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January 1969

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HIGH STRENGTH STEELS - PRESENT STATUS AND FUTURE PROSPECTS*

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Abstract

The factors limiting the ductility of high strength steels are discussed, and the development of a new class of high strength steels with enhanced ductility is reported. The elongation as measured in a tensile test decreases as the yield strength of the steel is increased, and above 200,000 psi elongation values of only 10-15% are characteristic. At high yield strengths, steels also become more susceptible to brittle fracture when notches or cracks are present. This investigation was undertaken to determine whether or not the ductility and the notch toughness of high strength steels could be enhanced in any way. A study of the problem showed that the tensile elongation was not a good criterion of the inherent ductility of steels. The reduction in area, which is a meaningful measure of the true ability of a steel to deform before fracturing, is about 50% for all of the commonly used high yield strength steels. This value translates into an elongation potential (e.g. in a gage length of 0.01 inch) of 100% for steels with yield strengths up to 350,000 psi. The low reported elongation values reflect a plastic instability characteristic caused by the strain hardening rate being too low to prevent necking at low strains. A means for increasing the strain hardening rate was needed for high yield strength steels if the elongation was to be increased. The authors and their co-workers designed high yield strength metastable austenitic steels that would transform to martensite when strained. This phase transformation increased the strain hardening rate and enhanced the elongation by factors of two to four. At yield strengths above 200,000 psi the notch toughness of these steels exceeds those of quenched and tempered steels and is comparable with those of the maraging alloys. High resistance to corrosion and to hydrogen embrittlement was also exhibited by these new steels. They are now available commercially in some forms.

Introduction

A generally accepted axiom is that "strong materials are normally brittle," and strong steels have been no exception. This concept has arisen because of the brittle behavior of high strength materials in some engineering structures, and also because when a given class of alloys is made strong by heat treatment or processing the ductility invariably decreases as the yield strength is increased. This is illustrated by Figure 1 which shows the yield strengths for various kinds of steel plotted against the elongation as measured in a standard tensile test. Essentially all of the test values fall in the shaded bands. The lower portion is that for quenched and tempered commercial SAE steels. Above that, and merging into it, is the band for maraging alloys and at still higher strength levels, the ausformed materials. Research efforts on ausformed and maraging steels have been successful in that they have resulted in stronger materials, but they have not produced materials with both high strength and enhanced ductility. In our recent work we elected to examine the basic concepts of flow and fracture in high strength materials (i.e. steels with yield strengths over 200,000 psi). Our objective was to see if the basic knowledge acquired in recent years could be applied to the study of high strength alloys in such a way that the ductility and toughness would be enhanced.

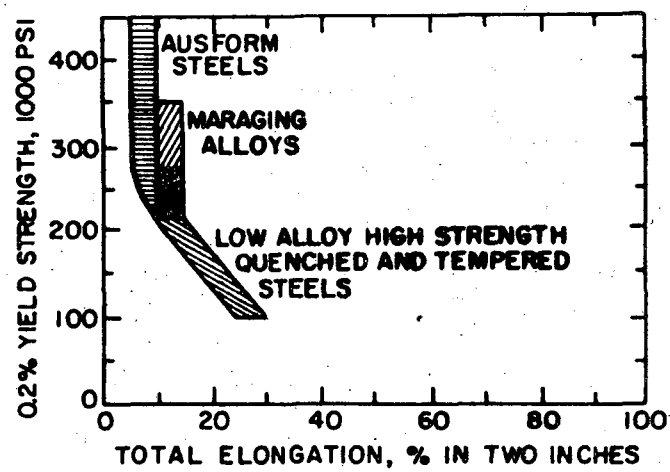

Figure 1. Range of elongations and yield strengths of commercially available steels.

