000	80,700	79,500	79,500	116,800	16.6	49.4
1000° T	72,000	76,400	75,400	75,400	112,200	18.0	53.6
1100° T	71,000	73,200	70,200	70,200	105,200	19.8	58.9
1200° T	67,500	69,500	65,100	65,100	96,300	22.2	63.8
1300° T	64,000	66,000	59,000	59,000	86,200	24.2	66.4
<u>SAE 1045 Steel</u>							
Annealed	52,500	52,500	47,500	47,500	86,800	21.8	52.8
As Quenched	51,500	- *	- *	77,300	119,900	13.1	35.6
200° T	60,000	-	-	77,600	119,600	13.3	37.8
500° T	62,000	-	-	76,000	119,400	13.4	37.1
800° T	70,000	-	-	78,500	119,400	13.4	40.0
1100° T	61,000	-	-	65,000	103,200	20.1	59.4
1300° T	58,200	58,200	55,900	55,900	87,900	24.0	67.7

*No upper or lower yield exists

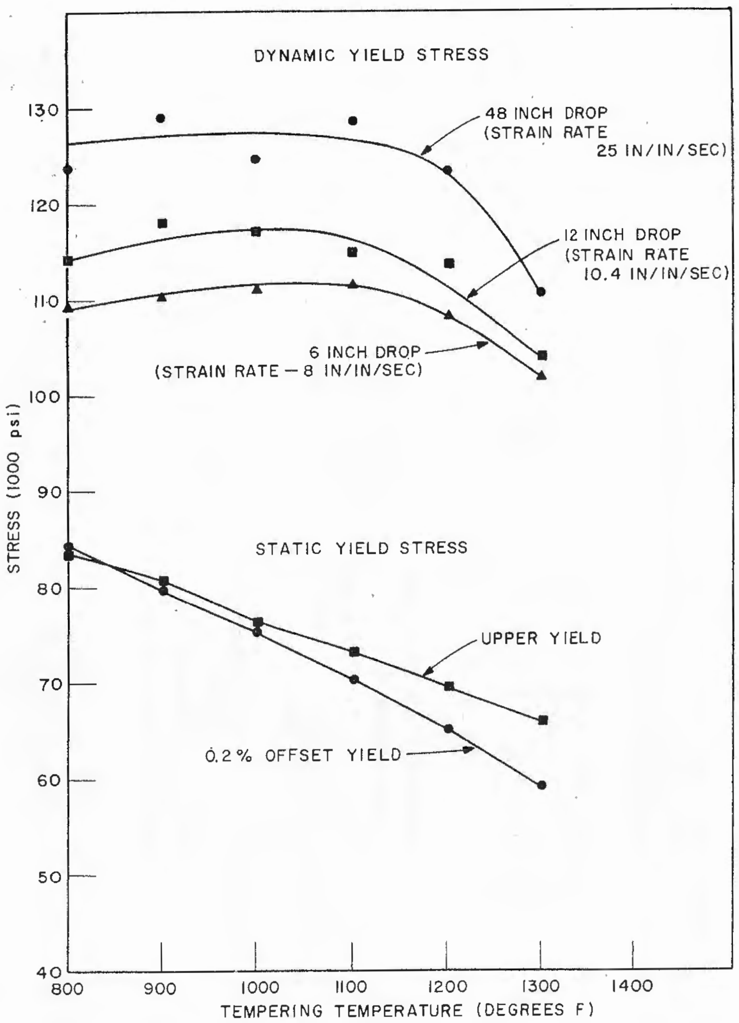


Fig. 5 - Dynamic and static yield test results for the SAE 1035 specimens

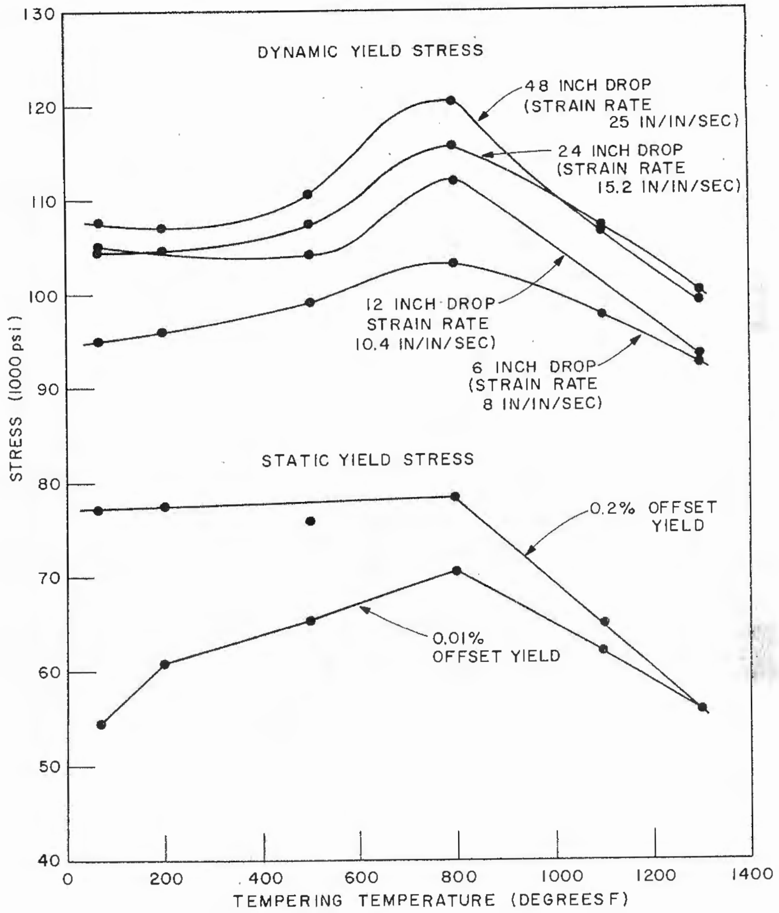


Fig. 6 - Dynamic and static yield test results for the SAE 1045 specimens

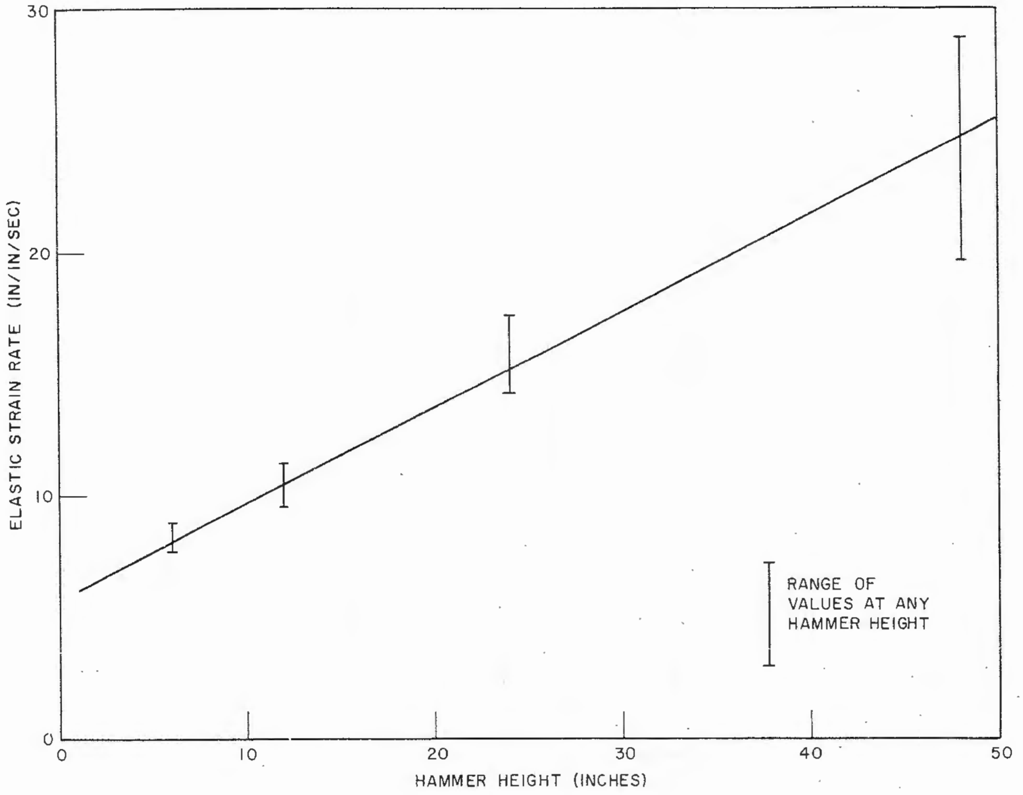


Fig. 7 - Specimen elastic strain rates for the rapid load testing machine

Comparisons between the two steels are handicapped because of a lack of information about the SAE 1035 in the "as quenched" end of the heat treatment range. Unfortunately no more of this specimen material is available.

