

Jan. 11, 1966

E. J. RIPLING ETAL

3,228,808

TOUGHENING HIGH STRENGTH STEEL BY WARM WORKING

Filed Jan. 28, 1963

2 Sheets-Sheet 1

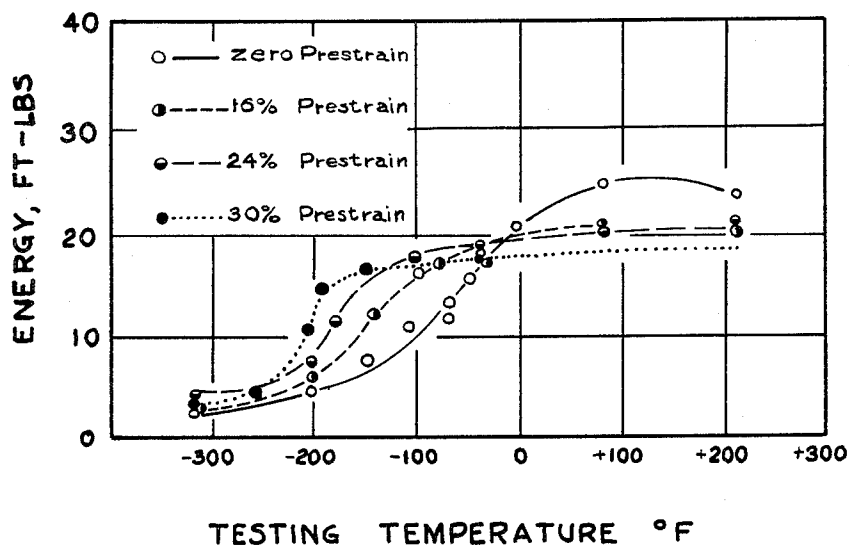


FIG. 1

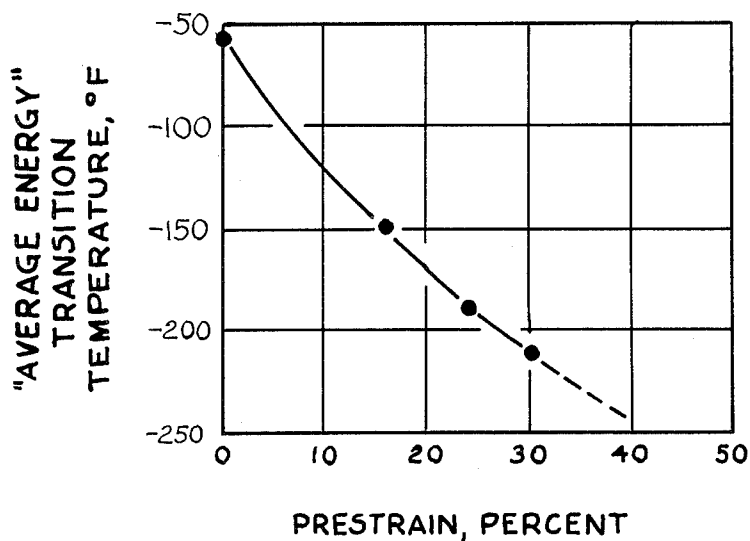


FIG. 2

E. J. RIPLING
R. S. LINDBERG
INVENTORS

BY *J. J. Rotondi, A. J. Dupont*
+ *E. P. Barthel*

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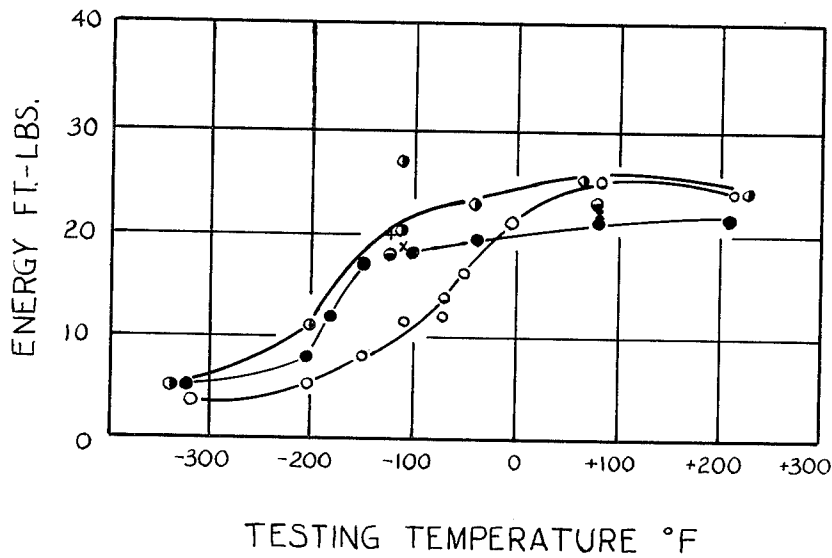
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- ZERO PRESTRAIN
● 24% PRESTRAIN 900°F
● 24% PRESTRAIN 900°F TEMPERED 900°F for 1 hr.
● 24% PRESTRAIN 900°F TEMPERED 700°F for 1 hr.
× 24% PRESTRAIN 900°F 3 steps, 7%, 14%, 24% TEMPERED 900°F 1 hr. Quenched after each step
+ 24% PRESTRAIN 900°F 3 steps, no quench TEMPERED 900°F 1 hr.

FIG. 3

E. J. RIPLING
R. S. LINDBERG
INVENTORS

BY *S. J. Rotondi, A. J. Dupont*
v *E. P. Barthel*

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3,228,808
TOUGHENING HIGH STRENGTH STEEL
BY WARM WORKING

Edward J. Ripling, Flossmoor, and Richard S. Lindberg,
Tinley Park, Ill., assignors, by mesne assignments, to
the United States of America as represented by the
Secretary of the Army
Filed Jan. 28, 1963, Ser. No. 254,526
1 Claim. (Cl. 148—12.4)

The present invention relates to a method of improving the toughness of steel subject to shock loading. This improvement in steel's properties is accomplished by a processing technique that lowers the transition temperature (the point at which steel goes from a ductile to a brittle state) without an accompanying loss in hardness. In many steel applications hardness plus toughness is essential, and, as toughness is related to hardness and the transition temperature, lowering the latter without reducing the hardness greatly increases the steel's toughness. Other steel treating processes, such as heat treating, can get lower transition temperatures only at the expense of hardness, offsetting the advantages of such reductions. Steel treated by this new process will find applications in any use that requires high strength plus good toughness characteristics, such as aircraft landing gears, and ordnance parts such as armor plate steels. Because the penetration resistance of armor is a function of both hardness and toughness, better ballistic performance will be obtained by this working process that yields a higher combination of these two properties. Also, weight reduction of military vehicles requires the development of higher strength structural materials that retain adequate toughness under severe service conditions.