Our first step was to examine the properties of existing high strength steels to determine, if possible, the cause of the low ductility and brittle behavior of high strength steels. It immediately became evident that these steels were not inherently brittle as the yield strength-elongation plot had indicated. The reductions in area in all cases up to strength levels in excess of 300,000 psi were in the range of 40 to 60% with an average of about 50%. Thus, if elongation had been measured arbitarily over a gage length of 0.01 inch, for example, instead of the conventional two inches, the plot would have looked like Figure 2. The concept that high strength steels are inherently brittle obviously has to be modified. The use of continuum mechanics concepts turned out to be more useful in leading us in a fruitful direction of research than did concepts of dislocation behavior. The problem of low ductility in high strength steels was resolved into the problem of local plastic instability caused by the inability of the material to strain harden at a rapid enough rate to compensate for the reduction in cross sectional area produced by the plastic flow as the material was stretched in the tensile test.

The criterion for local plastic instability in a tensile test in terms of true stress - true strain parameters is that when the true stress, σ, becomes

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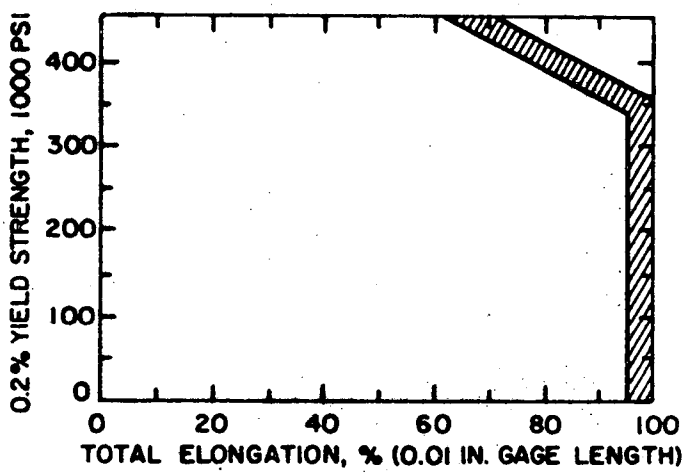

Figure 2. The 0.2% yield strength and the total elongation at failure as calculated from reduction in area measurements and translated into elongation in a 0.01 inch gage length.

numerically equal to the rate of strain hardening, $\frac{d\sigma}{d\varepsilon}$, necking begins. Thus, in order to retain high values of elongation in a two inch gage length as the yield strength increases, it is necessary to increase the rate of strain hardening in direct proportion to the increase in yield strength. Unfortunately, nature does not automatically provide this accommodation, as Figure 3 shows. In this figure, true stress - true strain curves are plotted for a 4340 steel that had been heat treated to different yield strength levels. All curves are substantially parallel beyond the yield strength. The rate of strain hardening, which is due to dislocations interacting with each other and with precipitate particles, is unaffected by the heat treatment. Consequently, necking begins at lower and lower values of true strain as the yield strength is increased. At present there is no known way in which dislocations can be made to interact to produce higher rates of

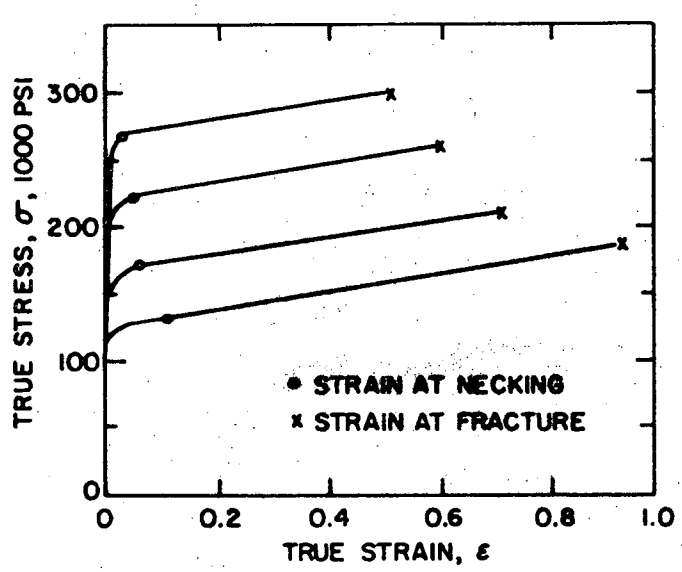

Figure 3. True stress - true strain curves for quenched and tempered SAE 4340 steel showing variation in necking strain with strength level, and that the rate of strain hardening, $d\sigma/d\varepsilon$, is substantially independent of the strength level.

strain hardening as the yield strength is increased. Some more effective mechanism of strain hardening had to be found in order to enhance the ductility of high strength steels.

