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Ultrahigh Carbon Steel for Automotive Applications

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ABSTRACT

Ultrahigh carbon steels (UHCSs), which contain 1-2.1% carbon, have remarkable structural properties for automotive application when processed to achieve fine ferrite grains with fine spheroidized carbides. When processed for high room temperature ductility, UHCS can have good tensile ductility but significantly higher strength than current automotive high strength steels. The material can also be made superplastic at intermediate temperatures and exhibits excellent die fill capability. Furthermore, they can be made hard with high compression ductility. In wire form it is projected that UHCS can exhibit extremely high strengths (5000 MPa) for tire cord applications. Examples of structural components that have been formed from fine-grained spheroidized UHCSs are illustrated.

INTRODUCTION

Ultrahigh-carbon steels (UHCSs) are plain carbon steels with carbon content (1 to 2.1% carbon) beyond the eutectoid composition. These steels, which contain 15-32 vol.% iron carbide, have historically been neglected by industry because of a belief that they are inherently brittle. The primary reason for this belief is that brittle proeutectoid carbide networks can be formed along grain boundaries if appropriate processing procedures are not used. However, novel thermomechanical processing and heat treatment techniques have been developed at Stanford University and the Lawrence Livermore National Laboratory to break up the carbide network and produce microstructures containing fine equiaxed ferrite grains and uniformly distributed carbides. These steels can possess a unique set of properties, unavailable in other materials, that make them well suited for structural applications [1]. Specifically, UHCSs can have high ambient-temperature strength, hardness and ductility, and excellent high-temperature formability via superplasticity. In this paper we describe the composition and processing of this unique steel, as well as the resulting properties, characteristics and applications that are relevant to the automotive industry.

COMPOSITION AND PROCESSING

The UHCSs investigated so far contained 1 to 2.1 wt.% C, and other alloying elements, such as, Al, Cr, Si, and Mn of varying contents. The Al is added to increase the A_1 transition temperature, the Cr to prevent graphitization, the Si to raise the A_1 temperature and to inhibit particle carbide growth and the Mn to neutralize the deleterious effects of sulfur and phosphorus.

Various thermomechanical and heat treatment processes have been developed [2-8] to eliminate the proeutectoid carbide network and convert the coarse lamellar pearlitic matrix in the starting material to fine grained ferrite matrix with finely spheroidized carbides. The thermomechanical and heat treatment processes employed include hot and warm working (HWW), divorced eutectoid transformation (DET), divorced eutectoid transformation with associated deformation (DETWAD), and their variations and combinations.

The HWW process refines the austenite grain size and more importantly, breaks down the proeutectoid carbide network. The starting UHCS material is heated to the austenite region where carbon is completely dissolved in the austenite iron and then continuously worked by rolling or forging until the material is cooled below the A_1 temperature. The hot working in the austenite region refines the austenite grain size and the subsequent warm working between the A_{cm} and A_1 temperatures allows the proeutectoid carbide to precipitate and grow discontinuously on the austenite grain boundaries instead of forming a continuous network. The refined austenite matrix then transforms to pearlite when cooled to room temperature. The HWW'ed microstructure thus consists of the proeutectoid carbides broken down into spherodized proeutectoid carbide particles and a pearlite matrix. The DET process converts the lamellar carbide in the pearlite matrix to spheroidized carbide. The pearlite structure is heated to a temperature above the A_1 point, where it is thermodynamically unstable, and most of the carbide rapidly dissolves in iron. The remaining undissolved carbides are finely dispersed and become spherical rapidly. The dissolved carbon atoms are non-uniformly distributed, at least for a short while, in the regions where the pearlitic carbides originally existed. During cooling, the undissolved carbides and non-uniform distribution of carbon act as sites for nucleation and growth of carbides and results in a fine, uniform carbide distribution with no pearlite formed. The DETWAD process accelerates the DET process by using concurrent deformation, increasing the extent of spherical carbide formation and refining the ferrite grain size. The concurrent deformation begins just above the pearlite - dissolution temperature and continues as the material cools through the A_1 temperature. Combination of these processes can produce submicron sized ferrite grains and spheroidized carbides.

The spheroidized carbide and equiaxed ferrite grain structure can be transformed to pearlite, bainite, or martensite in ultrafine structure form, or their combinations through appropriate thermal or thermomechanical processing methods for further strength or other property advantages.

ULTRAHIGH STRENGTH STEEL SHEET AND PLATE

PROPERTIES - Sheet steels based on ultrahigh-carbon contents represent a new and unique approach which is opposite to the current trend in steels. Specifically, over the last thirty years, the carbon content in commercially available sheet steels has been decreasing [9]. The ultralow-carbon steels that are currently available have been developed primarily for automotive sheet-stamping applications in which high formability and weldability are of paramount importance. However, reducing the carbon in these steels also reduces strength. As a result additional strengthening mechanisms, using solid-solution and precipitation hardening approaches, have been required to achieve improved strength. The welding problem that exists in low and medium carbon steels may not exist in UHCS because the metallurgy of transformation is so dramatically different from that observed in low carbon steels.