Figure 5 shows a broad peak in the dynamic yield stress for the 1035 steel, extending roughly through a tempering temperature range between 800° and 1100°F, while Fig. 6 illustrates a relatively sharp peak at 800°F for the 1045 steel. The ratios of the dynamic to the static yield stresses are given in Table 3. These are given for both the upper or 0.01-percent offset static yield and for the lower or 0.2-percent offset static yield.

Figures 8 through 11 show the total percent elongation and reduction of area for the two steels. These values remain essentially constant for tempering up to 800°F, as shown for the SAE 1045 steel. The ductility, as indicated by these measurements, increases for higher tempering temperatures until a maximum is reached between 1200° and 1300°F, above which lower values are obtained.

The increase in ductility, under dynamic conditions as compared to static, averages about 20 percent on the basis of elongation and less than 5 percent on the basis of reduction in area. This ratio remains essentially constant for tempering temperatures below 800°F and decreases for higher tempering temperatures.

Some question may be raised concerning the effect on ductility of the multiple number of blows as compared to failure under single blows. Since an experiment involved less tha an hour of test time, it was expected that the effects of aging between blows would be smal Experiments were made in which specimen failure was caused in one blow, and it was dete mined that no difference in ductility was observable within experimental accuracy.

TABLE 3
Ratio of Dynamic to Static Yield for 6-Inch Hammer Drop

Specimen	Ratio for Upper Static Yield or 0.01 Percent Offset	Ratio for Lower Static Yield or 0.2 Percent Offset
SAE 1035 Steel		
800° T	1.30	1.29
900° T	1.36	1.39
1000° T	1.45	1.47
1100° T	1.52	1.59
1200° T	1.55	1.66
1300° T	1.55	1.73
Annealed	1.95	2.14
SAE 1045 Steel		
As Quenched	1.74	1.24
200° T	1.58	1.24
500° T	1.51	1.30
800° T	1.46	1.32
1100° T	1.57	1.50
1300° T	1.59	1.64
Annealed	1.65	1.82

