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MATERIALS CHARACTERIZATION

Processing, structure, and properties of a rolled, ultrahigh-carbon steel plate exhibiting a damask pattern

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Abstract

A plate of ultrahigh-carbon steel (UHCS) was processed by hot and warm rolling, according to the Wadsworth–Sherby mechanism, to produce damask surface markings. The surface markings produced by this industrial processing method are similar to those of historical Damascus steels, which are also of hypereutectoid composition. The microstructure of the UHCS with damask contains fine, spheroidized carbides and a discontinuous network of proeutectoid carbides along former-austenite grain boundaries, which give rise to a surface pattern visible with the unaided eye. Tensile tests at room temperature measured tensile strengths and ductilities, which depend on sample orientation relative to the rolling direction of the plate. Hot and warm rolling causes a directional microstructure, giving rise to both an elongated, directional damask pattern and a directional dependence for strength and ductility. A maximum tensile ductility of 10.2% was measured at 45° relative to the rolling direction. The plate material was subjected to heat treatments creating pearlitic and martensitic microstructures, which retain visible damask patterns.

Keywords: Ultrahigh-carbon steel; Damask; Pearlite; Mechanical properties; Properties

1. Introduction

Investigations of hypereutectoid steels during the 1970s enabled the development of superplastic ultrahigh-carbon steels (UHCS) [1,2]. Key to this development was the understanding of the equilibrium and kinetic aspects of cementite formation in carbon steels of hypereutectoid composition. Low-alloy steels containing 1 to 2.1 wt.% carbon, called UHCS, can be made superplastic by preventing the formation of a proeutectoid carbide network. Prevention of a proeutectoid carbide network also provides high strength and good ductility in UHCS materials. Several of the UHCS materials in these studies bear a remarkable similarity to the famous Damascus steels of historical significance [3–10]. The similarity between UHCS and Damascus steels lies in their hypereutectoid composition. The majority of evidence indicates that ancient Damascus steels have typical carbon compositions of about 1.5 wt.% C [4,10]. Because of similar metallurgy, some of the same techniques which lead to high strength, toughness, and ductility in UHCS [9–16] are also thought to have

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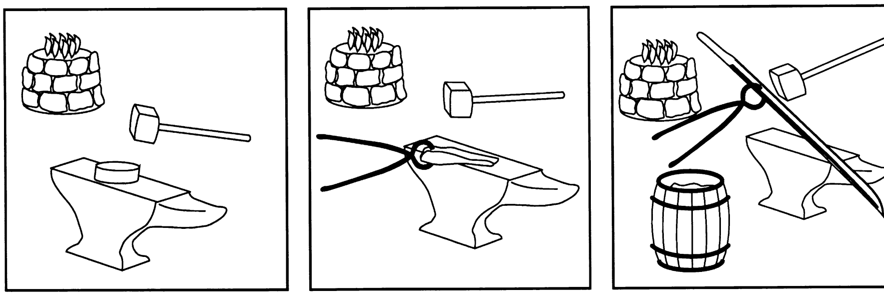

Fig. 1. This schematic illustrates a procedure by which ancient artisans might have produced Damascus steel blades [9]. A hypereutectoid steel ingot, *wootz*, is first upset forged (left) below a white heat, 800°C to 1200°C, to height reductions in the range of 3:1 to 8:1. This first step helps to homogenize the casting and to develop a discontinuous proeutectoid cementite network at austenite grain boundaries. The steel is then forged by complex folding and twisting (center) at a medium to bright cherry-red heat, 650–850°C, further refining the microstructure until the desired shape is produced. The final blade (right) can be quenched from about 800°C to achieve a high hardness.

produced the legendary strength and durable sharpness of Damascus steel blades.