An example of spheroidized microstructures and the corresponding room temperature stress-strain curves for a UHCS-1.8% C-1.6% Al material is shown in Fig. 1. Micrograph (a) shows large ferrite grains (~3.5 μm grain size) and large carbides (average carbide size -about 1 μm at grain boundaries and about 0.8 μm in the grain interiors). At the other extreme, micrograph (d) shows a very fine spheroidized structure that has a mean carbide size at grain boundaries and a mean ferrite grain size of about 0.3 μm, with a mean carbide size in grain interiors of 0.22 μm. The finest microstructure shown in micrograph (d) corresponds to the stress-strain curve (d) that has the highest yield strength (1470 MPa) but the lowest total elongation (2.2%). The coarsest structure (a) corresponds to curve (a), which shows the lowest yield strength (780 MPa) but the highest total elongation (25%). Syn, Lesuer and Sherby [10] have shown that the yield strength of the spheroidized UHCS-1.8% C-1.6% Al material is a unique function of the grain size and grain interior carbides, while the fracture strength is a unique function of the carbide particle size at grain boundaries and the carbide strength [11]. Room tem-

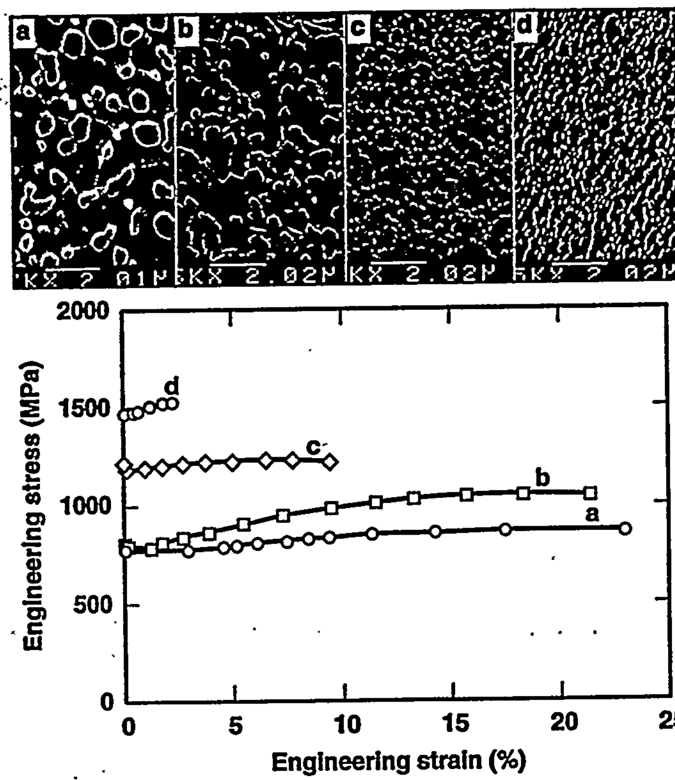

Figure 1. Micrographs of UHCS and corresponding stress-strain curves. The UHCS has been processed to various equiaxed ferrite grain sizes and spheroidized carbides.

perature properties of other UHCS materials are described elsewhere [2] and the effect of heat treatment is covered in a subsequent section.

APPLICATIONS - For sheet/thin plate applications, high strength and good cold-stamping characteristics are often required. UHCSs are a logical material substitution for high-strength sheet components that are strength limited rather than stiffness limited. The primary driver for high-strength steels in automotive sheet applications is often weight reduction which results in enhanced performance and fuel economy.

In Fig. 2 the tensile true stress - true strain curve for UHCS processed for high ambient temperature ductility (coarse ferrite grains and fine carbides at the grain boundaries) is compared with the tensile behavior of four steels suitable for automotive applications. The data for these four steels was obtained from reference 12. One of the steels in Fig. 2 is a plain, low carbon steel with properties representative of steels currently used in cold stamping operations. The remaining three steels are dual phase steels with properties representative of the so-called high strength steels. As can be seen the UHCS has comparable tensile elongation to the other steels; however, it has significantly higher yield and flow stress. The formability of UHCS has not been evaluated; however, the high tensile ductility and high work hardening rate of this material, as shown in Fig. 2, suggests that, in the appropriate microstructural condition, UHCS can have forming limits as good as the dual phase steels shown in the figure.

Another important characteristic of UHCS is that the material retains its high strength at typical tempering temperatures. This property is important for elevated temperature-high strength applications such as high strength clutch plates, where a loss in strength would occur in martensite-containing steels. The UHCS materials described here retain their strength at tempering temperatures because the ferrite-carbide microstructures are stable.

SUPERPLASTIC FORMING

One of the biggest advantages of the fine-grained UHCS reported here is the opportunity for net shape forming using superplasticity [2,13]. Because of the fine grain sizes developed in these materials, elongations in excess of 600% have been obtained in plain-carbon UHCSs at warm-working temperatures [14,15]. For plain-carbon and dilute-alloyed UHCSs, the range of temperature and composition over which superplasticity has been observed is shown on the Fe-C phase diagram in Figure 3. Grain sizes evaluated were typically around 2 μm. For the UHCS-composition range (1.0-2.1% C), superplasticity can be observed at temperatures from 650°C-800°C. This temperature range extends above and below the A_1 transformation temperature and thus includes microstructures containing ferrite and carbides or austenite and carbides. The carbides help maintain a fine-grained microstructure by pinning the grain boundaries and retarding the grain-growth kinetics. In the austenite-plus-carbide region, the maximum temperature for superplasticity is determined by grain growth kinetics and the loss of the fine-grained microstructure. Grain growth is rapid in the austenite-plus-carbide region because much of the carbide that is present in the initial ferrite-plus-carbide structure is lost due to the high solubility of carbon in austenite. Superplastic behavior has also been achieved with carbon contents in excess of 2.1% C (Fig. 3). These are the cast irons (2.1%-4.3% C) and hypereutectic irons (5.25% C) [16-19]. For hypereutectic irons, the matrix is iron carbide with discontinuous ferrite. The fine equiaxed grains required for superplasticity in these materials were prepared by powder metallurgy routes.