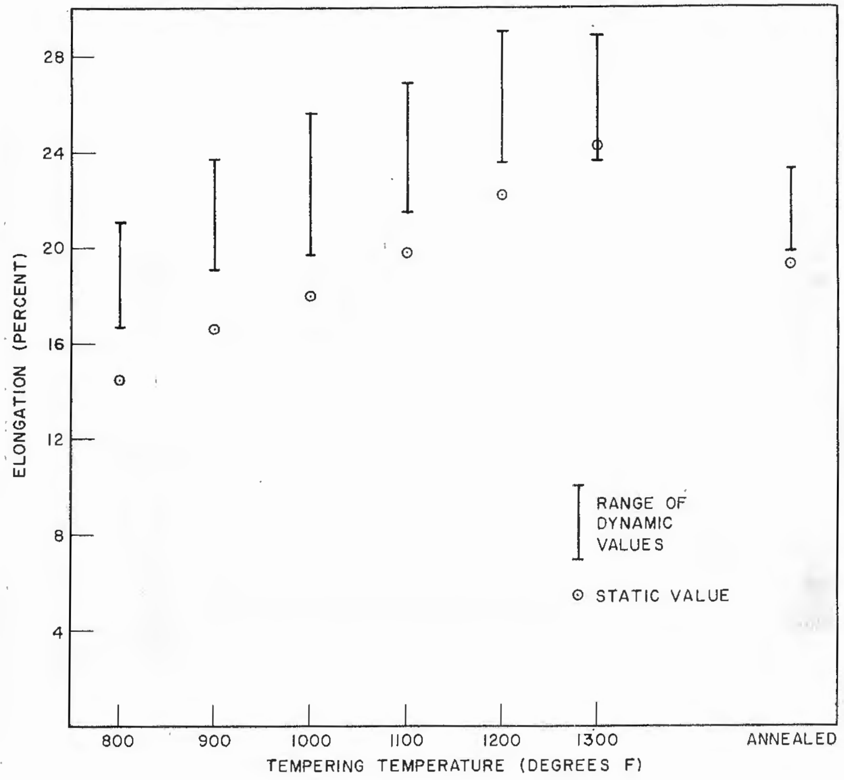


Fig. 8 - Elongation at rupture of the SAE 1035 specimens

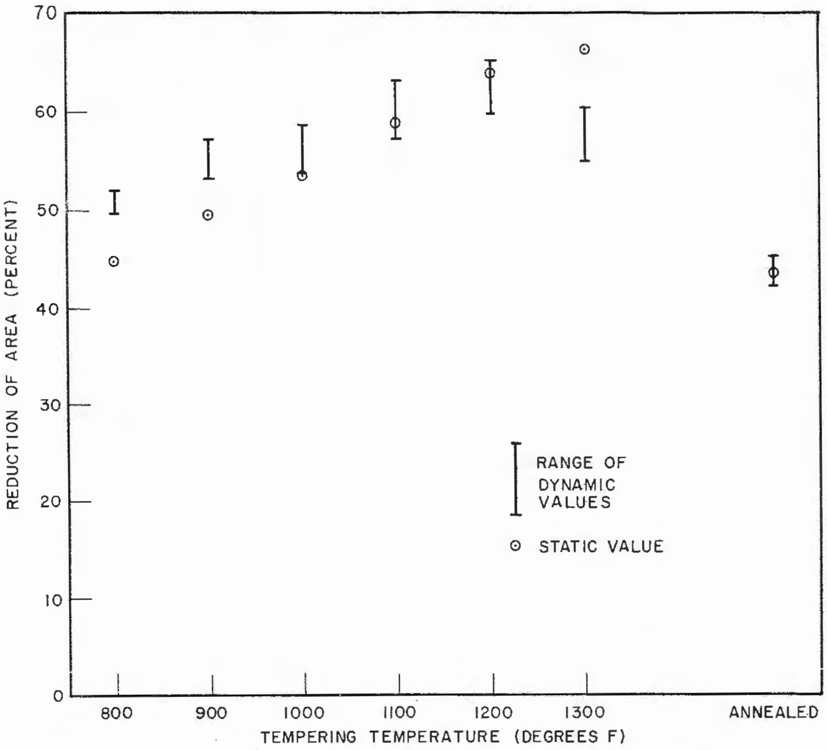


Fig. 9 - Reduction in area at rupture of the SAE 1035 specimens

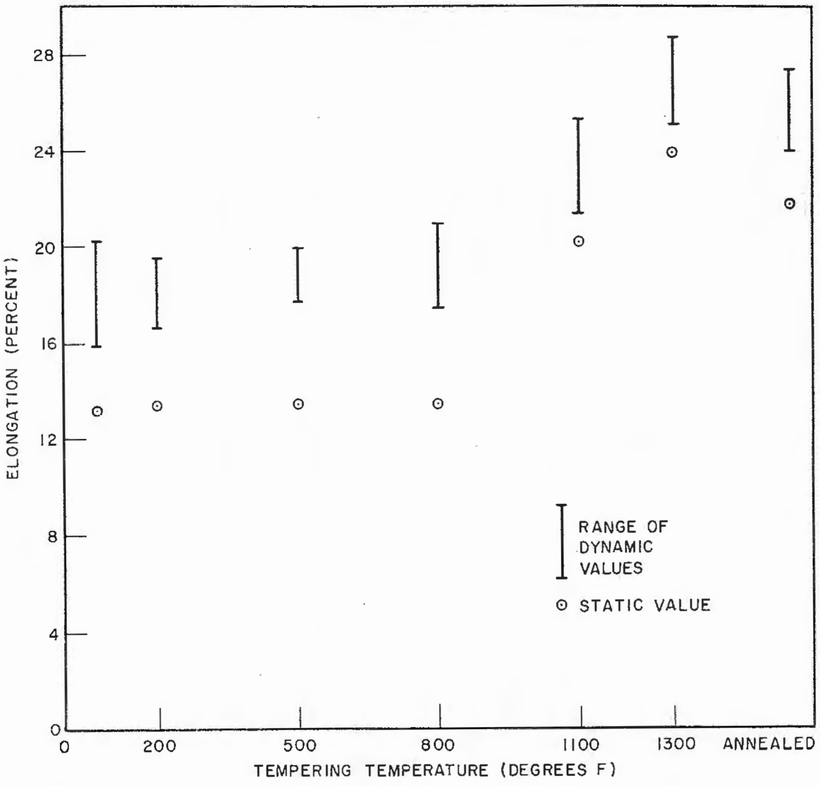


Fig. 10 - Elongation at rupture of the SAE 1045 specimens

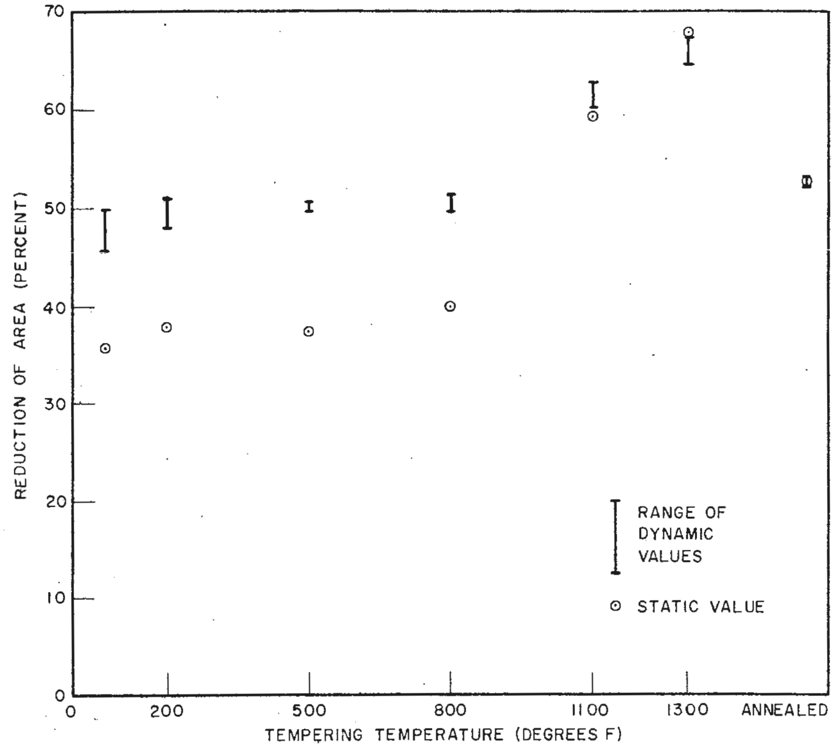


Fig. 11 - Reduction in area at rupture of the SAE 1045 specimens

DISCUSSION AND CONCLUSIONS

The static values for yield stress and tensile strength indicate immediately that the materials were not fully hardened, because of the 7/8 inch diameter of the bars which were initially heat treated. With the type of test specimen presently employed the test section would be a bainite or tempered bainite composition. The equipment is presently being modified to permit an extension of the tests to a flat type specimen 0.100 inches thick in which the cross section could be fully hardened. References to the work of Averbach, Cohen, et al, (3, 4, 5) must be limited to qualitative comparisons.

Inspection of the stress-strain curves of Fig. 12, or the proportional limit values in Table 2, illustrates the characteristically low value of stress at which plastic flow is initiated in the as-quenched condition. As the tempering temperature is increased, the proportional limit increases and reaches a maximum at 800°F for SAE 1045. Muir, Averbach, and Cohen reported on a 0.41 percent carbon steel in which the effect was quite pronounced. They indicated that a possible explanation for the low elastic limits in as-quenched steels lies in the presence of quenching and transformation stresses. They state further that the improvement in elastic limit on tempering may be associated with the partial relief of these stresses. The influence of tempering upon the dynamic upper yield stress could be expected to follow the same pattern.

The proportional limit observed upon tempering seems to be a unique characteristic of the tempering temperature. No changes in the proportional limit, 0.2 percent offset yield, or ultimate strength have been observed in specimens tempered for periods varying from 2 to 100 hours at 500°F. It does not seem possible to achieve the greater proportional limit of a higher temperature by longer tempering times at a lower temperature.

The following speculations as to the mechanisms responsible for the yield and flow phenomena are similar to Cottrell's ideas (6). They also provide explanations that agree qualitatively with the observed results.