Damascus steels are more legendary for their beautiful surface markings, known as a damask, than for their strength and toughness. The origin of the damask, as with the superb mechanical properties, is in the metallurgy of the hypereutectoid region of the iron–carbon phase diagram. A processing route which produces a damask in UHCS was demonstrated by Wadsworth and Sherby [4], and contains a likely explanation for the surface markings found in Damascus steels. In recent work, other modern investigators have also shed light on the mysteries of Damascus steels [17–22]. It is the purpose of this investigation to process an UHCS alloy by an industrial thermal–mechanical procedure according to the concepts of Wadsworth and Sherby [4,8]. The goals are to create an UHCS plate with a visible damask, and to then evaluate the mechanical properties of this material, both as processed and with additional heat treatments.

2. Historical background

Damascus steels are named for the city in which western Europeans possibly came first into contact with them. The best of the Damascus steels from ancient times were forged using steel ingots, called *wootz*, which originated in India [6,10]. The composition of the *wootz* ingots is thought to be in the range of 1 to 2 wt.% C [4,10]. The geographical distribution of Damascus steel blades generally followed the regions of Islamic population, but the best blades were likely forged by blacksmiths in Persia. Although Damascus steel blades were made well into the 19th century, the secret of their manufacture was lost. Numerous investigators during the period of 1820–1920 were drawn to rediscover the secret of Damascus steel, including such notables as Michael Faraday and Pavel Anossoff. Although the work of these investigators greatly increased understanding of high and UHCS, a full description of Damascus steel making remains elusive even today.

There is now enough understanding of the metallurgy behind Damascus steels to propose a procedure by which Damascus steel blades might have been produced. The proposed procedure is shown schematically in Fig. 1. An important key to understanding the metallurgy of hypereutectoid steels comes from the processing used to make superplastic UHCS alloys. In order to prevent brittleness in hypereutectoid steels, mechanical deformation must be used to break up the continuous network of proeutectoid cementite, which can precipitate at austenite grain boundaries during cooling from the A_{cm} to the A_1 temperature; this region is depicted by the Fe–C phase diagram (modified by 1.6% Al) in Fig. 2. In order to break up the proeutectoid cementite network,

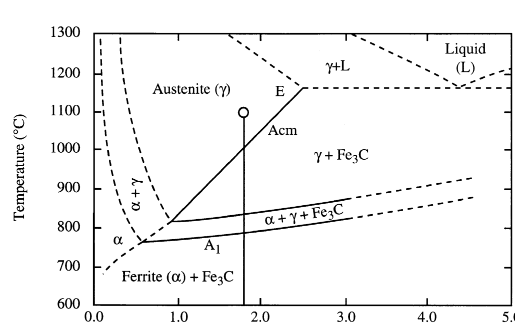

Fig. 2. An approximate phase diagram for the UHCS-1.8C alloy containing 1.6% Al is shown.

mechanical processing must occur below the A_{cm} temperature, which is much lower than the temperatures at which blacksmiths are accustomed to working low- to medium-carbon steels. It is the break-up of the proeutectoid cementite network that allows the combination of high strength and toughness obtained by Damascus steels. The broken network, which is visible and appears continuous to the unaided eye, is one origin of damask surface markings.

A damask is intentionally avoided during typical processing of UHCS in order to obtain the finest possible microstructure, but a surface pattern which closely resembles the damask of genuine Damascus steels can be created in UHCS if desired [4,9]. It should be noted that ancient and modern blacksmiths have also created damask markings by the pattern welding of low-carbon steel layers to hypereutectoid steel layers, and such steel composites are referred to as welded Damascus steels [7,10]. Although welded Damascus steels exhibit a pattern formed by the two layers of different composition, the metallurgy of these composites is very different from that of genuine Damascus steels in which the damask is intrinsic to the bulk material.

3. Experimental procedure

An UHCS containing 1.8 wt.% C was processed by industrial techniques of hot and warm rolling to produce a plate with damask surface markings. The processing procedure is derived from that previously used by Wadsworth and Sherby to produce a surface damask in a similar UHCS alloy, and is known as the "Wadsworth–Sherby Mechanism" [4,8,9]. A 227-kg ingot was cast by Bethlehem Steel, Bethlehem, PA, and was analyzed to have the composition given in Table 1. The ingot was subjected to thermal–mechanical processing according to the following schedule, which is also represented schematically in Fig. 3.