For plain-carbon UHCSs, the maximum strain rate for superplasticity is about $10^{-3}\ s^{-1}$ which is achieved just below the A_1 transformation temperature [15]. This strain rate can be increased dramatically through suitable

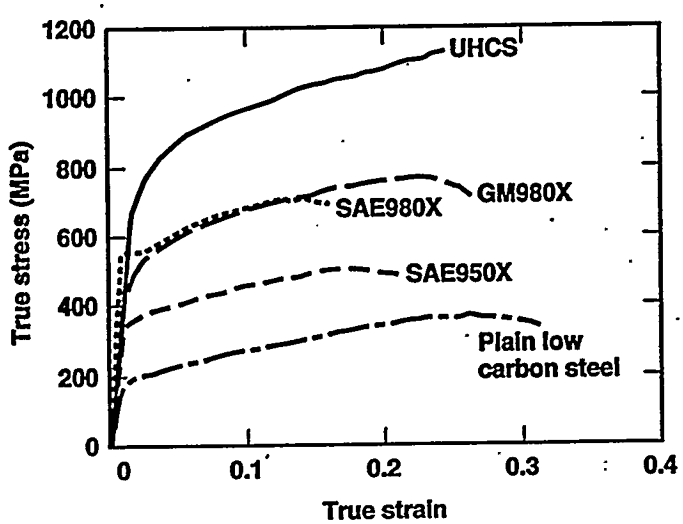

Figure 2. Comparison of the tensile stress-strain behavior of UHCS and four other steels suitable for automotive applications. The UHCS has been processed for high room temperature ductility.

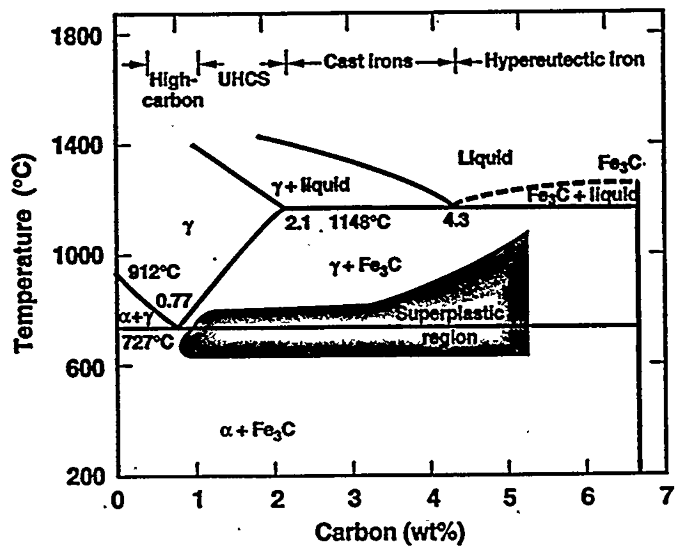

Figure 3. The Fe-C phase diagram showing the region of composition and temperature within which superplasticity has been observed in UHCS.

alloying additions such as aluminum or silicon [20-22], which either (a) permit UHCSs to be deformed at higher temperatures within the range of superplastic flow without objectionable amounts of grain growth, or (b) inhibit the transition from grain-boundary sliding (superplastic behavior) to slip creep (non-superplastic behavior) by raising the flow stress for slip creep. Higher superplastic-deformation temperatures are obtained with these alloying additions because they influence the characteristics and microstructure of UHCSs in at least one of four ways, by (a) increasing the A_1 transformation temperature, (b) inhibiting carbide coarsening because the activity of carbon in ferrite is increased, (c) forming complex carbides that resist coarsening, and (d) increasing the amount of proeutectoid carbides.

An example of high strain rate superplasticity in UHCS containing high aluminum content is illustrated in Fig. 4 for UHCS containing 1.5% C and 10% Al. The figure shows a sample before and after tensile deformation at 950°C and a strain rate of $3x10^{-2}$ s^{-1}. At this temperature the material was below the A_1 transformation temperature. The sample was stretched to an elongation of 1250% elongation without failure, which, at the strain rates indicated, required approximately 6 minutes to achieve. These results show the excellent potential for these fine-grained materials in high throughput commercial forming operations.

Figure 5 shows the maximum strain rate for superplasticity as a function of temperature for four different UHCS alloys containing aluminum and silicon [21,23]. All materials have a common initial grain size of 2 µm. UHCSs containing either 3% Si or 1.6% Al both exhibit superplastic flow at a maximum strain rate of 10^{-2} s^{-1} in the temperature range of 770°C-800°C. Aluminum appears to be much more effective than silicon in raising the superplastic forming rate. The figure also shows the predicted maximum superplastic-forming rate for a UHCS containing 12% Al with a grain size of 2 µm. This material should exhibit a maximum superplastic forming rate of $3x10^{-1}$ s^{-1} at 950°C, which is close to commercial forging rates. The very high strain rates possible with high aluminum concentrations illustrates the excellent potential for these fine grain materials for automotive applications.

Figure 4. High rate superplasticy in a UHCS-1.5C-10Al alloy. The figure shows a sample before and after tensile deformation at 950°C and a strain rate of .03 s-1. The sample was stretched to an elongation of 1200% without fracture in approximately 6 minutes.

FORGED PRODUCTS

NET SHAPE PROCESSING - The superplastic forming characteristics described in the previous section result from the presence of grain boundary sliding as a deformation mechanism which exhibits high strain rate sensitivity with low flow stress. Forging at temperatures and strain rates where this mechanism is activated can thus produce excellent die fill capacity and the opportunity for net shape processing. The excellent die fill capacity of these materials has been illustrated with the forging of prototype components which will be illustrated in a later section.

PROPERTIES AFTER HEAT TREATMENT - When a UHCS is processed to develop an ultrafine structure, it can then be heat treated to achieve unique microstructures and properties. Examples are the development of unique martensitic, bainitic and pearlitic structures [2,8,24,25].