This new process accomplishes the reduction in transition temperature without a change in the composition of the steel and without excessive added cost. Data presented over the last decade have indicated that these needed property improvements may be obtained in steels if the traditional quench and temper treatment is modified to include some mechanical working. The added deformation can be applied to the steel either while it is austenitic, prior to its transformation, or else after it has been completely quenched and tempered. As will be shown in detail later on, by deforming steel in certain prescribed fashions after it has been heat treated, it becomes less sensitive to the ordinary embrittling agents, i.e., its ductility loss at low temperature is less and it becomes less sensitive to brittle failure in the presence of notches or cracks.

Results of this invention showed that the Charpy "V" notch transition temperature of quenched and tempered armor steel was lowered by warm working the steel at a temperature just below that at which it was initially tempered. The amount by which this ductile to brittle fracturing temperature was lowered was almost a linear function of the prestrain, and with 30 percent working, the transition temperature was suppressed approximately 150° F. The toughness improvement occurred with no change in hardness although there was a loss in supertransition temperature shelf height. The initial tensile strength of the steel was unchanged and ductility reduced. The enhanced toughness persisted through retempering after warm working. The added heating did not change the hardness while the supertransition shelf was brought back to its "as-received" level. In addition, the tensile strength, yield strength, elongation and reduction in area of the warm worked plus tempered and "as-received" steel were essentially identical, resulting in a net increase in toughness.