1. The ingot was soaked at 1093°C for 8 h.
2. The ingot was subsequently hot-rolled in several steps from 1093°C to 900°C into a billet of 102 × 102 mm in cross-section, which was then hot-sheared into segments.
3. One segment of the 102 × 102-mm billet was soaked at 1093°C for 48 h and then furnace-cooled.
4. This 102 × 102-mm billet segment was reheated to 810°C and warm-rolled continuously to a temperature of about 750°C and a final thickness of 3.2 mm.

Table 1
Chemical composition of the UHCS plate is given in weight percent

Element:	C	Mn	P	S	Cr	Al[a]
Composition (wt.%):	1.75	0.50	0.007	0.008	1.46	1.60

[a] Aluminum content determination is approximate.

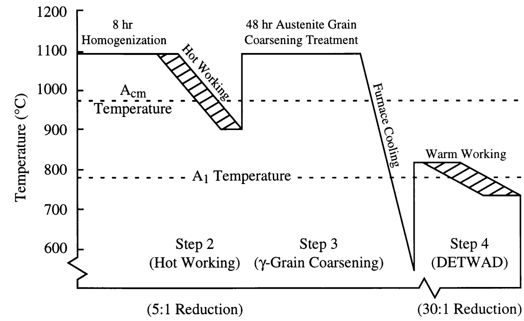

Fig. 3. The above schematic illustrates the four thermal–mechanical steps used in producing a damask in the UHCS material [9]. Step 1 is the homogenization annealing of the ingot. Step 2 is the hot working to homogenize the casting and obtain a billet of suitable size. Step 3 is an austenite grain coarsening treatment involving a long-time soak at 1093°C, followed by furnace cooling to develop a continuous proeutectoid cementite network at austenite grain boundaries. Step 4 involves a DETWAD treatment. This later procedure leads to a fine-grained ferritic matrix with fine spheroidized cementite particles and a visible discontinuous network of proeutectoid carbides.

Processing Step 1 provides homogenization of the casting, dissolves all the iron-carbide, and produces a large austenite grain size. Step 2 further homogenizes and refines the microstructure, and provides a convenient billet size for additional mechanical processing. Step 3 allows the austenite grain size to grow large enough so that the proeutectoid carbide network, which precipitates at austenite grain boundaries during furnace cooling, will create a pattern visible to the unaided eye. Step 4 is a thermal–mechanical process known as Divorced Eutectoid Transformation With Associated Deformation (DETWAD) [23]. In Step 4, the billet was first heated to about 40°C above the A_1 transformation temperature. At this temperature, the eutectoid carbides are mostly dissolved and the continuous proeutectoid network remains essentially intact. The material is weak (soft) because the diffusion rate of iron in austenite is enhanced by the presence of dissolved carbon. It is also very ductile, and during deformation, continuous cementite in the network breaks up. The result is elongated, but visible, prior-austenite grains outlined by a discontinuous network of carbides. The temperature of the billet decreases rather slowly during repetitive rolling because of adiabatic heating. When the temperature