Figure 6 illustrates coarse and fine martensitic structures in a UHCS material containing 1.8% C and 1.6% Al. Figure 6a shows the structure of the UHCS material after water quenching from 1000°C. At this austenitizing temperature, most of the carbides are dissolved and the austenite grain size is coarse. Thus, the quenched structure is seen to be coarse martensite. Such a coarse martensitic UHCS material, although very hard, does not have any significant compression ductility at room temperature [24]. When a fine-grained spheroidized structure is achieved, such as that shown in Figure 1, and the material is heated to a low austenitizing temperature (e.g. 810°C) and water quenched, the result is optically unresolvable martensite. An example of the fine martensitic microstructure obtained in the UHCS-1.8% C-1.6% Al material is given in Figure 6b. The SEM micrograph is

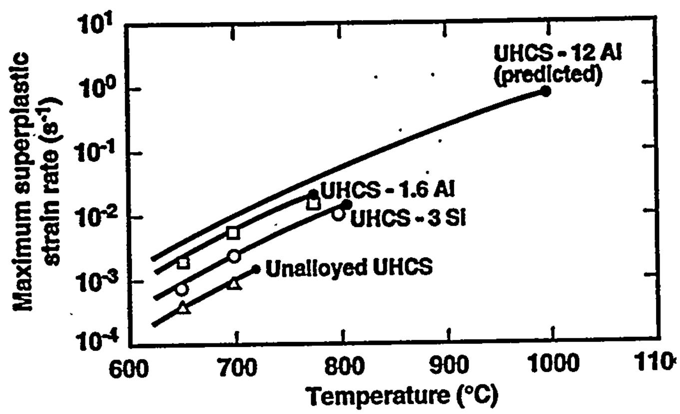

Figure 5 The influence of aluminum and silicon on the maximum strain rate for superlasticity. The maximum strain rate at the A_1 temperature is indicated by a solid circle.

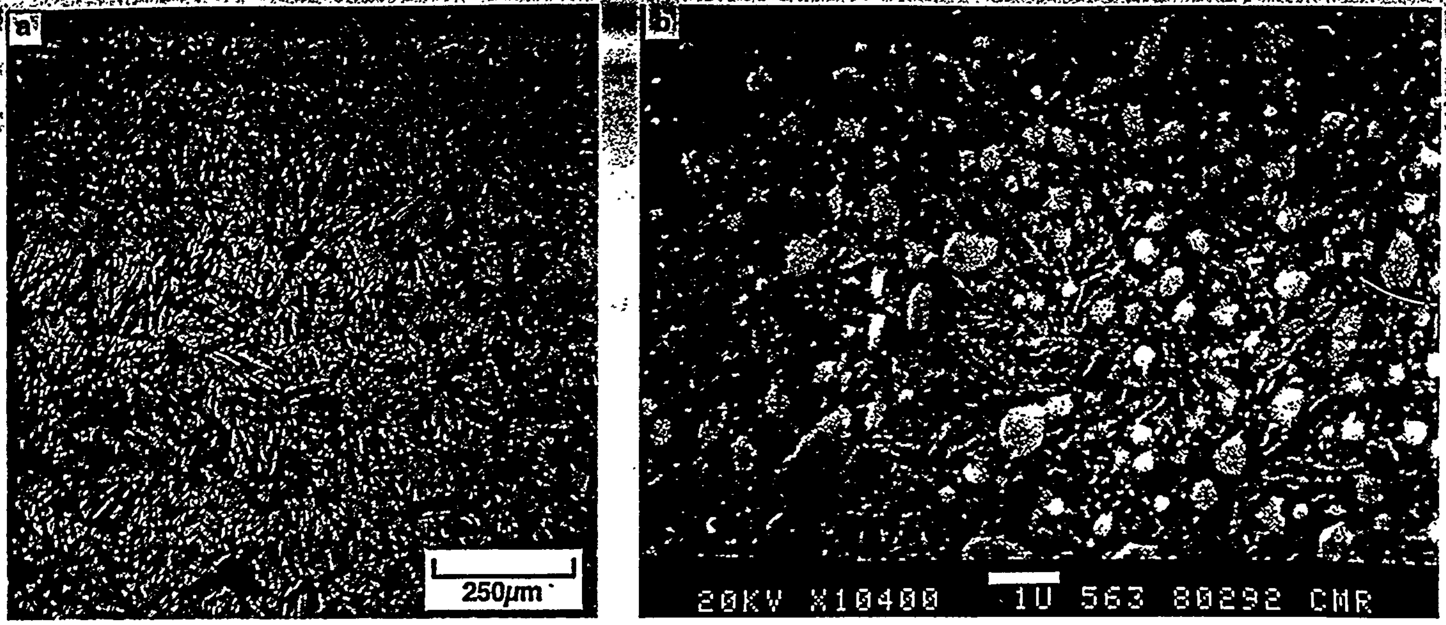

Figure 6 (a) Optical photomicrograph of UHCS-1.8% C-1.6% Al showing coarse (100 μm) martensite needles, and (b) SEM of UHCS-1.8% C-1.6% Al showing fine (<1 μm) martensitic structure with undissolved proeutectoid iron carbide particles.

at a magnification that is one hundred and twenty times higher than for the optical photomicrograph of coarse martensite (Figure 6a). The structure is seen to be ultrafine, with the martensite having a nondescript appearance and the background consisting of submicron-size spherical (undissolved) pro-eutectoid carbides.

Ultrafine martensite in a UHCS has remarkable compression properties [24,26]. Figure 7 compares the compression engineering stress-strain curve of a UHCS-1.25% C steel with a number of tungsten-cobalt alloys. The result is impressive: the fine martensitic UHCS is comparable to WC-12% Co in strength and has a considerably greater compression ductility. The UHCS achieved an engineering strain in compression of 26% with an engineering fracture stress of 4690 MPa (680 ksi). The curves also show that the UHCS absorbed large amounts of energy before fracture. This is an important characteristic for crashworthiness of structural members.