It is therefore one of the objects of this invention to

increase the toughness of high-strength steels by warm working.

It is also an object of this invention to lower the Charpy "V" notch transition temperature of quenched and tempered steel.

It is a further object of this invention to show that the lowering of the transition temperature by warm working persisted through retempering.

A further object of this invention is to bring about elevation of the supertransition shelf and tensile ductility while lowering the tensile yield strength, all to their initial "as received" values.

FIG. 1 is a diagram showing the effect of prestraining various amounts at 900° F. on the transition temperature of Mn-Mo steel.

FIG. 2 is a diagram showing the average energy transition temperature of Mn-Mo steel as a function of prestrain at 900° F.

FIG. 3 is a diagram showing the effects of tempering after prestraining on the transition curve of Mn-Mo steel.

The Mn-Mo and Mn-Cr-Mo steels used in this invention were obtained as 1-inch and ½ inch thick plates, respectively. The composition of the steels is shown in Table I. The Mn-Mo plate was austenitized at 1650° F. for two hours, water quenched, tempered at 950° F. for two hours, and again water quenched. The Mn-Cr-Mo specimen "as received" heat treat conditions were austenitized at 1580° F. for 82 minutes and water quenched followed by tempering at 890° F. for 81 minutes and air cooled.

TABLE I

| | Mn-Mo | Mn-Cr-Mo |
|------------------|--------|----------|
| Carbon..... | 0.29 | 0.3 |
| Manganese..... | 1.72 | 1.00 |
| Silicon..... | 0.26 | ----- |
| Sulfur..... | 0.019 | 0.58 |
| Phosphorous..... | 0.011 | 0.017 |
| Nickel..... | 0.16 | 0.013 |
| Chromium..... | 0.09 | 0.08 |
| Molybdenum..... | 0.60 | 0.020 |
| Boron..... | 0.0005 | 0.0012 |

Before warm working to evaluate the property changes that could be produced by deformation, it was necessary to establish the steels' "as-received" properties. Charpy "V" notch transition temperatures were measured on both steels in the longitudinal and transverse direction. In all cases the test pieces were cut out of the center of the plate thickness, and the notch was made to run normal to the plate surface.

Since stretching was selected as the prestraining procedure, the tensile fracture strain over the range of potential working temperatures had to be ascertained. For this reason the tensile properties between ambient and 900° F. for the Mn-Mo steel, and between ambient and 800° F. for the Mn—Cr—Mo steel, were measured. These maximum straining temperatures were selected to be enough below the tempering temperatures of the steels to be certain that heating alone would not influence the test results. Standard ASTM threaded-end 0.505 inch diameter bars were used for these tests on the Mn-Mo steel.

Warm working was evaluated primarily by stretching samples various amounts at elevated temperatures after which Charpy bars were machined from the deformed pieces. It became apparent in the course of the study that the length of time the specimen was held at temperature after straining was a significant variable. The test piece and loading fixture were brought to the straining temperature in approximately twenty minutes and was then held at temperature for approximately ten minutes

prior to straining. Immediately after stretching, the specimen was removed from the assembly and water quenched. In all cases tests on prestrained samples were conducted within a week of the time of initial stretching.

In service, armor plate is subjected to tensile stresses in the short transverse direction. If plates were to be commercially warm worked, e.g., by rolling, this direction would be given a compressive rather than tensile prestrain. To evaluate the property changes that occur when the sense of the stress and strain state are reversed between prestraining and testing, some samples were pre-compressed after which Charpy bars were machined from the pieces.

The specimens could not be cut with their long dimensions in the short transverse direction of the plate so that the properties measured in this test series are not directly applicable to actual plates. Nevertheless, the property changes brought about by prestraining are expected to be reasonably independent of initial plate anisotropy so that the changes in short-transverse properties should be predictable. An actual difficulty arises, however, in that both the stress and strain state are uniaxial compression and deformation in the short transverse direction of the plate during rolling are different. At present there is no way of evaluating this difference.