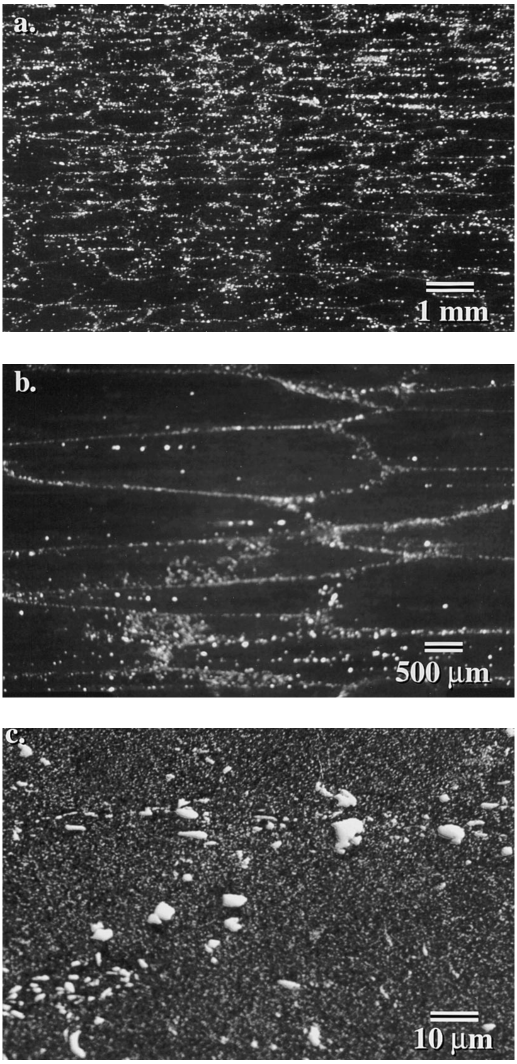

Fig. 4. Photo-micrographs of the UHCS plate are shown. The direction of rolling passes is horizontal and the orientation is perpendicular to the plate surface.

descends below the A_1 transformation point, austenite transforms into a structure which is partially pearlitic and partially spheroidized, the latter from a divorced eutectoid transformation (DET). With additional warm rolling below the A_1 temperature, the pearlite becomes fully spheroidized. Processing Step 4 permits a height reduction of over 30 to 1 by repetitive rolling without reheating. The initial 102×102-mm billet of 0.2-m length yields a 3.2-mm-thick plate about 6-m long.

Polishing and etching of the final UHCS plate reveals a clear damask pattern. Fig. 4 contains micrographs of the plate surface; the direction of rolling passes is horizontal. Fig. 4(a) and (b) clearly show the damask pattern and indicate that the pattern varies in size and shape between different regions of the plate, depending on initial austenite grain size and degree of deformation in each region. Fig. 4(c) is a micrograph at a higher magnification showing the broken proeutectoid cementite network. It is this broken network which creates the visible damask. Because the network is not continuous, the UHCS plate has significant ductility. The damask pattern is elongated along the direction of rolling passes. This elongated morphology of the damask is somewhat different from the swirling patterns produced in Damascus steel blades from the multidirectional deformation of hammer forging. The morphology of a damask pattern indicates the type of mechanical working used to break up the proeutectoid cementite network. The matrix of the plate material, Fig. 4(c), consists of fully spheroidized, ultrafine carbides in a fine-grained ferrite.

Tensile coupons were cut from the UHCS plate with damask according to the schematics given in Fig. 5. Samples were cut in three different orientations relative to the direction of rolling passes, as shown in Fig. 5, in order to test for the directionality of mechanical properties. Samples were cut at 0°, 45°, and 90° to the direction of rolling passes. Samples of each orientation were tested in tension, using an extensometer, to evaluate mechanical behavior of the material. In one test of a 45° sample, a strain gage was attached in order to measure the value of elastic modulus. The elastic modulus was measured to be 190 GPa.

Samples taken from the plate in the 0° orientation were heat-treated to form various microstructures. Each of these samples was tested in tension. One

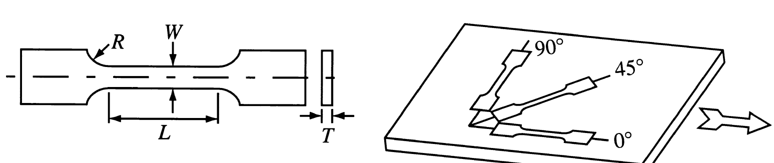

Fig. 5. Dimensions of samples machined for mechanical testing are shown at the left. Values are $R=6.35$ mm, $W=6.35$ mm, $T=3.2$ mm, and $L=25.4$ mm, except for the 45° samples, for which $L=19.05$ mm. Orientations of the three types of samples machined from the processed plate are shown at the right. The arrow indicates the direction in which the plate was passed through the rolling mill.

sample was soaked at a temperature slightly above the A_1 temperature, 780°C, and water-quenched to form martensite. Two additional samples were heat-treated to produce pearlite. These samples were soaked at 840°C and 870°C, respectively, for 20 min in a reducing, H_2 atmosphere to prevent oxidation, and were subsequently air-cooled.