The tensile properties of UHCS have also been evaluated for different heat-treated conditions: bainitic, tempered martensitic, and fine pearlitic conditions. Examples are as follows. An ultimate tensile strength (UTS) of 1810 MPa (262 ksi) with 18% elongation was obtained for a fine bainitic structure in a UHCS-1.0% C-1.5% Cr material [8]. A UTS of 1400 MPa (190 ksi) with 25% elongation was obtained for a fine pearlitic structure in a UHCS-1.25% C-1.6% Al material. When an ultrafine pearlitic structure was developed, a UTS of 1655 MPa (240 ksi) with 12% elongation was obtained for a UHCS-1.8% C-1.6% Al material [25].

The range in tensile properties that can be obtained with heat treatment of a fine-grained UHCS with spheroidized carbides is shown in Fig. 8. In this figure the tensile strength is plotted as a function of elongation to failure for UHCS as well as three other common automotive steels - traditional mild steels, dual phase steels and HSLA steels. The figure shows that higher strength-ductility combinations are possible with UHCS than with the other steels.

A major deficiency of unalloyed ultrafine grained UHCSs is that they have low hardenability [8]. This is because grain boundaries are sources of nucleation of bainite and pearlite inhibiting the formation of martensite. It has been shown, however, that dilute alloying can enhance the hardenability of fine-grained UHCSs [27]. The method of Grange [28] was used for determining the hardenability and the results are reported in Table 1. It can be seen that the critical diameter is only 6.9 mm for

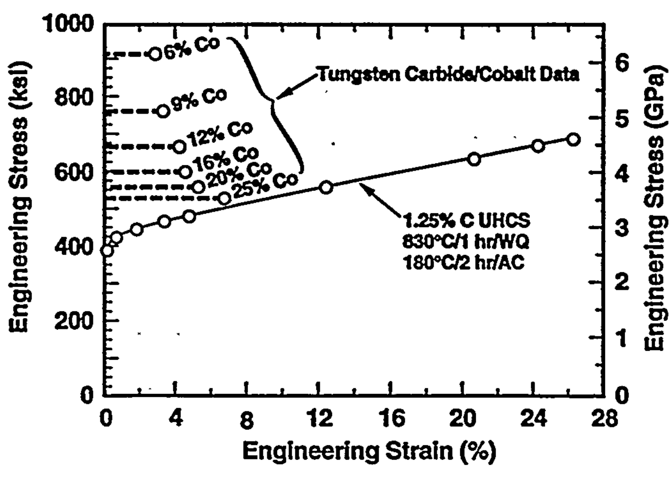

Figure 7. Engineering stress-engineering strain curve for a fine-grained martensitic structure UHCS-1.25% C material tested in compression at room temperature. Comparison is made with a number of tungsten carbide-cobalt alloys [25]

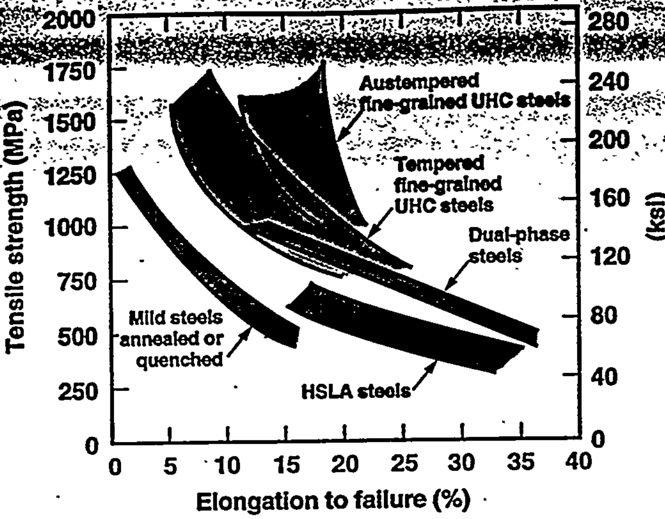

Figure 8. Tensile strength - ductility combinations that are possible with a fine-grained UHCS containing spheroidized carbides after heat treatment. Strength - ductility properties for mild steels, dual phase steels and HSLA steels are also shown on the figure.

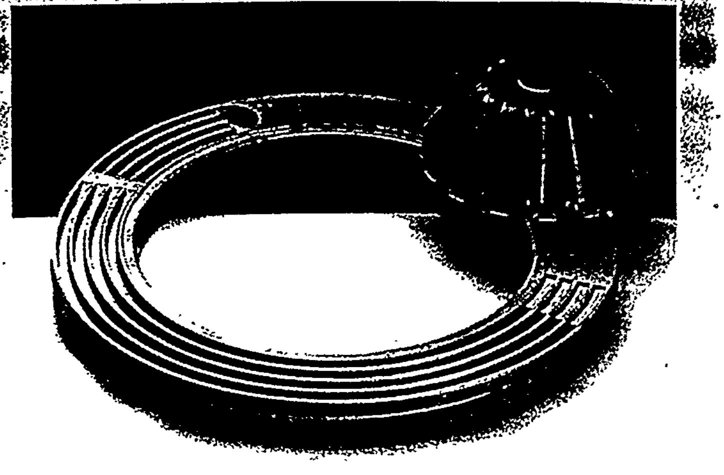

Figure 9. Two fine-grained UHCS components that were forged in one operation in air. The ring, which is approximately 25 cm in diameter, was superplastically formed in five minutes at 950°C (courtesy of B. Walser, Sulzer Brothers, Winterthur, Switzerland). The gear was forged at 650°C at conventional forming rates (courtesy of Robert O'Shea, International Harvester).

a fine-grained plain carbon UHCS but can be increased to over 20 mm with dilute alloying additions of Mn, Cr and Al.