Experimental Procedure and Results

There are very few changes in internal structure other than those associated with dislocations that can be made to occur as a consequence of plastic flow. Nonetheless, there is one that can have a pronounced effect on mechanical behavior, namely the "martensite" transformation, in which a face centered cubic form of iron is changed into a body centered tetragonal one. In certain alloys, this change can be made to take place during straining. It normally occurs during cooling to room temperature in the quenched and tempered type of SAE steels, in the maraging, and in the ausform alloys; in the austenite type of stainless steels the transformation does not occur at all during cooling and it may not even occur on cooling to liquid nitrogen temperature.

Nickel and chromium are the elements used in combination to produce a stable austenite (face centered cubic) structure at room temperature. When the nickel and chromium contents are adjusted, along with other alloying elements, the austenitic material becomes unstable at room temperature. It can be made to transform to the thermodynamically more stable body centered cubic structure characteristic of ordinary steels by plastic deformation. Chemical compositions of some steels that have this metastable structure are shown in Table I. As mentioned earlier, barriers stronger than dislocation tangles must be introduced during plastic straining if the onset of necking is to be delayed so that the inherent ductility, as indicated by the reduction of area, can be utilized in the form of uniform strain. It is important that these barriers be introduced during straining, not before, otherwise they would increase the yield strength but would not necessarily increase the rate of strain hardening. Strain induced martensite plates can act as strong barriers, particularly when the carbon content exceeds about 0.2%.

Table I

PRELIMINARY CORROSION DATA FOR TRIP STEEL [a]

Composition	Corrosion Rate, mils/year
0.24C, 9Cr, 8Ni, 4Mo	8
0.24C, 12Cr, 8Ni, 3.5Mo	3
Commercial 302 stainless [b]	5
Commercial 310 stainless [b]	0.4

(a) Tested in 10% H_2SO_4
(b) Data from literature included for comparison

The strain induced martensite transformation has been recognized and studied by numerous investigators. Particularly relevant to the present study are two recent papers. Banerjee, Capenos and Hauser[1] were among the first to recognize the role of the transformation in delaying necking. Bressanelli and Moskowitz[2] made a comprehensive study of the combined and individual effects of composition, test temperature, and deformation rate on the tensile properties of Type 301 stainless steel. They clearly demonstrated that the mechanical properties of metastable austenite are dependent on the formation of strain induced martensite, and that the production of this martensite is in turn dependent on

the conditions imposed during the test. They showed that martensite produced during straining can prevent early failure by necking by increasing the rate of strain hardening.

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Figure 4. The microstructure of a steel tensile bar containing 8.9%Cr, 7.6%Ni, 4.0%Mo, 2.0%Mn, 2.0%Si, and 0.25%C that had been thermomechanically processed by reducing thickness 80% by rolling at 840°F and then broken at room temperature. Narrow dark bands are martensitic regions formed from the austenite during plastic straining. 1000X. Original magnification reduced by 25% in reproduction.

Previous efforts to obtain high levels of strength and ductility by composition control have not been particularly successful. Kula[3] concluded, in a critical review of this problem , that all attempts to strengthen these steels by increasing the carbon content above about 0.06% invariably led to embrittlement. A different approach to the problem was clearly needed if a significant increase in strength, without an accompanying loss in ductility were to be obtained. In our work, we used thermomechanical processing to avoid the formation of the unfavorable microstructures that had caused the poor ductilities in the earlier investigations.[4] Briefly, the process consists of deforming the austenite at an elevated temperature, for example, 840°F by a substantial amount (up to 80% reduction in thickness). During this processing networks of dislocations are introduced into the material and carbides precipitate in the deformed regions of the crystal lattice. The carbides thus formed are dispersed essentially uniformly throughout the crystals. The austenite, when cooled to room temperature, exists in the precipitation hardened state. Steels thus processed have yield strengths ranging from 150,000 psi to 300,000 psi. Because of the loss of carbon, the austenite is then less stable at room temperature. When this austenite is deformed it transforms to martensite. This is illustrated by the photomicrograph in Figure 4. The bands of martensite that form in the austenite interfer with plastic deformation in an effective manner. The consequence of this is to increase the strength of the steel at a rapid rate during plastic straining. The difference between the quenched and tempered 4340 steel and the metastable austenitic steel in the rates of strain hardening is shown in Figure 5. The higher rate of strain hardening increases the strain prior to the onset of necking and hence enhances the ductility of the steel. Various combinations of yield strength and elongation are possible with metastable austenitic steels. A summary of results obtained to date are shown in Figure 6. In this same figure the strengths and elongations of commercially available steels are shown, as is the upper limit of strength and elongation known to be possible from reduction in area measurements. It is evident that there is still a large gap even between the values obtained to date with the metastable austenitic steels and the potential upper limit. Continued research should reveal additional steels that will have properties in the unexplored regions above the combinations of strength and ductility obtained to date.