4. Results and discussion

As shown in Fig. 4, the damask pattern of the UHCS plate material has a specific orientation relative to the direction of rolling passes. In order to examine the effect which this directionality has on mechanical properties, samples were tested in the orientations shown in Fig. 5. Data from tension tests on the UHCS plate with damask are presented in Fig. 6 as a plot of engineering stress against engineering strain. Slight differences in strength with sample orientation are evident from the data of Fig. 6. Measurements of yield stress and tensile plastic elongation are given in Table 2. The sample taken along the direction of rolling passes, 0°, exhibits the highest yield strength and the second highest tensile ductility. The sample taken perpendicular to the direction of rolling passes, 90°, exhibits the lowest yield strength and the lowest tensile ductility. The sample taken at 45° to the direction of rolling passes exhibits a yield strength between that of the other two orientations and exhibits the highest tensile ductility.

The directional dependence of tensile ductility in the UHCS plate with damask is explained by the morphology of coarse cementite particles. The tensile ductility of UHCS depends directly on the size of coarse carbide particles, which initiate failure by tensile separation at carbide–carbide boundaries [13]. Warm rolling breaks up the proeutectoid cementite network formed at austenite grain boundaries into individual coarse carbide particles. Because deformation is highly directional, the morphology of the coarse carbide particles is also highly directional, as seen in Fig. 4(c). Arrays of coarse carbide particles are aligned along the direction of rolling passes. More adjacent coarse carbides are subjected to tensile stresses in the 90° orientation than in any other orientation. Furthermore, many of the coarse carbides have an aspect ratio greater than one; the carbides are longer in the direction of rolling passes. The relative values of ductility presented in Table 2 can be explained by two major factors. First, the greater the density of carbide particles normal to the tensile axis, the greater is the ease of crack interlinkage. Second, the higher the angle of inclination between a carbide–carbide boundary and the tensile axis, the greater is the ease of carbide fracture. The orientations of carbide–carbide boundaries are believed to be normal to the direction of rolling passes. This is because boundary energy will drive carbide–carbide boundaries to the shortest dimensions of a coarse carbide, which is typically at a right angle to the direction of rolling passes.

The lowest ductility, 7.2%, is observed in the 90° orientation. This can be explained by the high density of carbide particles aligned perpendicular to the tensile axis. Next higher in ductility is the 0° orienta-

Table 2
Yield stress and tensile elongation for each of the three sample orientations are shown

Orientation:	0°	45°	90°
σ_y (MPa):	1127	1098	1087
Elongation (%):	9.0	10.2	7.2

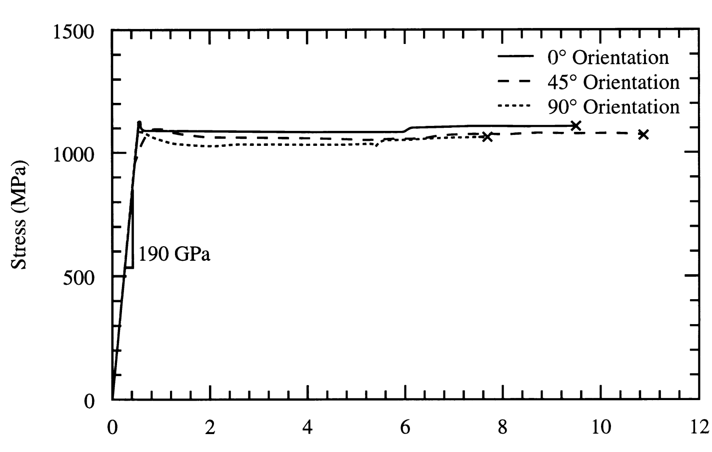

Fig. 6. Data from tensile tests of the three orientations are shown as engineering stress vs. engineering strain.