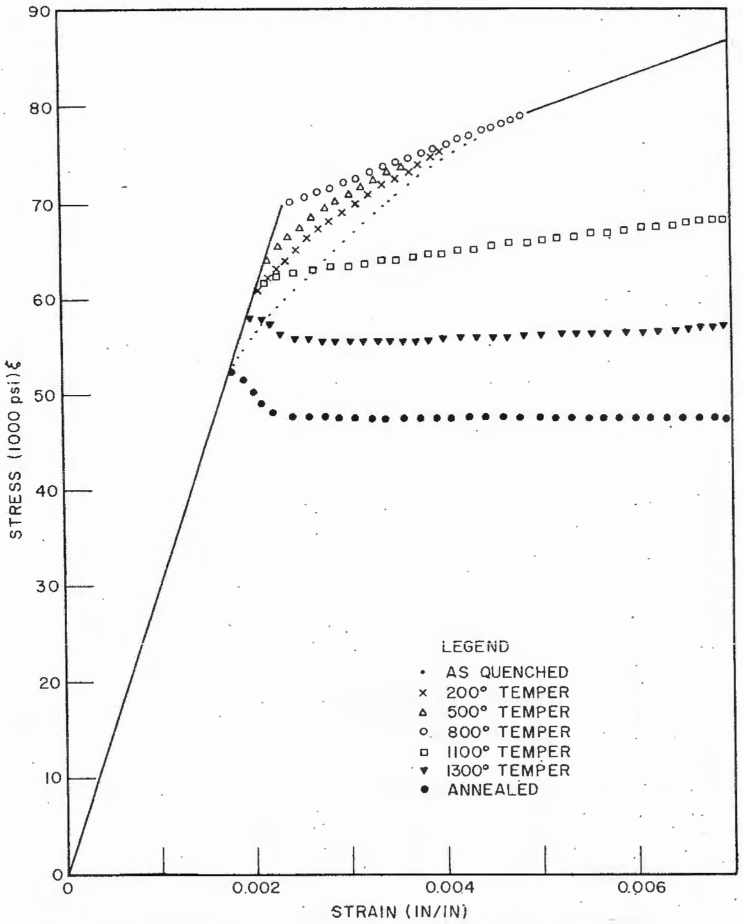


Fig. 12 - Static stress-strain curves for the tempered SAE 1045 specimens

1. The time dependent effects relative to the delayed yield are caused by the gradual diffusion of pinning atoms from dislocation sites.

2. As dislocations break loose, under the influence of stress, they travel to imperfection sites that prevent further motion. This continues until a sufficient number of dislocations have piled up at a given site to cause a stress concentration great enough to initiate flow. The period of time before flow in initiated relates to the delay times and to the upper yield stress. The initial part of the flow period relates to the lower yield stres Work hardening results from the multiplication of imperfection sites by plastic flow.

According to these notions, yield will occur when a sufficient number of dislocations pile up at major imperfections, the most important of which are grain boundaries. The number to arrive at a given area of a boundary in a given time will be proportional to the linear dimensions of the grain minus a factor dependent upon the number of imperfections per unit volume within the grain. The yield point and the delay time will therefore decrea as the grain size increases. If no upper yield point exists, it is assumed that the imperfections sites within the grains have more effect than do the grain boundaries, and that work hardening begins immediately.

It has sometimes been assumed that the higher tempering temperatures within this range (200° to 800°F) would result in a greater migration of carbon atoms to dislocation areas. Quenching from the critical temperature would leave the carbon atoms scattered in the martensitic structure, and tempering would then permit the carbon to diffuse to dislocations causing the elastic limit to rise. Such a simple mechanism could not account for the increase in the static proportional limit or the dynamic upper yield stress observed tempering temperatures between 200° and 800°F, if one assumes the activation energy for the process to be that of carbon in iron. Since there are no changes in the principal features of the grain structure within this temperature range, and since the activation energy for dislocations is too high to permit their appreciable change, these increases must be attributable to the gradual migration to lower potential sites of imperfections and foreign atoms having activation energies of intermediate value. This would, of course, result in a more stable structure. The studies of Lement, Averbach, and Cohen (4,5) show that in the first stage of tempering, ϵ carbide precipitates along subboundaries in the martensite, and that one should not necessarily find a correlation with diffusion coefficients for atomic carbon in iron. In the tempering range above 800°F, there is an obvious change of crystal structure, observable in Fig. 3, which results in a decrease in both yield and flow stress.

ACKNOWLEDGMENTS

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* * *

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