A second consideration that had to be given to the practical application of warm working was the fact that hardened steel could not be easily deformed with commercial equipment to the same extent to which it could be stretched. Rolling is the obvious commercial process for warm working heat treated plates, and since armor is generally used in widths of at least five feet, the roll force for large deformations would be excessive. If numerous light passes are used, however, the commercial feasibility of the process is greatly enhanced. Hence, a few tests were also conducted in which the total deformation was made up of numerous small tensile strains.

The effect of tensile prestraining on hardness made at the threaded end of the specimens showed the hardness to be unchanged by just heating to the prestrain temperature. For both steels, the BHN was increased after straining in the region of 600° F. The increase was especially pronounced in the Mn-Cr-Mo steel. In addition to using the tensile bars for hardness testing, Brinell data were also collected during each prestrain series.

Groups of transverse specimens were stretched 16, 24 and 30 percent at 900° F. to determine the effect of tensile prestraining on toughness. The Charpy "V" notch transition temperature of each group was then measured and compared with the "as-received" toughness. As shown in FIG. 1, the transition temperature of the steel was continually lowered as the amount of prestrain was increased. It was to determine whether or not such behavior would occur in armor plate that this project was undertaken. To evaluate the rate at which prestrain lowered the transition temperature, the "average energy" transition was plotted as a function of prestrain magnitude in FIG. 2. The decrease was found to be almost linear with the percent of prestrain. Unfortunately, warm working, in addition to lowering the transition temperature, lowered the supertransition temperature shelf as well. This lowering appeared to be independent of the amount of prestrain (see FIG. 1).

One specimen from each prestrain group was also machined to the dimensions of a Charpy bar, but instead of being notched, was used for collecting hardness data. Measurement was made on each of the four machined faces at the positions represented by the bottom of the prestrain sample neck. In all cases the hardness of test bars prestrained at 900° F. were unchanged from the "as-received" values.

Stretching at a lower temperature, instead of being beneficial to toughness, harmed it. Working at 500° F. not only failed to lower the transition temperature, but lowered the toughness level at all testing temperatures as

well. The hardness of the steel after prestraining at this temperature, however, was increased to 388 BHN.

Stretched samples were remachined into small tensile bars in order to evaluate the effect of elevated temperature prestraining on room temperature tensile properties. As shown in Table II, stretching at 900° F. increased the yield strength of the metal from 156 or 158 to 170K p.s.i., caused little change in tensile strength and reduced the ductility slightly.

TABLE II

| | | Room Temperature Tensile Properties After Stretching Approximately 24 Percent at 900° F. | | | |
|---------------|---|--|--------------------------------|---------------------------|----------------------------|
| | | Yield Strength, 1,000 p.s.i. | Tensile Strength, 1,000 p.s.i. | Elongation, percent in 1" | Reduction in Area, percent |
| Longitudinal: | As-Received | 156 | 167 | 14 | 48.5 |
| | Stretched 24% at 900° F. | 170 | 170 | 10 | 44.3 |
| Transverse: | As-Received | 158 | 168 | 11 | 43.0 |
| | Stretched 28% at 900° F., quenched and retempered one hour at 900° F. | 169.5 | 169.5 | 9 | 33.2 |
| | | 158 | 167 | 13 | 43.0 |

As stated above, plates would probably be warm worked by rolling in commercial practice. This results in a compressive strain state and a multiaxial compressive stress state in the short transverse direction of the plate. Neither this strain or stress state could be conveniently duplicated in the laboratory, which is indeed unfortunate since stress state has previously been shown to be a particularly important variable in establishing the properties of worked metals. In spite of this limitation of laboratory working, the thickness direction properties of plate is of such importance that the effect of reversing the direction of working between prestraining and testing was studied. Samples of the Mn-Mo steel were upset (uniaxial compression) various amounts at 900° F., after which Charpy bars were machined from the deformed pieces. Impact tests were then carried out at room temperatures and -110° F. At ambient temperatures very small prestrains improved the toughness of the plate, but a precipitous drop in toughness occurred between 10 and 20 percent deformation.