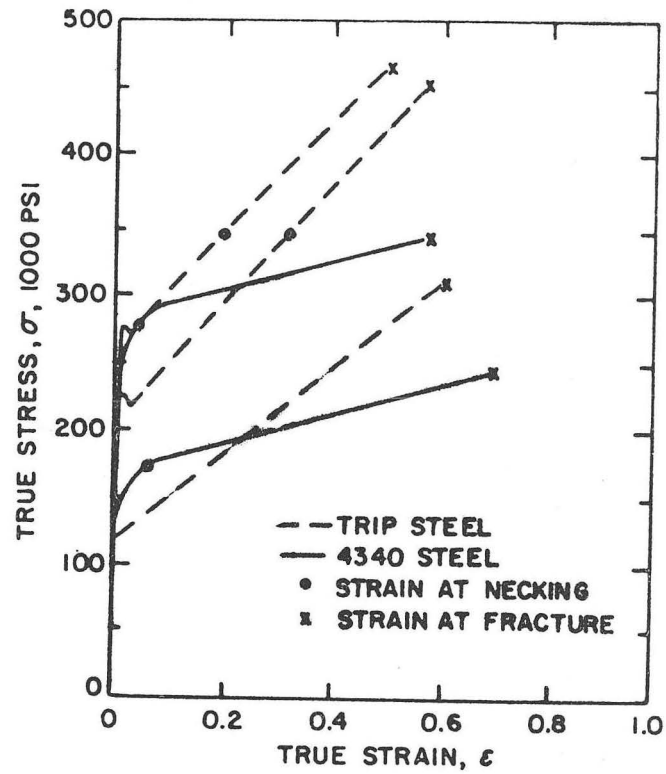

Figure 5. True stress - true strain curves for quenched and tempered SAE 4340 steel and the metastable austenitic (TRIP) steel, showing the higher rate of strain hardening of the latter and the consequent enhanced ductility.

Discussion

The unusually good combinations of strength and

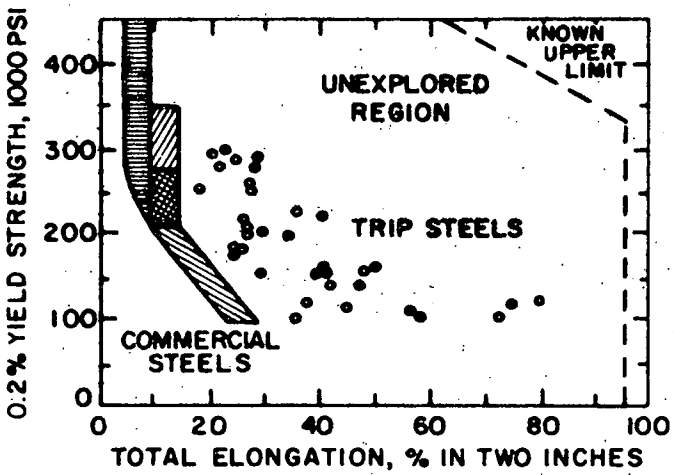

Figure 6. The 0.2% yield strength and the total elongation in two inches at failure for commercial steels and metastable austenitic (TRIP) steels, showing how the TRIP steels have advanced into the unexplored region.

