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BAINITIC STABILIZATION OF AUSTENITE IN LOW ALLOY STEELS

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ABSTRACT

The stabilization of retained austenite via bainitic transformation was studied in a "triple-phase" ferrite/bainite/austenite steel of composition 0.26C-1.52Si-1.2Mn. The volume fraction and stability of retained austenite are varied by the isothermal transformation time at 752F (400C) following intercritical annealing at 1418F (770C). Austenite stability is measured using the Bolling-Richman technique for determination of the M_s^σ temperature. Austenite content is measured by X-Ray diffraction, and austenite carbon content is estimated from lattice parameter measurements. Strength and ductility measured in both uniaxial and plane-strain tension are correlated with the amount and stability of austenite. While austenite content peaks at 3 minutes transformation time, stability continues to increase out to 5 minutes in association with a saturation of austenite carbon content and a continued refinement of austenite particle size.

Despite the reduced austenite content of 8 percent, the higher stability provided by the 5 minute treatment gives superior mechanical properties, achieving a plane-strain uniform ductility of 25 percent with a 3 percent flow strength of 83 ksi (570 MPa). The austenite stability appears to be less than the theoretical optimum, and further ductility enhancement should be achievable with increased stability.

The beneficial role of transformation plasticity in the uniform ductility of microalloyed sheet steels was firmly established by the definitive tempering experiments of Gil Speich.(1, 2) Recent work supporting this role has demonstrated effective stabilization of retained austenite employing an isothermal bainitic transformation after intercritical annealing (3,4,5,6), thus providing a "triple-phase" ferrite/bainite/austenite microstructure. In this paper the relationship between austenite stability and mechanical properties is further explored. The mechanical property objectives of this research are a three percent flow stress between 75 and 100 ksi with a uniform ductility between 20 and 30% under plane-strain tension (Fig. 1). The austenite stability is quantified by determining the temperature at which the mode of retained austenite transformation changes from stress-assisted to strain-induced. This temperature is above the M_s temperature and known as the M_s^σ temperature (Fig. 2). Below this temperature the retained austenite transforms to martensite via pre-existing nucleation sites. Above this temperature up to the M_d (above which no martensite is produced), martensite is nucleated at both pre-existing and, predominantly, new nucleation sites produced by the plastic strain. These temperatures are stress state dependent (7,8,9). The reversal of the yield strength temperature dependence at the M_s^σ temperature allows for an easy technique to determine this temperature in fully austenitic steels. In steels with small volume fractions of retained austenite a more sensitive technique is employed to measure the temperature dependence of microyielding.(10)

Two factors affecting the retained austenite stability are also studied. The enrichment of austenite with carbon has previously been acknowledged as a technique to stabilize retained austenite. In these experiments a second factor, retained austenite pool size, was demonstrated to provide a significant stabilizing effect. This is predicted by the statistical transformation kinetic model developed by Olson and Cohen (8), based on the distribution of potencies of nucleation sites in austenite for the transformation to martensite. Smaller retained austenite pools contain lower potency nucleation sites and require greater total driving force for nucleation.

EXPERIMENTAL PROCEDURE

Two steels were produced at the Inland Steel Research Laboratory as 100 lb. (45.36 Kg) vacuum degassed ingots (Table I). The ingots were milled to remove surface scale and hot rolled to a thickness of 0.29 inches (7.366 mm). The hot band was milled 0.035 inches (.889 mm) from each side to remove the decarburization layer, resulting in a final thickness of 0.221 inches (5.613 mm). The hot band was then cold rolled to a final thickness of 0.067 inches (1.702 mm) (a 69.7% reduction). The cold rolled material was machined to the required specimen size prior to heat treatment. This was done to avoid transformation of retained austenite to martensite due to the machining forces and to avoid any localized tempering due to the heat generated during machining. The heat treatment cycles (Fig. 3) were conducted in two neutral salt baths. The intercritical annealing bath was held at 1418F (770C), where experiments in a fluidized bed showed the microstructure was 50% austenite after a five minute anneal. The isothermal transformation bath was at 752F (400C). All specimens after heat treating were quenched in an ice brine water solution. The majority of the analysis was completed solely on the .26% C-1.22% Mn-1.52% Si steel.

