

Spheroidization of Medium-Carbon Steels

J.M. O'Brien and W.F. Hosford

Spheroidization experiments were made on a medium-carbon AISI 4037 steel, using both intercritical and subcritical annealing cycles. The results indicate that in the subcritical cycle the spheroidization occurred much more quickly than expected, so that shorter times were sufficient to achieve high formability. On the other hand, the hardness dropped faster in the intercritical cycle. Although more work needs to be done, these results suggest that using a subcritical spheroidization process instead of an intercritical process could achieve considerable savings in time, energy, and cost.

Keywords
carbon steels, formability, heat treating, spheroidization

1. Introduction

STEEL BOLTS are typically formed from rod by cold heading. In this process, rod is fed into the heading machine from a coil and is held in a set of dies while the protruding end is upset forged with a female die to form the bolt head. The deformation during cold heading is quite severe, and unless the steel has a high degree of formability, cracks (splits) may form at the outer edge.

Bolts that are to be hardened by subsequent heat treatment are made from medium-carbon steel (0.35 to 0.50% C), alloyed for hardenability with elements such as chromium, manganese, and molybdenum. Rods of these alloy steels are hot drawn to final diameter, coiled, and cooled for delivery. The structure at this point is ferrite and pearlite, with the coarseness of the pearlite depending on the rate of cooling after coiling.

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This microstructure is not ductile enough for cold heading. Therefore, a spheroidization anneal is performed to convert the carbide in pearlite to a spheroidal shape. These spheroidization treatments are long (12 to 20 h) and therefore energy intensive. Approximately 160,000 tons per year of medium-carbon steel is spheroidized for fastener applications alone. Any reduction of the temperature or time of the spheroidization could result in a major energy savings.

A typical spheroidization treatment consists of heating the steel into the intercritical temperature region (740 to 760 °C) for 2 h and then slowly cooling below the lower critical temperature (700 to 715 °C) and holding at this temperature for 8 to 20 h before cooling to room temperature (Fig. 1a).

Alternatively, the coil could be spheroidized by a subcritical annealing operation, simply by heating it to just below the lower critical temperature (700 to 715 °C) rather than first heating into the intercritical region (Fig. 1b). Quicker spheroidization would be expected, because the pearlite would be finer than that developed on slow cooling through the lower critical temperature. Why the intercritical anneal is commonly used is not clear. Samuels (Ref 1) has given an excellent review of spheroidization. There is little in the literature that would justify the higher temperatures and longer times. In two papers (Ref 2, 3) it is suggested that carbides remaining in the intercritical region serve as nuclei for later growth of carbides at