APPLICATIONS - For forged/bulk rolled components, the primary characteristics of UHCSs are wear resistance, and their potential for net-shape processing (via superplasticity). The latter characteristic can minimize machining and welding steps and the amount of scrap material produced. UHCSs are excellent materials for wear resistant components where high fracture toughness is not required. An added advantage of using a fine-grained UHCS is that the carburizing step normally required to harden the surface of components is eliminated.

Numerous components have been forged from UHCS for technology development and demonstration. Some of these components have been forged in a strain rate and temperature regime where superplasticity (high strain rate sensitivity) is observed. Other components have been forged at higher strain rates and lower temperatures where low strain rate sensitivities are observed. Examples are shown in Figures 9 and 10. All components were formed in one operation. Figure 9 shows a ring component that was formed under superplastic conditions from a UHCS-9.3% Al-1.25% C alloy [29] and a bevel gear that was formed under non-superplastic conditions from a UHCS-1.25% C alloy. Both components were formed in air. It is important to note that the ring component was formed at a temperature and strain rate (900°C and 10^{-3} s^{-1}) where the material had a high strain rate sensitivity, whereas the gear was forged at a temperature and strain rate (650°C and 10 s^{-1}) where the material had a low strain rate sensitivity. Both components were formed close to net shape and illustrate the excellent die fill characteristics of fine-grained UHCSs.

Two additional components that were formed at conventional forging rates (10 s^{-1}) are shown in Figs. 10(a) and (b). The UHCS used for both components contained 1.25% C and 1.6% Al. The back-extruded tube and trunion were shaped at conventional forming rates (~10 s^{-1}) and illustrate the high formability of fine-grained UHCS at high (non-superplastic) strain rates. The tube (Fig. 10(a)) was formed at 750°C and the trunion (Fig. 10(b)) was formed at 700°C. The height reduction for the trunion was approximately 4 to 1. Two components forged under superplastic conditions are shown in

Table 1. Hardenability of ultrahigh-carbon steels as a function of alloying additions

Material Composition	Austenizing temperature A_1+50°C	Critical brine temperature T_c (°C) to achieve R_c=62	Critical cylinder diameter D_c (mm)
Fe-1.25%C-0.5%Mn	773	66	6.9
Fe-1.25%C-0.5%Mn-0.2%P	795	72	10.9
Fe-1.25%C-0.5%Mn-1.0%Cr-0.25%Mo	790	73	11.4
Fe-1.25%C-0.5%Mn-1.4%Cr-3.0%Si	860	78	15.5
Fe-1.25%C-0.5%Mn-1.5%Cr-1.6%Al	825	93	22.4
Fe-1.25%C-2.0%Mn-1.0%Cr	790	>100	>23.1

Figs 10(c) and 10(d). The guided missile aft-closure (Fig. 10(c)) was forged at a temperature (815°C) and a strain rate (10^{-3} s^{-1}) at which the UHCS-1.6% C material exhibits superplasticity. The material for this component was obtained from fine-structure powders that had been prepared via liquid atomization. The dome on this component was subjected to biaxial stretching and has a very uniform wall thickness illustrating very uniform flow during forming. The sub-scale compressor hub (Fig. 10(d)) was forged at near superplastic conditions (at 750°C and a strain rate of 10^{-3} s^{-1}) from a 40-mm-tall and 76-mm-diameter cylinder. This component, made from a UHCS-1.3% C-1.6% Al material, was formed as a part of a Department of Energy Metals Initiative project at the Lawrence Livermore National Laboratory on superplastic steel processing [3, 30]. The component was formed to demonstrate the die-filling capability of UHCS by manufacturing a complex part to net shape.

ULTRA-HIGH STRENGTH WIRE

PROPERTIES - Ultrahigh carbon steel also has the potential for dramatically increasing the strength of wire used in tire cord and other high strength wire applications. The basis for this important technical development is derived from the graph shown in Fig. 11. The graph shows the ultimate tensile strength of cold-drawn wire