Tensile tests were conducted on an Instron 4206 machine at a crosshead speed of 0.1 inch/minute (0.254 cm/minute) for a strain rate of 0.033/minute. The strain was recorded using a standard Instron extensometer. M_s^σ(uniaxial tension (U.T.)) measurements were conducted on a Gleeble 1500, also at).1 inch/minute (0.254 cm/minute) for a strain rate of .847/minute, at the temperatures indicated. The microyield load was measured at a strain of .16% using a transverse LVDT. The M_s^σ(U.T.) determination was made using the Bolling-Richman single specimen technique (11). The above specimens were all made to ASTM specification A 370 for a longitudinal, sheet specimen.

The plane-strain specimens were based upon the design of Corrigan (Fig. 4).(12) The specimens were marked using a Vickers DPH tester at 500g prior to testing to confirm that the plane-strain constraint was followed. The strain was measured at the completion of the test using a point micrometer.

The volume fraction of retained austenite was determined by X-Ray diffraction (XRD) using the relationship determined by Miller (13) and compared with NIST certified standards. The carbon content of the austenite was determined via lattice parameter measurements and the relations determined by Ruhl and Cohen (14) and Ridley,Stuart, and Zwell (15). The specimens used for XRD were taken from tensile specimen grip ends. The analysis was conducted with a Mo K(alpha) X-Ray tube in a Scintag XDS 2000. Metallographic specimens were also taken from the tensile specimen grip ends. The specimens were polished down to a one micron diamond paste finish. A two component tint etchant consisting of two grams of sodium meta-bisulfite dissolved in 100 milliliters of distilled water which was mixed with four grams of picric acid dissolved in 100 milliliters of pure ethanol just prior to use (16). An etching time of fifteen seconds was used.

THEORY

The first step in the research was to obtain stable retained austenite at room temperature. The technique used to achieve this was an intercritical anneal to form approximately 50% austenite (770C) followed immediately by an IT heat treatment in the upper bainite region. The holding at the IT temperature, 752F (400C), permitted the transformation of some of the austenite to bainitic ferrite. A high silicon content was used to inhibit cementite precipitation. The manganese served a dual purpose of slowing the austenite to ferrite transformation and increasing the stability of the retained austenite. Since cementite precipitation is inhibited by the silicon, the carbon rejected by the bainitic ferrite enriches the remaining austenite and helps stabilize it.

Another stabilizing effect on the retained austenite is a small particle or pool size as seen by Rigsbee (17) and Cech and Turnbull (18), and explained in the kinetic model developed by Olson and Cohen (8). Another prediction of the Olson and Cohen model is the stress-state dependence of M_s^σ. A more stable retained austenite is required for a material that will be deformed under plane-strain tension, as in stretch-forming of sheet, compared to uniaxial tension. The uniform ductility can be increased by

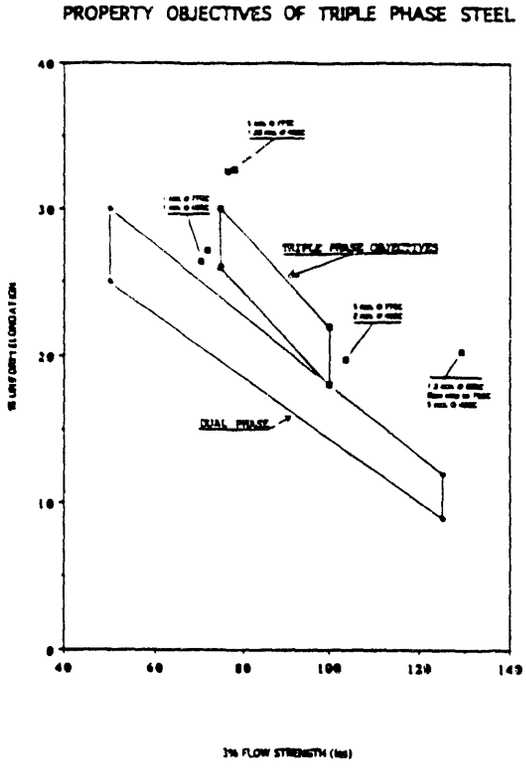


Fig. 1. Mechanical property objectives of this research under plane-strain tension. Data points are for uniform elongation under uniaxial tension.