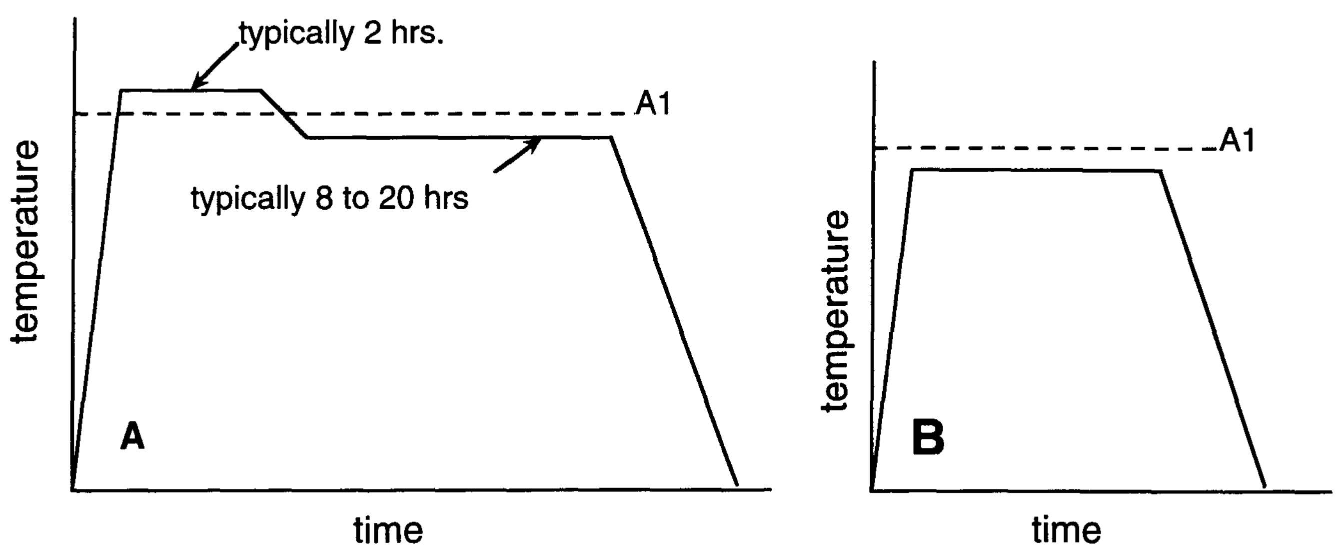


Fig. 1 Spheroidization cycles (a) A typical intercritical annealing cycle. (b) A possible subcritical annealing cycle

lower temperatures. Others (Ref 4, 5) merely recommend the intercritical anneal, while still another (Ref 6) claims it is essential to spheroidization. Intercritical spheroidization is necessary for high-carbon steels (those containing more than 0.80% C) in order to spheroidize the proeutectoid carbide. Perhaps intercritical annealing was adopted for medium-carbon steels because of its necessity for higher-carbon steels.

The mechanisms (Ref 7, 8) and kinetics (Ref 9-15) of subcritical spheroidization have been studied by a number of workers. A number of these studies concentrated on the acceleration of spheroidization by prior cold working or concurrent hot working (Ref 10-15). It has also been found that the rate of spheroidization is inversely related to the pearlite spacing (Ref 14, 15).

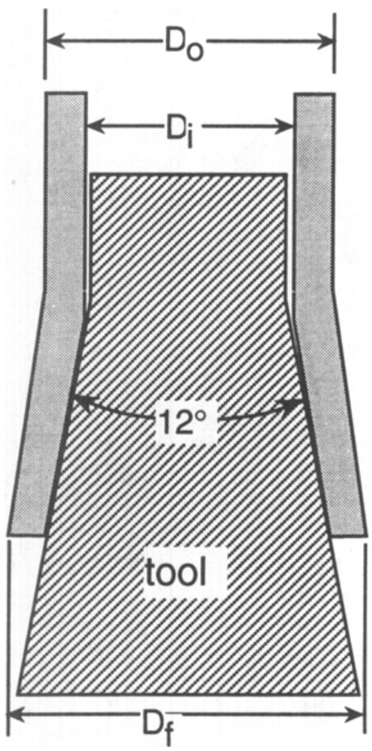


Fig. 2 Tooling used to test formability

2. Experimental Procedures

Experiments on a 3/8 in. (9.5 mm) rod of AISI 4037 steel (0.37C-0.80Mn-0.22Si-0.25Mo) were made to compare the rates of spheroidization using intercritical and subcritical anneals. For the intercritical cycle, the rod was heated to 748 °C