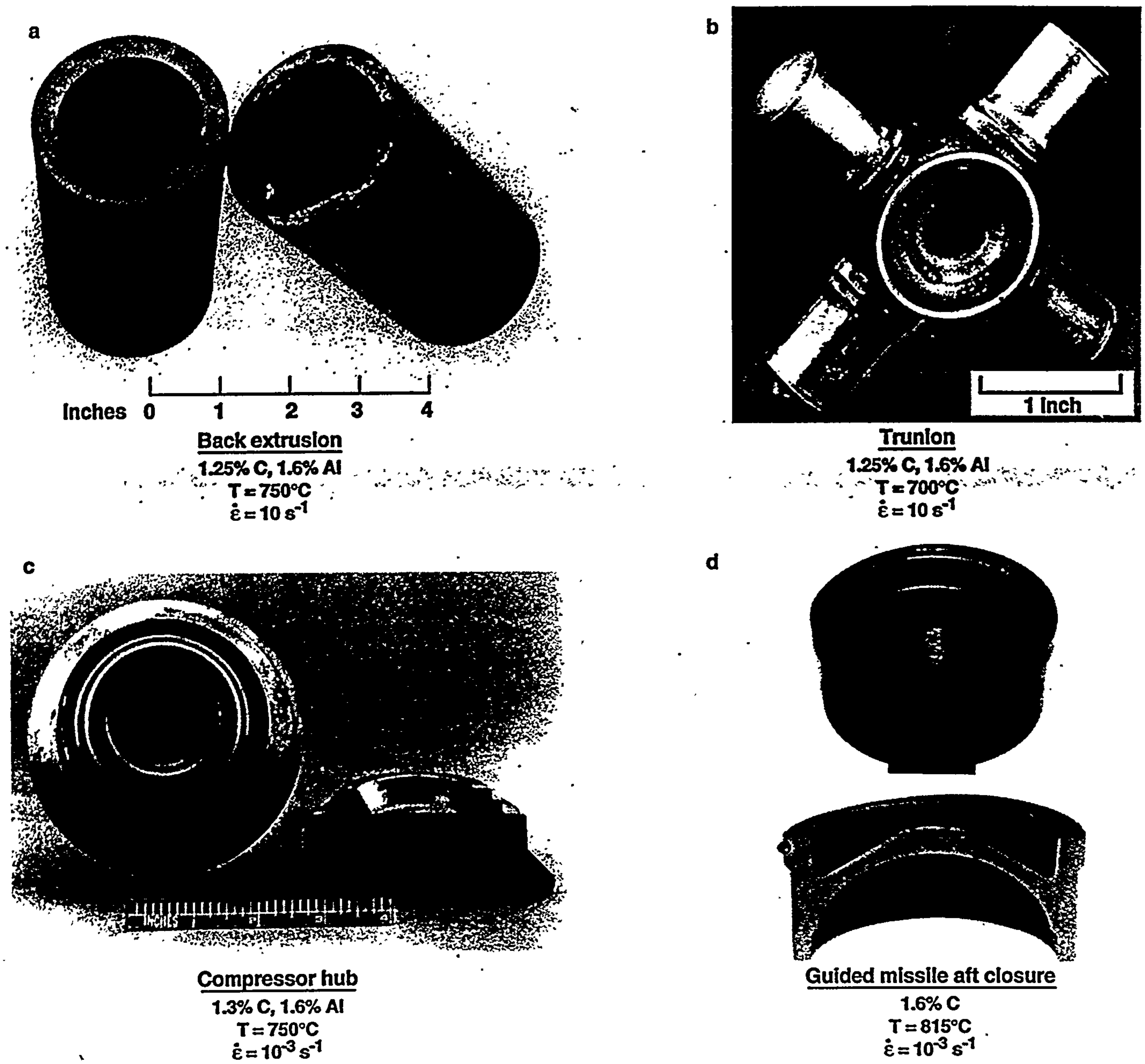

Figure 10. Components that have been formed from fine-grained UHCS containing spheroidized carbides. The back extrusion was made at Raychem Corp. (courtesy of Dieter Stöckel); the trunion was forged at the General Motors Technology Center (courtesy of W. Mueller); the sub-scale compressor hub and guided missile aft-closure were forged at Pratt and Whitney - West Palm Beach, Florida (courtesy of Bryant Walker and Roy Athey).

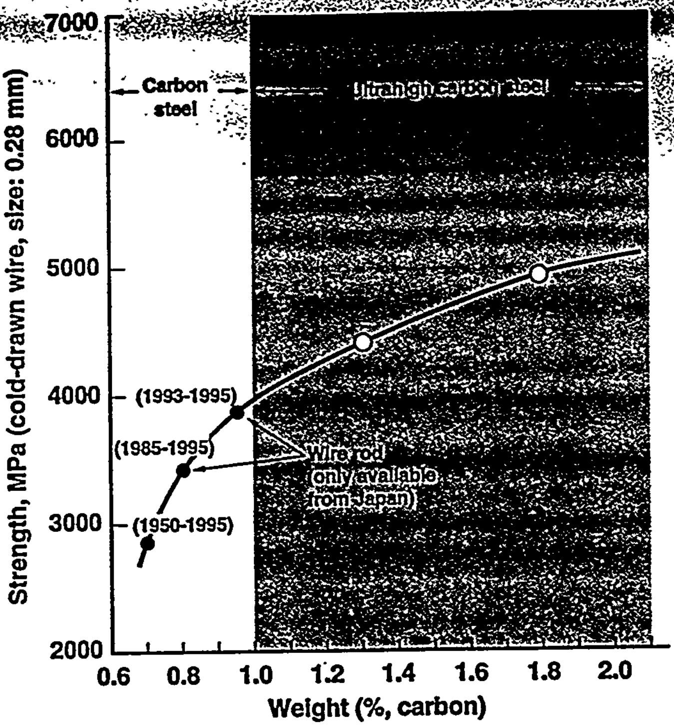

Figure 11. Influnce of carbon content on the strength of steel wires. Solid circle data points represent measured tensile strengths obtained with carbon steels. The open circle data points for UHCS represent predicted strengths based on an extrapolation of the carbon steel data. Results predict a strength of 5000 MPa for a UHCS-1.8C alloy.

used in tire cord as a function of carbon content. It is well established that, for steels with less than 1% carbon, the cold drawn strength of .28 mm diameter tire cord wire increases with carbon content. The data point at .7% C (2800 MPa) represents the strength of wire traditionally used for tire cord. During approximately the last ten years, higher strength wire has been available from eutectoid composition steel (0.8% C) with 3200 MPa tensile strength [31]. This wire has been developed by Japanese researchers [32] and is currently used in some premium passenger and light truck tires. Recently a different group of Japanese researchers have reported on laboratory results with a hypereutectoid steel (.92% C), which achieved a strength of 3650 MPa. The UHCSs described in this paper present the opportunity for dramatically increasing these strengths. Figure 11 shows an extrapolation of the data for the three carbon steels that have been developed to date and the results suggest that a strength of 5000 MPa can be obtained with UHCS-1.8C. The strength of these highly drawn wires is derived primarily from cold work, which is strongly influence by the spacing of barriers to dislocation motion. For UHCS the fine carbides in the microstructure present non-shearable barriers to dislocation motion and thus decreasing the interparticle spacing by increasing the carbide volume fraction can produce dramatic increases to strength.