C	Mn	Si	Al	P	S	N
0.2700	0.8100	1.5200	0.0390	0.0070	0.0040	0.0043
0.2600	1.2200	1.5200	0.0500	0.0020	0.0030	0.0008

Table I

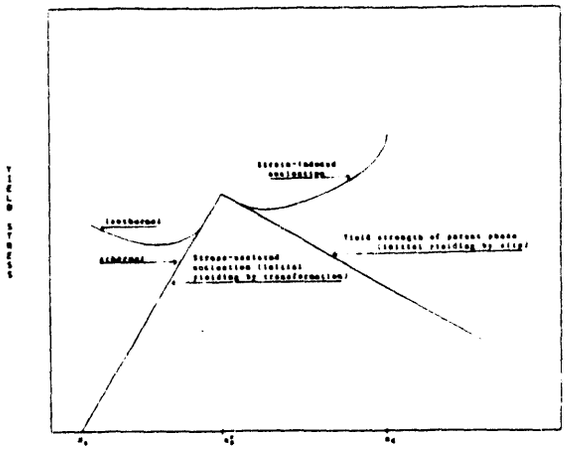


Fig. 2. Schematic representation of M_s^σ, M_s, and M_d.

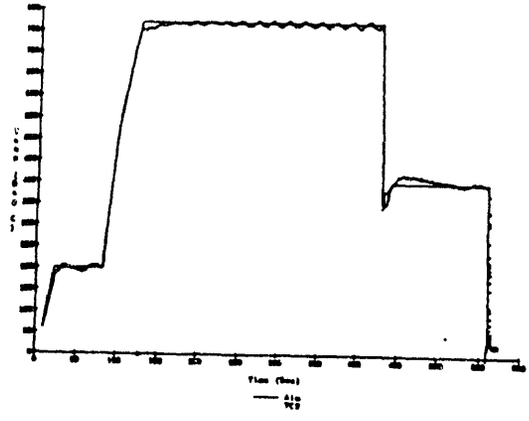


Fig. 3. Representative heat treatment cycle.

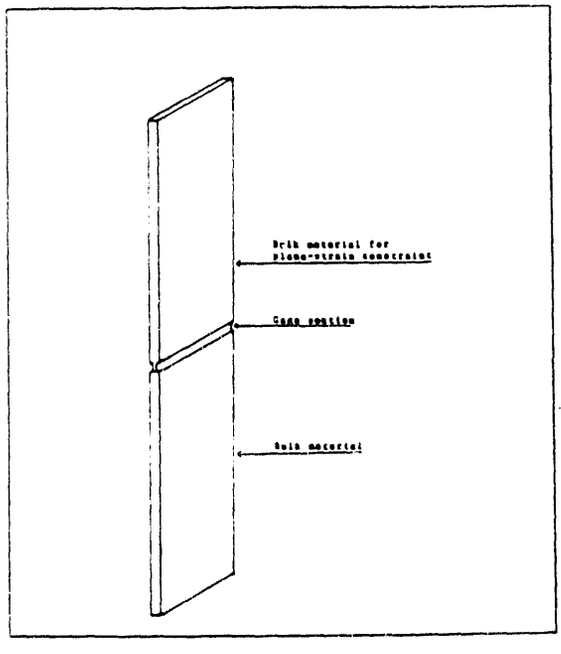


Fig. 4. Perspective drawing of the plane-strain specimen geometry.

transformation strain hardening if the retained austenite has the optimum level of stability.(19,20)

In this study the effect of the stability of the retained austenite upon the uniform ductility under uniaxial and plane-strain tension was studied. The effects of carbon content and particle size of the retained austenite were correlated with the austenite stability.