The property loss resulting from compressive prestraining is often thought to be caused by a reorientation of microcracks or other flaws into a direction that is more harmful in the subsequent test. Cracks, of course, cannot be relieved by simple heating, so that samples of compressed test pieces were retempered at 900° F. prior to machining Charpy bars from the pieces to ascertain whether or not a realignment of flaws was the cause for the toughness loss. The insertion of an one-hour temper greatly improved the toughness of the steel, and deformation between 5 and 25 percent increased the toughness about 40 percent above that of the original plate. The abrupt property loss that had occurred between 10 and 20 percent prestrain, now was delayed to between 25 and 30 percent. Retempering also improved the low temperature toughness but not to the same extent as it did from room temperature.

The effects of retempering after tensile straining was evaluated by stretching some bars 24 percent at 900° F. after which they were quenched and retempered at the same temperature for one hour. These were then machined into Charpy bars. Again one specimen was used for hardness measurement and again retempering was found not to change hardness.

The remainder of the stretched and heated samples were used for toughness measurements. As shown in FIG. 3, the lowering of the transition temperature produced by prestraining persisted through retempering, and, in addi-

tion, the super-transition temperature shelf was elevated to its "as-received" value. It is interesting to note that for the single specimen prestrained, and retempered at a lower temperature (700° F.), the room temperature toughness was between the untempered and 900° F. value. Therefore a processing treatment consisting of warm working followed by retempering is capable of lowering the transition temperature without any loss in super-transition temperature shelf heights.

Retempering after stretching lowered the yield and tensile strength of the metal so that its tensile properties after stretching and heating to 900° F. for one hour were almost identical with those of the "as-received" steel, Table II.

Because armor plate is quite hard even at temperatures in the vicinity of 900° F., it would be difficult to make reductions of the order of 30 percent in a rolling mill in a single pass. To determine whether or not the property improvements obtained in a single stretching operation would also occur if the deformation were in a series of steps, samples were stretched 24 percent in three increments, water quenched after each step and retempered after final quenching.

As shown in FIG. 3, after these pieces were machined into Charpy bars and tested at -110° F. and room temperature, the toughness was about the same as that produced by a single step deformation. Another specimen stretched 24 percent in three steps was held at 900° F. for one hour in the testing device after prestraining so that it was tempered without any intermediate quenches. This piece had an impact energy comparable to the other, i.e., 20 ft. lbs. at -110° F., FIG. 3.

In summary, the foregoing test results show the Charpy "V" notch transition temperature of quenched and tempered armor steel was lowered by warm working. The working temperature had to be just below the original tempering temperature for deformation to be beneficial. At this temperature the transition was continuously lowered with increased amount of strain, and 30 percent stretch lowered the transition temperature approximately 150° F. This toughness improvement occurred without a hardness loss although impact energy over the range of the super-

transition temperature shelf was lowered. The tensile strength was also unchanged, while the yield strength was increased and tensile ductility reduced.

The lowering of the transition temperature persisted through retempering. The added heating was beneficial in raising the supertransition shelf and tensile ductility while lowering the tensile yield strength, all to their initial "as-received" values. The net result of working then became solely a decrease in transition temperature. Stepwise working appeared to be as effective in this process as one large deformation. Compressive prestrain in excess of 10 percent caused an abrupt loss in toughness at room temperature. This discontinuity in the toughness prestrain curve was moved to approximately 25 percent by retempering. In addition, retempering raised the room temperature toughness of the compressed specimens by approximately 40 percent.

We claim as our invention:

The metallurgical process of producing a manganese-molybdenum alloy armor plate steel having high combination of hardness and toughness which comprises heating the steel which contains a weight percent composition of carbon 0.30 maximum, manganese 1.7 maximum and molybdenum 0.6 maximum to an austenitizing temperature, quenching to form martensite, tempering said steel in the temperature range of 950° F., heating said steel to a temperature in the range of 900° F. just below said tempering temperature, warm working said steel so that it is prestrained in the range of 15% to 30% with a resultant progressive lowering of the Charpy "V" notch transition temperature together with a lowering of the super-transition temperature shelf height, heating said steel to said warm working temperature for a period of approximately one hour with the resultant restoration of the super-transition temperature shelf height while maintaining the lowered transition temperature.

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DAVID L. RECK, *Primary Examiner.*