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REVIEW PAPER

Spheroidisation Treatment for Steels

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ABSTRACT

The materials used in components are now highly diversified with many applications historically reserved for steels now taken by plastics, composites, and ceramics. There are, of course, many applications for which steels are still the most suitable material. Presently, it is important that the type of steel chosen for a given application and the heat treatment given to it be critically examined to justify its use. This study highlights the selection of steels for spheroidisation treatments and their commercial uses.

Keywords: Steel, spheroidisation, alloying elements effects, commercial grade steel, pure grade steel, eutectoid steel, graphitisation

1. INTRODUCTION

The materials made of plastics, composites, and ceramics used for components are a replacement for steels for many applications. This change has been brought about by economic factors, environmental factors (ie, lighter weight automobiles for better gas mileage and less air pollution), and by global competition. These three factors are not independent of one another. There are, of course, many applications for which steels are still clearly the most suitable material. And there are firm applications of steels which may, in the future, be reclaimed if the factors listed in the preceding paragraphs become more favorable for the use of steels. Thus, presently, it is especially important that the type of steel chosen for a given application, and the heat treatment given to it, be critically examined to justify its use[1-5].

The choice of a steel type, in general for an application, and specific steels in particular, rests not only on the cost of the starting stock material (ie, bars, plates), which is closely related to the alloy content, but also on the cost of the heat treatment, and on the subsequent success of the manufactured component. The current (and future) manufacturing climate requires extremely careful consideration of the choice of steel and heat treatment. This requires an understanding of the factors that affect the response of steels to heat treatment and a knowledge about how to use these factors in choosing the steel and in designing the heat treatment. This paper reviews the suitability of a given steel for an application in which the main property of concern is formability desired for subsequent hardening treatment.

2. METHODS OF SPHEROIDISATION

Spheroidising is an annealing treatment for improving cold formability and machinability of steels. Here, a structure of coarse carbides in

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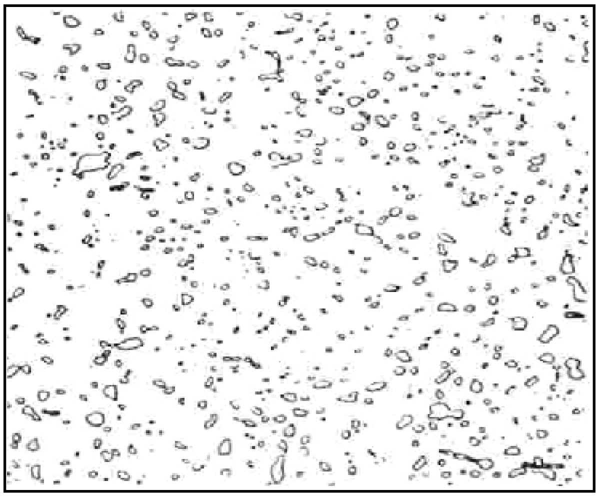


Figure 1. Microstructure of a typica1 991l spheroidisation annealed steel[6] (1000X).

ferrite is developed. The spheroidised structure[6] is illustrated in Fig. 1. If the initial microstructure is martensite, its decomposition precedes the coarsening, which leads to the spheroidised structure. If the structure is bainite, the fine carbides just spheroidise during the anneal. If the structure is pearlite then the carbide plates spheroidise and finally the structure coarsens. The development of a uniform distribution of coarse carbides in ferrite occurs rapidly in the initial structure of martensite than in one of primary ferrite and pearlite as shown in Fig. 2. The nucleation of the carbides in the martensite is uniform, so initially a fine uniform distribution of carbide spheres in ferrite is formed, which then coarsens into a uniform distribution. However, in the primary ferrite-pearlite beginning microstructure, the carbide plates in the pearlite must first spheroidise in place, which forms a nonuniform distribution of carbides. This then develops into a uniform dispersion of carbides.

Here, the spheroidising structure is developed upon reheating steel from 25 °C to the spheroidising temperature, which is below the austenite region A_{c1} and A_{cm} temperature. However, a spheroidised structure can be formed from austenite if the steel is cooled quite slowly or if it is isothermally transformed and held for quite long time. The latter is called isothermal annealing. In some steels, the spheroidisation process is accelerated by cycling just above and just below the eutectoid temperature. This is especially useful in high carbon steels[7] (Fig. 3).

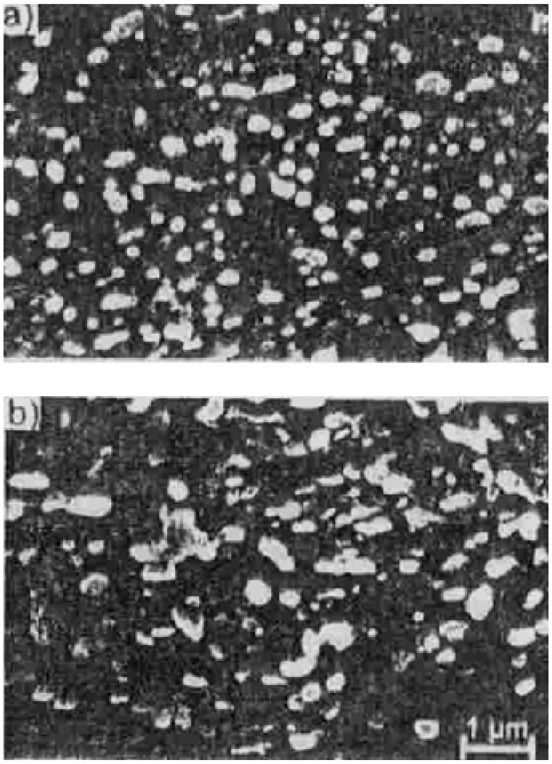


Figure 2. Comparison[5] of the: (a) spheroidised pearlite and (b) tempered martensite microstructure (a) ε_p=1.5; (b) tempering at 630 °C, (1µm).