RESULTS

The mechanical properties of the steel were studied in three ways: 1) Uniaxial tension test; 2) Plane-strain tension test; and 3) Uniaxial tension M_s^σ measurements. The uniaxial tension tests are especially useful in comparing these results to other published data. The uniaxial tension tests also provide a convenient way to monitor the influence of thermo-mechanical processing (TMP) on the stability and volume fraction of the retained austenite. The ultimate mechanical property objectives of this research are specified for plane-strain tension as the stress-state encountered at the site of failure in sheet steel forming. The M_s^σ(U.T.) measurements show more explicitly and quantitatively the increased stability of the retained austenite with increasing IT times. XRD analysis of the specimens showed that the stability of the retained austenite was of greater importance to mechanical properties then the volume fraction of retained austenite. The XRD also showed the effects of carbon content and, indirectly, size upon the stability of the retained austenite.

UNIAXIAL TENSION TEST- The general trend of the ultimate tensile strength is to decrease as the IT time is increased (Fig. 5). A log-log plot of the true stress versus true strain flow curves at various IT times (Fig. 6) shows that the curves are almost parallel. This allows for an easy way to model the effect of IT time in the form of:

$$\sigma=\sigma_o(1+K\varepsilon^n)$$

The 'K' parameter is a function of IT time and provides a way to judge the effectiveness of the TMP. This will be used in future modeling of the effects of IT time upon mechanical properties. The amount of uniform and total elongation increases rapidly at first and then levels off at two minute and greater IT times (Fig. 7). This is due to unstabilized austenite transforming to martensite at short IT times. At longer IT times it decomposes to ferrite and bainitic ferrite which can then stabilize the remaining austenite. As the IT times increase past the retained austenite peak the volume fraction of retained austenite is continuously decreasing due to decomposition but the stability of the remaining retained austenite is continuously increasing due to carbon enrichment and decreasing pool size. This is discussed more fully later.

The yield strength increases slightly with IT time (Fig. 8) due to the greater strength of the bainitic ferrite which is produced by the decomposition of the austenite as compared to marginally stabilized retained austenite which decreases the strain hardening rate as it transforms and induces early yielding. As the IT times increase up to two minutes the martensite formed from retained austenite is increasing in carbon content and hence strength. After two minutes the retained austenite has effectively reached its maximum carbon content and increases in yield strength are due to increasing volume fractions of bainitic ferrite.

The 3% flow strength is relatively unaffected by increasing IT times. The increase in bainitic ferrite and greater stability of the retained austenite as the IT time increases apparently offsets the greater amount of martensite formed at small strains after short IT times due to the reduced stability of the retained austenite (Fig. 8). Similar to figure 1, a plot of uniform elongation under uniaxial tension versus the three percent flow stress for two steels undergoing the same TMP (Fig. 9) shows the effect of composition upon these properties, defining a band of possible properties for each composition as a function of time.

PLANE-STRAIN TENSION TEST- The plane-strain tension test showed the sensitivity of the retained austenite to stress state. A greater increase in uniform ductility was experienced during plane-strain testing due to increasing IT time than during uniaxial tension tests (Fig. 10). This can be attributed to an increased importance of the retained austenite stability and volume fraction. Before the volume fraction peak of retained austenite the retained austenite is of insufficient stability to provide much mechanical stability, i.e. delay the onset of localized necking. After the volume fraction peak a substantial reduction,

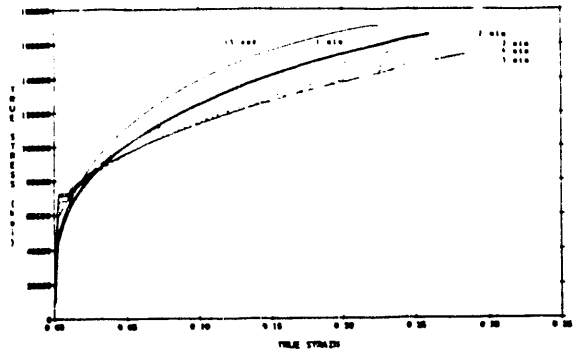


Fig. 5. True stress v. true strain flow curves showing the effect of varying IT time.