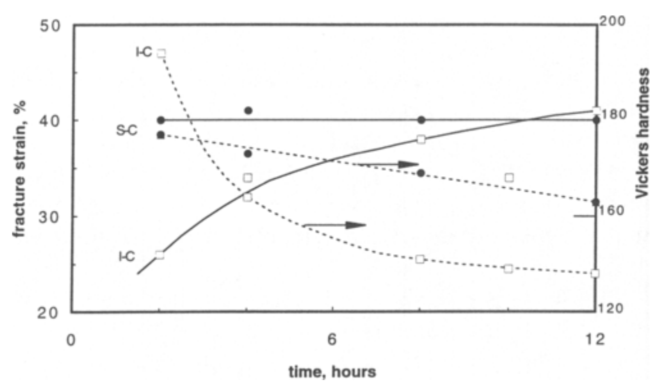
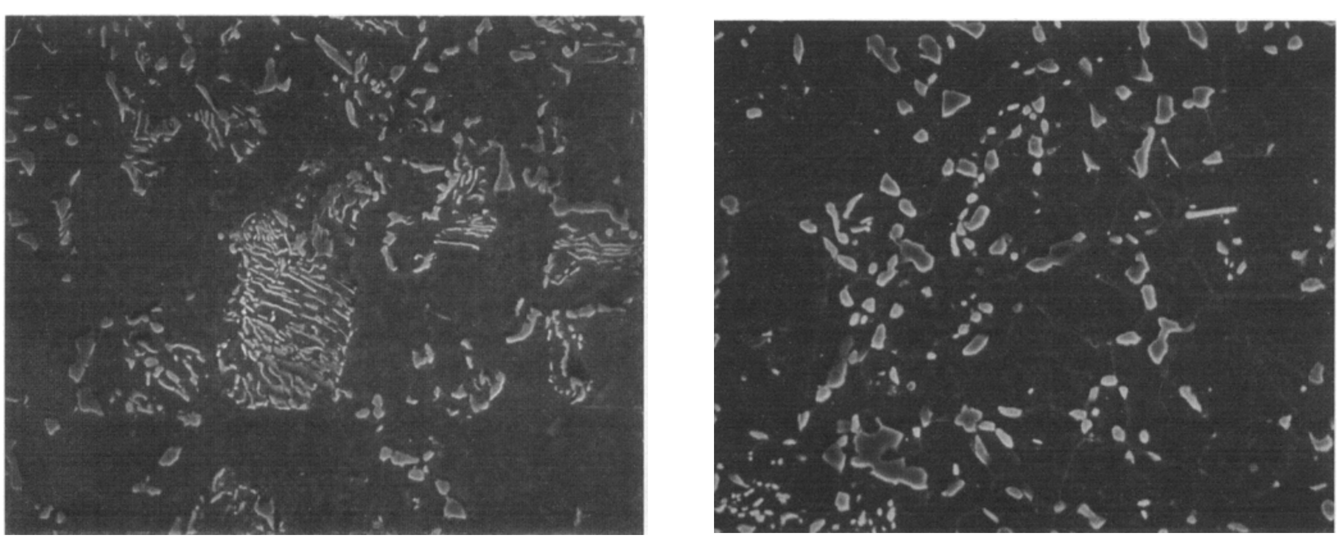


Fig. 3 Increase of formability with spheroidization (solid lines) and the decrease of hardness (dashed lines, read right). Open squares indicate the intercritical cycle. Solid circles are for the subcritical cycle. Note high formability (40%) is reached in 2 h with the subcritical anneal but takes 12 h with the intercritical anneal.



(a) **(b)**

Fig. 4 Microstructures after intercritical annealing cycles of (a) 4 h and (b) 12 h (SEM, 2200×). After 4 h there is unspheroidized coarse pearlite that formed after cooling from the intercritical region. The spheroidization is nearly complete after 12 h.

for 2 h, slowly cooled to 704 °C, and held at that temperature for up to 10 h before cooling at approximately 5 °C per minute. The subcritical anneal consisted of heating to 704 °C for up to 10 h before cooling at approximately 5 °C per minute.

The progress of spheroidization was monitored by examining the microstructure and measuring hardness and formability for specimens spheroidized for various times. To measure the formability, a simple test was developed in which a 1/4 in. (6.35 mm) diameter hole was bored in the end of the specimen, and then a conical tool was forced into the hole, causing the diameter to expand until a split was observed (Fig. 2). This test simulates the flow during forging at the outer edge of the bolt head where the cracking occurs. In both the test and in the actual heading operation, circumferential expansion is forced to occur in a region that sees negligible compression. The formability, ε_f, was taken as the true circumferential strain to produce the split:

$$e_f = \ln(D_f/D_0) \quad \text{(Eq 1)}$$

where D_f and D_0 are as defined in Fig. 2. The results are shown in Table 1 and Fig. 3.