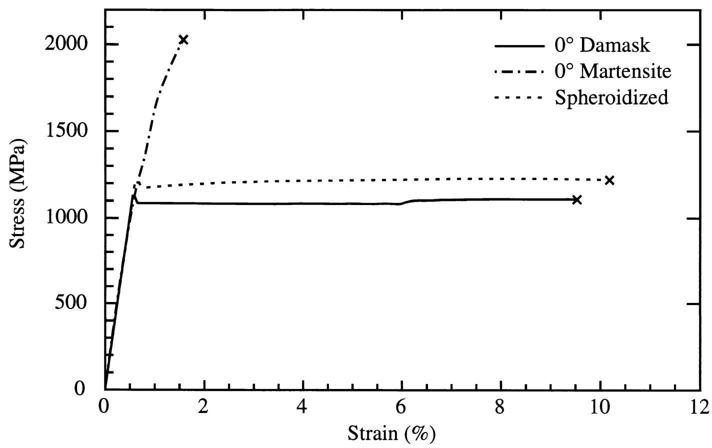

Fig. 7. Tensile test data are shown for a 0° sample, 0° sample quenched to form martensite, and a spheroidized UHCS [12] of the same alloy composition.

tion, with a ductility of 9.0%. This orientation is expected to have the highest number of carbide–carbide boundaries perpendicular to the tensile axis. Highest in ductility is the 45° orientation, with a ductility of 10.2%. This result is attributed to the 45° orientation minimizing the deleterious effects of both coarse carbide density and carbide–carbide boundary orientation. Based on these results, coarse carbide particle density is the most important factor affecting ductility, and carbide–carbide boundary orientation is the second.

One sample of the UHCS plate with damask taken along the direction of rolling passes, 0° orientation, was heated to slightly above the A_1 temperature, 780°C, and water-quenched to form martensite. This sample was tested in tension, and the resulting data are presented in Fig. 7. The martensitic sample exhibits a fracture stress of over 2000 MPa and less than 1% plastic ductility. The very high fracture stress is an indication of the high strengths that Damascus steel weapons might have obtained. A tensile test, taken from Syn et al. [12] for spheroidized UHCS of the same composition as that in the present study, is plotted in Fig. 7 for comparison. Although most of the carbide particles in the UHCS with damask are in a fine spheroidized form (Fig. 4c), coarse particles from the broken proeutectoid cementite network are retained. The spheroidized UHCS studied by Syn et

Fig. 8. This optical micrograph of the UHCS damask material heat treated at 870°C to form pearlite shows that a damask is retained after heat treatment.

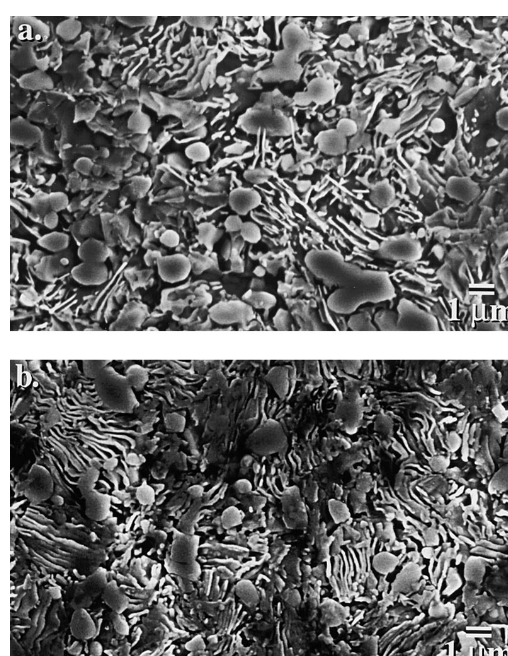

Fig. 9. Scanning electron micrographs are shown of samples given a post-treatment consisting of a 20-min soak at (a) 840°C and (b) 870°C, respectively, in an H_2 atmosphere followed by air cooling.