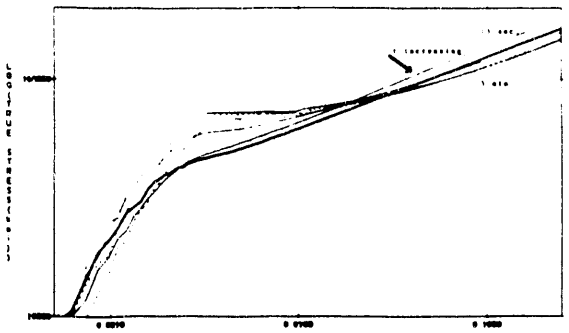


Fig. 6. Log-log plot of the true flow curves showing approximate parallelism of curves after a minimal strain was achieved.

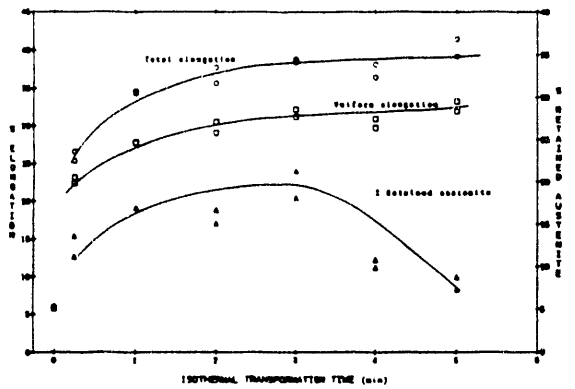


Fig. 7. Effect of IT time upon elongation.

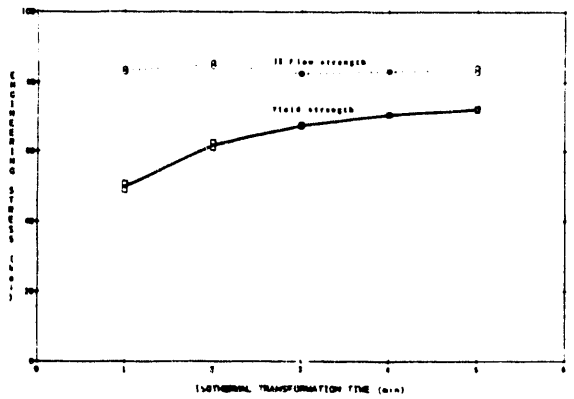


Fig. 8. Effect of IT time on the yield strength and 3% flow strength.

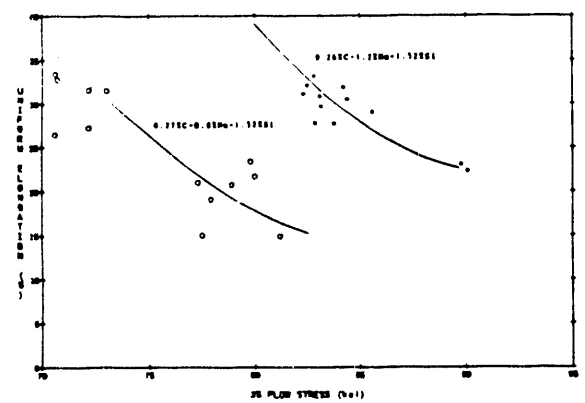


Fig. 9. Correlation between 3% flow strength and uniform elongation under uniaxial tension for both steel compositions.

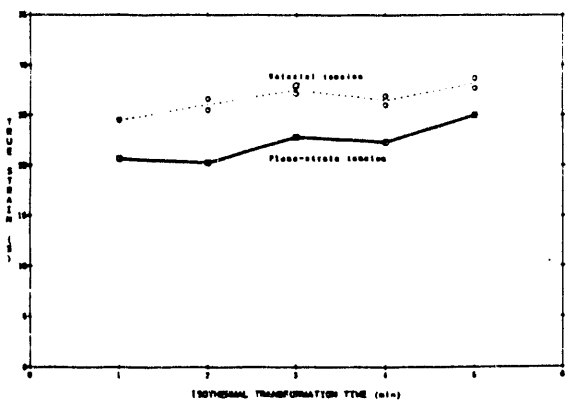


Fig. 10. Variation in true uniform ductility as a function of IT time demonstrating the greater effect of austenite stability under plane-strain conditions than uniaxial tension.