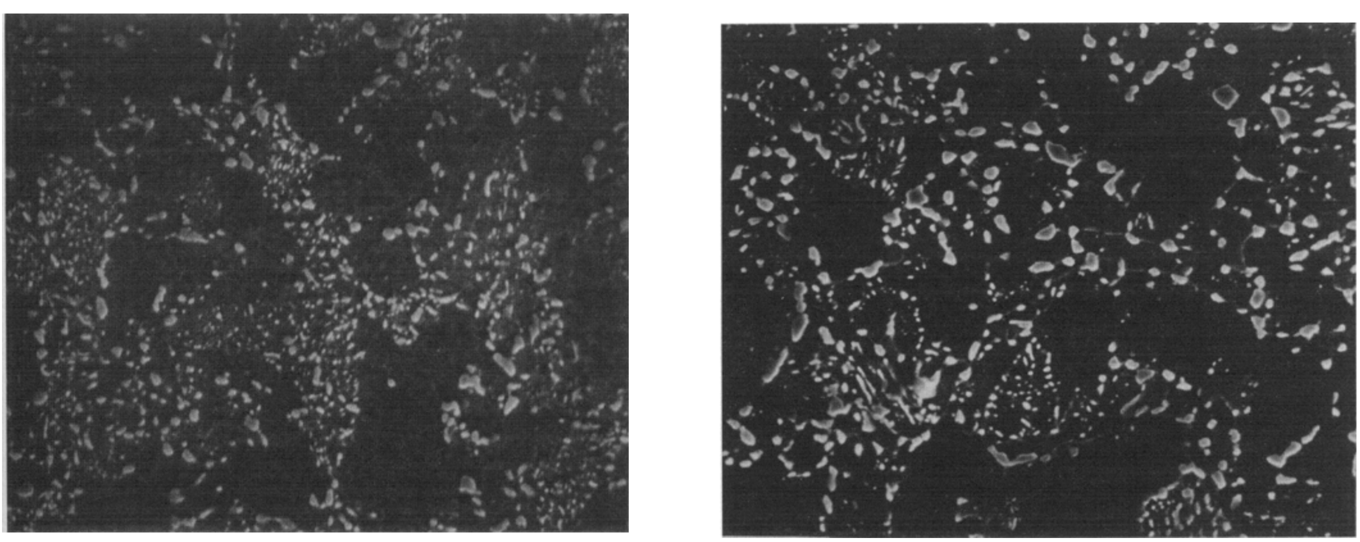
The microstructures developed at each stage were examined by scanning electron microscopy (SEM) after sectioning, polishing, and etching a picral-nital mixture. The microstructures of the intercritically annealed material after 4 and 12 h are shown in Fig. 4. Figure 5 shows the microstructures of the subcritically annealed material after 4 and 12 h. These figures show that after 4 h spheroidization is nearly complete in the subcritical anneal, whereas there is still unspheroidized coarse pearlite in the intercritical cycle. It is also apparent that when spheroidization is complete, the intercritical cycle results in a much coarser structure.

The more rapid spheroidization during the subcritical process is attributable to the fact that a much finer pearlite was being spheroidized. In the intercritical process, the pearlite that spheroidizes is that formed on cooling from the intercritical region to 704 °C. However, the intercritical process produces larger carbide spheroids. These observations are consistent with the results in Table 1. With the more rapid spheroidization in the subcritical anneal, high formability was produced in a

Table 1 Spheroidized hardness and formability

Total time(a),	Subcritical anneal		Intercritical anneal	
h	Hardness(b), HV	Formability, ε_f	Hardness(b), HV	Formability, ε_f
2	177	0.40	194	0.26
4	173	0.41	164	0.34
8	169	0.40	151	0.38
10	NA	NA	149	0.34
12	163	0.40	149	0.41

NA, No subcritical annealing was done for 10 h. (a) for the intercritical anneals, the time includes 2 h at 748 °C. For all tests the subcritical temperature was 704 °C. (b) Average of 5 readings with a 200 gm load



(a) (b)

Fig. 5 Microstructures after subcritical annealing cycles of (a) 4 h and (b) 12 h (SEM, 2200×). After 4 h the spheroidization is nearly complete, though the carbide size is very small. After 12 h the carbide size has increased but is still much finer than in Fig. 4(b).

much shorter time. The higher hardness values in Table 1 are a result of the finer dispersion of carbides.

3. Summary

Spheroidization experiments on a medium-carbon AISI 4037 steel indicate that in the subcritical cycle spheroidization occurred much more quickly than in the intercritical cycle, so that shorter times were required to achieve high formability. On the other hand, the hardness dropped faster in the intercritical cycle.

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