The 5000 MPa wire strength shown in Fig. 11 represents a very high value - exceeding 20% of the theoretical cohesive strength of steel. Figure 12 compares the

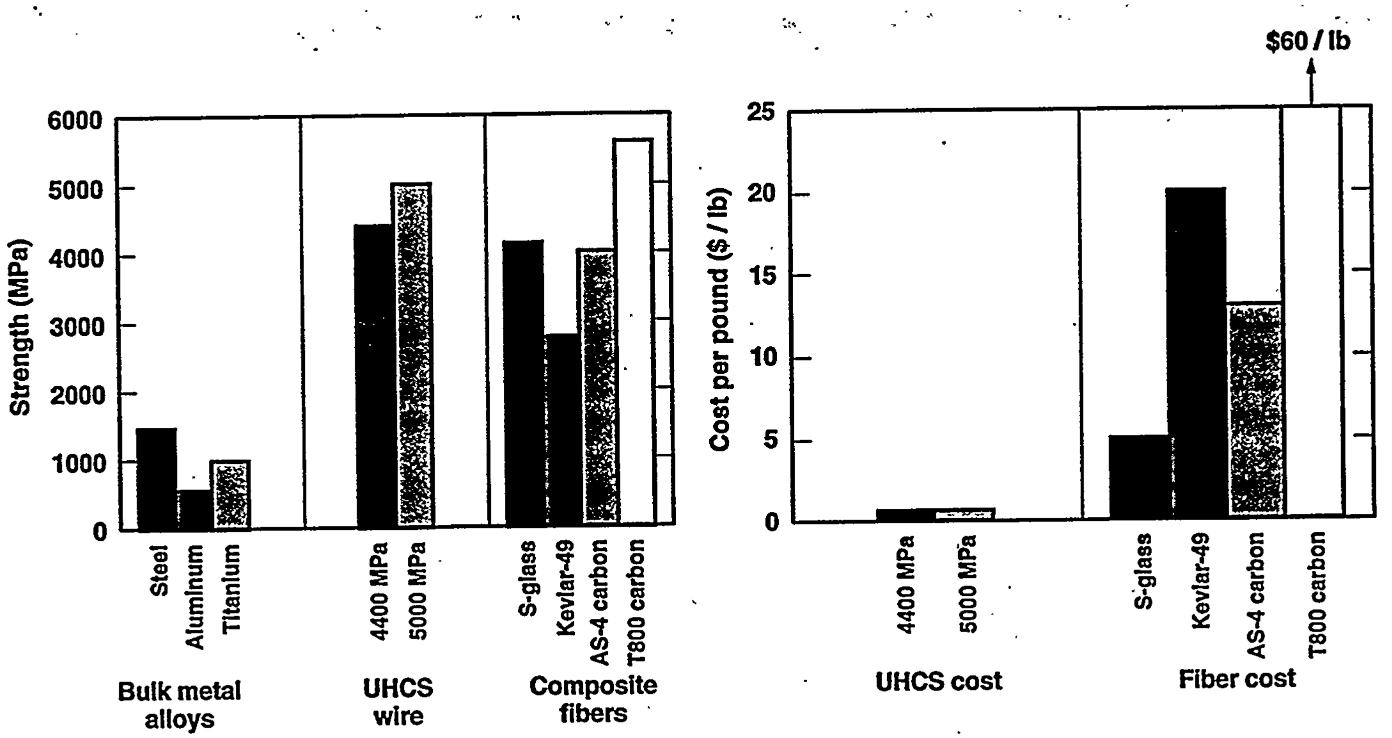

Figure 12. Comparison of strength and cost of UHCS wire with other bulk structural metals and reinforcing fibers used in composite materials.

strength of these highly drawn UHCS wires with the strength of bulk materials as well as other fibers that are used as reinforcement in composite materials. The highly drawn UHCS wires are significantly stronger than bulk metals used in structural applications but more importantly the strength of these wires compares favorably with those of other reinforcing fibers such as S-glass, Kevlar-49 and carbon fiber. The figure also shows the cost of the reinforcing fibers; UHCS wire (with an estimated as-processed cost of $.60/pound) is significantly less expensive than other reinforcing fibers.

APPLICATIONS - As discussed above the ultrahigh strength wires produced from UHCS could be used in tire cord with significant increases in strength over current tire cord steels. These new materials could reduce the weight and rolling resistance of tires, which can result in significant increases in overall vehicle fuel economy. The annual energy savings in the United States resulting from a wire strength of 4700 MPa (compared to a wire strength of 3400 MPa) is estimated at 520 million gallons of gasoline per year. Fuel efficient tires that result from higher strength tire cord can have a significant impact on the goals of the Partnership for a New Generation Vehicle, since 7.1% of the energy consumed in highway driving (4.2% for city driving) is lost to rolling resistance in the tires. In addition to tire cord, the higher strength wires resulting from UHCS could find automotive application in high strength hydraulic hose and fan belts.

CONCLUDING REMARKS

Ultrahigh carbon steels can have remarkable structural properties when processed to break up the proeutecoid carbide network and achieve fine ferrite grains with fine spheroidized carbides. These materials can find application as an ultra-high strength steel for sheet and plate applications. When processed for high room temperature ductility, UHCS can have a tensile ductility comparable to automotive high strength steels and plain, low carbon steels but significantly higher strength. It can also be made superplastic at intermediate temperatures and has demonstrated excellent die filling capability on a number of components during forging trials at intermediate temperatures. Furthermore, UHCS can be made hard with excellent compressive ductility and energy absorbing capability. The material also has unparalleled potential as ultra-high strength steel wire. A tensile strength of 5000 MPa has been predicted for UHCS-1.8C. This material should find application for the reinforcing cord in an energy-efficient tire.

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