approximately one half (Fig. 11), in volume fraction of retained austenite occurs at four minutes IT time without a corresponding increase in retained austenite stability. The next IT time studied, five minutes, shows a marked increase in mechanical stability. This is due to the significant increase in retained austenite stability. The increased stability is not from an increase in percentage carbon in the retained austenite (Fig. 11), which levels out after about two minutes IT time, but due to the smaller size of the retained austenite pools (Fig. 12).

M_s^σ(U.T.), XRD, and METALLOGRAPHY- The M_s^σ(U.T.) results when combined with the XRD and metallography results are very informative. The M_s^σ(U.T.) tests show a decrease in M_s^σ(U.T.) temperature with increasing IT time (Fig. 13) as expected. The XRD results provide both the volume fraction of retained austenite (13) and carbon content, via lattice parameter measurements (14,15) (Fig. 11). These results show the maximum carbon content is achieved at about two minutes IT time, while the retained austenite volume fraction peak occurs at three minutes. Prior to the peak, insufficient carbon has diffused into all of the (nonuniform) austenite to stabilize it against transformation upon cooling to ambient. After the peak in volume fraction of retained austenite, since the carbon content is approximately constant, it is suspected that the excess carbon is precipitated as cementite. Previous research (6) has found carbides precipitating after four minutes. Transmission electron microscopy is planned to determine definitively if that is the case in this study.

The metallography results then provide the reason for increasing stability with increasing IT time. The results (Fig. 12) show a decrease in retained austenite pool size with increasing time. Determination of mean intercept lengths was not possible using optical microscopy due to the concavity and connectivity of the retained austenite. Further analysis is planned using a Tracor Northern Image Analyzer. The austenite is the white phase, the dark phase is the ferrite and bainite. This factor provides additional stability to the retained austenite. Further analysis by a JEOL JXA-8600 Electron Microprobe X-Ray Analyzer showed only a minor partitioning of Mn to the austenite, 1.48% ± 0.08 versus 1.35% ± 0.17 in the ferrite, and Si to the ferrite, 1.27% ± 0.05 versus 1.18% ± 0.08 in the austenite, during the intercritical anneal. The microanalysis results can only be viewed qualitatively due to the use of a tint etchant to provide phase identification.

DISCUSSION

The effect of stress-state upon the transformation kinetics of austenite to martensite have been well studied. An early model that successfully predicted the change in the M_s temperature was the Patel-Cohen model (7). They showed that the M_s temperature was raised by uniaxial tension, raised less by uniaxial compression and lowered by hydrostatic pressure.

A later model developed by Haezebrouck (9) was based upon the earlier model of Olson and Cohen (8). Haezebrouck studied the effect of stress-state upon the free energy change due to stress in the driving force term of the Olson-Cohen minimum defect size model required for the nucleation of martensite. Haezebrouck developed a relationship between stress-state and the mechanical driving force contribution.

An understanding of the relationship between the amount of retained austenite, its' stability as a function of pool size and carbon content, and mechanical properties is critical to properly exploiting the benefits of a triple phase steel. The specimen with the maximum volume fraction of retained austenite (three minute IT time) did not provide the best mechanical properties. A larger carbon content would be required for the steel composition to stabilize approximately 20% retained austenite compared to the specimen with the best mechanical properties and lower retained austenite of approximately 8%. Contours of constant uniform ductility vs. austenite amount and stability (measured as $T\text{-}M_s^\sigma$, where T is here room temperature) are drawn in Fig. 14 employing the experimental measurements. Based on previous studies of transformation plasticity in austenitic steels (21), optimum austenite stability for ductility enhancement would correspond to $T\text{-}M_s^\sigma$ = +68F (20C) and the contours of Fig. 14 are drawn to reflect this experience. The best properties should be achieved with an M_s^σ slightly below room temperature. Since the maximum carbon content in the retained austenite was reached fairly early, two minutes IT time,