elongation discussed in the preceeding section are important for many engineering applications, particularly those involving certain kinds of forming operations. For structural components, uniaxial ductility is not a good or sufficient indicator of service performance. In such applications ductility must also be present when the stress is triaxial in nature, such as at the tip of a crack or structural discontinuity. It has recently been shown that elongation and reduction in area measurements may have little bearing on the strain energy release rate (or the fracture toughness) of cracked plates having the same tensile yield strengths.[5,6] Consequently, preliminary investigations of the plane strain, K_{Ic}, and plane stress, K_c, fracture toughness were made on metastable austenitic steels.[6] Single edge notch specimens were used in these tests, with the notch extended by a fatigue crack prior to testing. Even at a thickness of 0.5 inch thickness no brittle fractures occurred, consequently it was not possible to obtain reliable values of K_{Ic}. Therefore, comparative values of K_c for quenched and tempered steels, maraging alloys and the metastable austenitic steels are shown in Figure 7. The resistance of the TRIP steels to crack propagation in the ductile or tearing mode is evidently about the same as that of the maraging alloys at room temperature. A test on a 0.5 inch thick specimen was also made at -196°C where the specimen was found to fracture in a flat mode. The K_{Ic} for this test was 139 ksi-in$^{1/2}$, which was very high for this 230 ksi yield strength material. Thus, the evidence to date indicates that the metastable austenitic TRIP steels have high notch toughness for both shear and flat modes of fracture.

A number of the high yield strength steels are sensitive to stress corrosion cracking and to hydrogen embrittlement. While the corrosion and hydrogen embrittlement tests made to date are preliminary in nature, the results obtained have been encouraging. In a recent article[8] some preliminary corrosion test results were reported. In this investigation, when stress corrosion and hydrogen cracking tests were run on 0.1 inch thick sheet specimens of TRIP steel with bent beam specimens stressed to 75% of the yield strength in a 5% neutral salt spray, no cracking was found after 500 hours. However, in similar specimens that had been cold rolled to produce some martensite, substantial general corrosion was found. In the hydrogen cracking test, similar specimens loaded to the same value were charged cathodically in a 0.1 normal H_2SO_4 solution containing 3 mg of arsenic per liter. No cracking was found in the TRIP specimens after 62 hours at 0.6 amps per sq. inch. In cold-worked specimens cracking occurred in about 10 hours under the same test conditions. The investigators concluded that TRIP steel in the processed condition is immune to both hydrogen cracking and stress corrosion cracking, but in the cold rolled condition the steel had a hydrogen cracking tendency similar to that of 12%Cr martensitic stainless Type 422. Preliminary corrosion tests made in our own laboratory are also encouraging. The results obtained are reproduced in Table I.

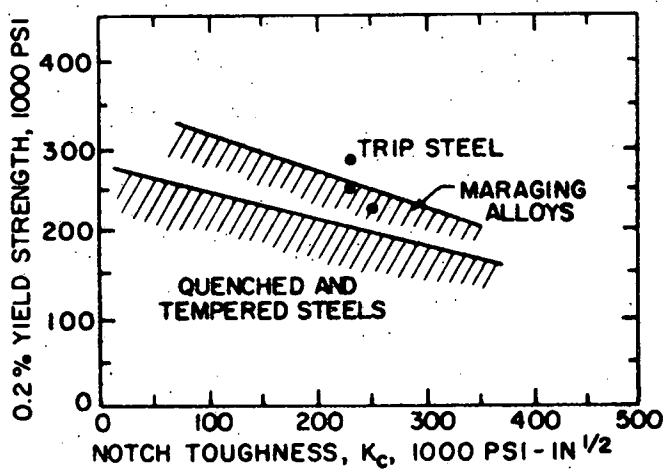

Figure 7. Typical values of the room temperature notch toughness parameter, K_c, vs yield strength for quenched and tempered steels and the maraging alloys. The few points available for metastable austenitic (TRIP) steels have been plotted as points on the graph.

Summary and Conclusions

The research on metastable austenitic high strength steels has revealed that there is a possibility of developing steels with yield strengths above 200,000 psi, elongations of the order of 40%, with high values of fracture toughness and with good corrosion resistance.

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