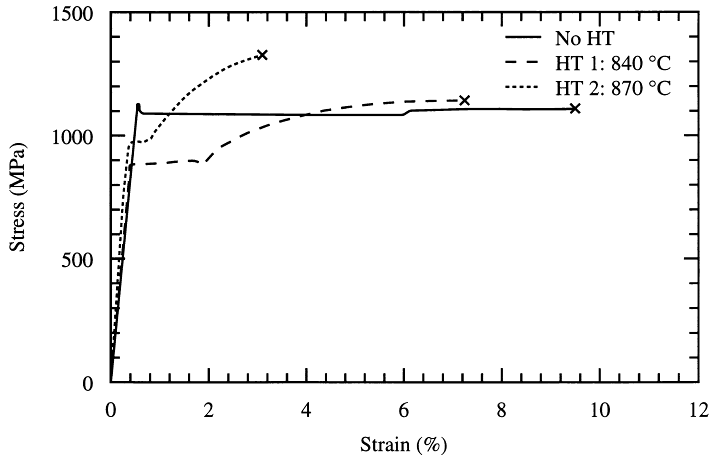

Fig. 10. Data from tension tests at room temperature are presented for the plates heat-treated to obtain pearlite. Data from material before heat treating are also shown.

al. [12] contains only very fine spheroidized carbide particles, without coarse proeutectoid carbide particles associated with a damask. Because this spheroidized UHCS does not exhibit a damask, it achieves slightly better mechanical properties. The spheroidized UHCS has both a higher strength and a higher ductility than the UHCS with damask.

Samples from the UHCS plate with damask were given two heat treatments to produce pearlite. The procedures for producing pearlite in UHCS from a spheroidized microstructure are available in Refs. [14,15]. The sample treated at 840°C retains a visible damask and exhibits fine pearlite between spheroidized carbides retained during the heat treatment. The sample treated at 870°C retains a less obvious damask, shown in Fig. 8, and exhibits finer pearlite than the sample treated at 840°C. Micrographs taken of each pearlitic material using a scanning electron microscope, S.E.M., are presented in Fig. 9. These samples were tested in tension, and data are shown as engineering stress vs. engineering strain in Fig. 10. Both heat-treated samples have lower yield strengths and higher fracture stresses than the material before heat treating, which is represented by the 0°-orientation sample labeled as "No HT" in Fig. 10. Despite higher fracture stresses, the fracture strains are reduced after heat treating. The sample heat-treated at 870°C is stronger than the material heat-treated at 840°C because of finer pearlite spacings (Fig. 9).

5. Conclusions

An UHCS alloy containing 1.8 wt.% C and 1.6 wt.% Al has been processed by the Wadsworth–Sherby Mechanism to achieve surface markings similar to those of Damascus steels. Tensile tests have been conducted on this material at room temperature in three different orientations. Mechanical properties of this material in martensitic and two pearlitic conditions have also been evaluated. Analysis of the data obtained provides the following conclusions.

1. A surface damask can be obtained in UHCS through the standard industrial processing techniques of heat treating and hot and warm rolling.
2. Rolling deformation results in a directional damask and directionality of mechanical properties.
3. The directional dependence of ductility in the UHCS with damask arises from the morphology of coarse proeutectoid carbide particles.
4. UHCS with damask can be quenched to form martensite of very high strength but low ductility.
5. UHCS with damask can be heat-treated to form pearlite of different interlamellar spacings with retained, spheroidized carbides. The damask can be retained after such heat treatments.

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