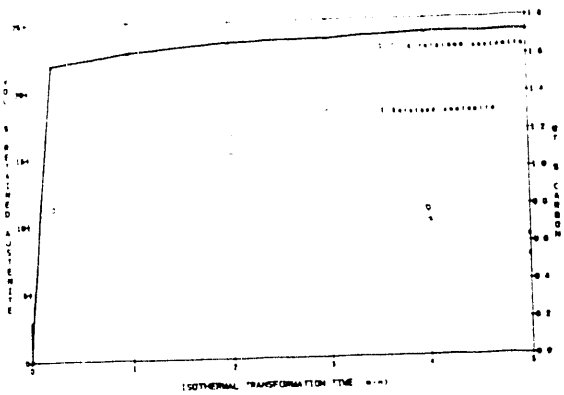
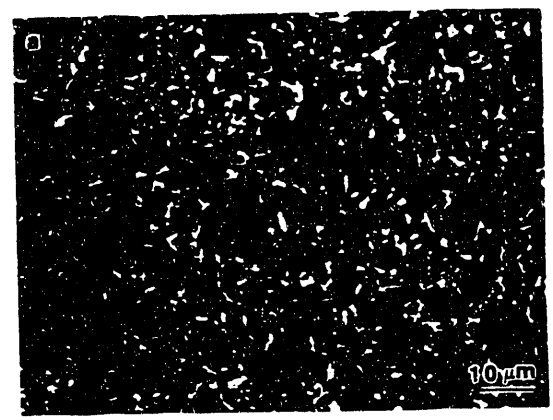
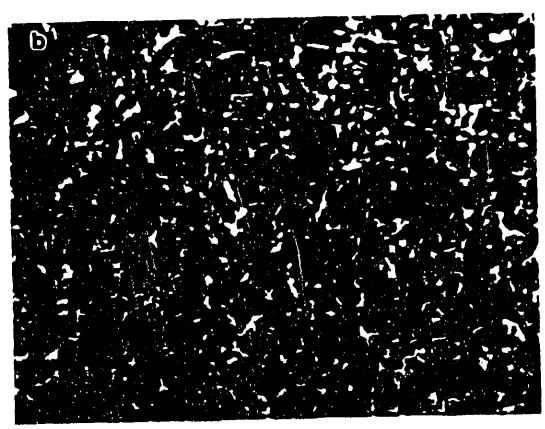
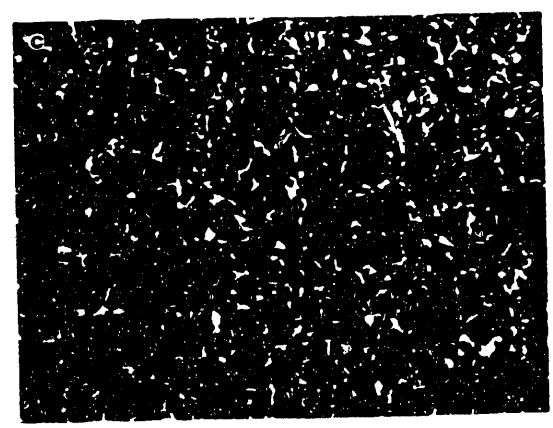
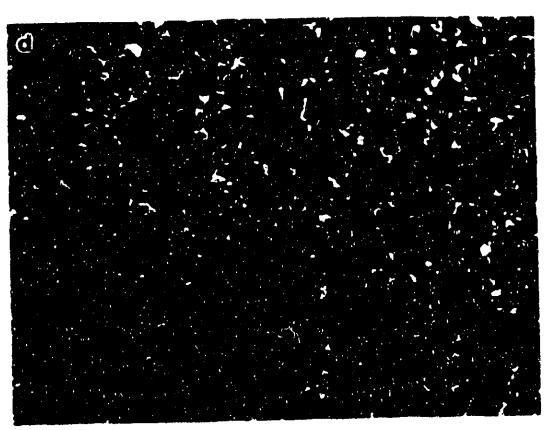


Fig. 11. X-Ray analysis of the percentage retained austenite and corresponding carbon content as a function of IT time.









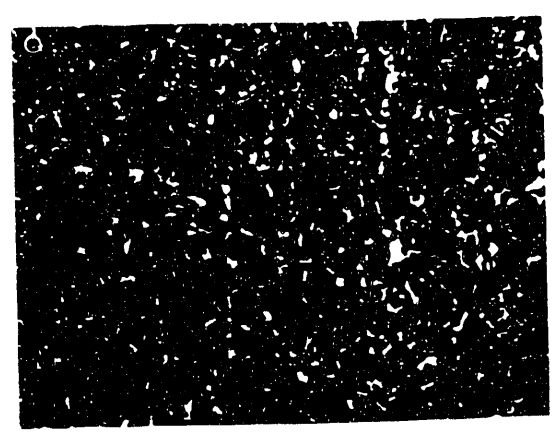


Fig. 12. Optical micrograph with a tint etchant showing the effect of IT time upon the retained austenite pool size. White phase is retained austenite, dark phase is ferrite and bainite: a) 1 min. IT time; b) 2 min.; c) 3 min.; d) 4 min.; and e) 5 min.

DISCLAIMER

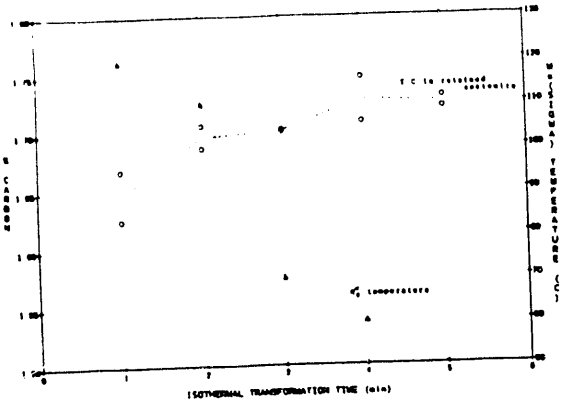


Fig. 13. Correlation of M_s^σ measurements with IT time and carbon content of the retained austenite.

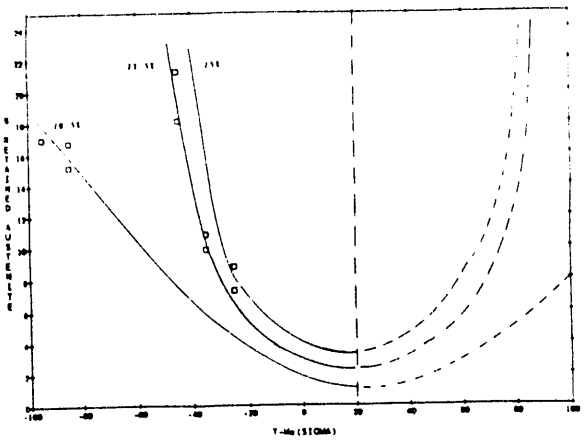


Fig. 14. Correlation of the amount of retained austenite as a function of ($T-M_s^\sigma$). Isocontours of true uniform ductility under plane-strain are plotted demonstrating the effect of austenite stability upon ductility.

a steel with retained austenite of sufficient stability due to small pool size might be developed with a more appropriate composition for commercial use. The decreasing M_s^σ(U.T.) temperature is due to the decreasing pool size (Fig. 13) after two minutes. Prior to that point it is a combination of pool size and carbon content that is affecting the stability.

CONCLUSIONS

The results obtained here emphasize the important role of austenite stability in the enhancement of uniform ductility in triple-phase steels. Superior properties are obtained with only 8 percent austenite compared to 20 percent austenite when the austenite stability is sufficiently increased toward the optimum. The results further indicate that particle size refinement is an important contribution to enhanced stability in addition to carbon enrichment. Further ductility enhancement should be attainable with relatively modest amounts of austenite, if the M_s^σ temperature can be depressed below ambient.

ACKNOWLEDGEMENTS

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