3. APPLICATIONS OF SPHEROIDISED CARBON STEELS

High carbon steel grade SAE 52100 was widely used in the manufacture of rolling element bearings. Steel AISI 1045, AISI 4135 are the typical steels spheroidised for cold forging. It has long been the practice to anneal tool steel and high carbon steel to produce a structure of dispersed carbide spheroids in a ferrite matrix. The heat treating process of spheroidising steel produces a structure which is soft and much easier to machine than any other structure obtainable with these steels, as illustrated in Fig. 4.

Yoshikaju Kawabata,[8] *et al.* have mentioned the necessity of spheroidised steel in the automotive industry where hollow parts made from electric resistance welded steel tubes, are progressively been adopted in parts such as stabilisers and drive shafts to satisfy the mutually contradictory requirements of high rigidity and weight reduction. These parts

Figure 3. Iron-carbon phase diagram with the approximate temperature ranges shown for various heat treatments[7].

require extremely high fatigue strength, and are manufactured by repetitive quenching and tempering of high carbon steel. On the other hand, electric resistance welded tubes for these applications show considerable work hardening and quench hardening of the seam as a result of the pipe-making process. For such applications, forming and heat treatment are necessary after pipe making. With spheroidisation, the small diameter, thick walled tubes, generally used in parts such as stabilisers and drive shafts, can be produced having much larger size with thin walls.

High strength steel bolts are made from alloy steels containing 0.35 per cent to 0.5 per cent carbon and enough alloying elements to achieve the required hardenability. Wire rods were produced by hot rolling to the diameter of the bolt shank, cooling by fans and coiling. After pickling and coating with line, the coils are spheroidised to achieve the necessary formability. These are then sheared and cold-headed and threads are rolled into the shank. Finally, the finished bolts are austenitised, quenched, and tempered. In the cold heading, the shank is held in a set of grips while the end is struck with a female die with a cavity having the desired shape. The upsetting causes large tensile hoop strains that may cause splitting (Fig. 5) if the

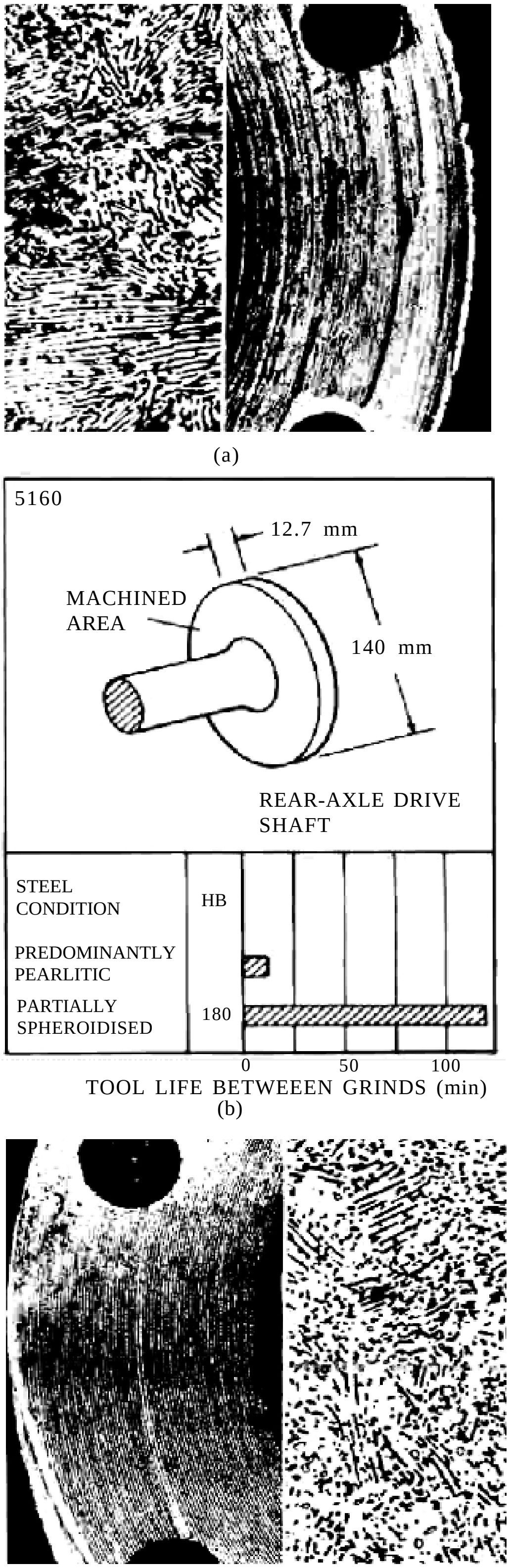


Figure 4. Example of the improvement in machinability of steel using a spheroidised structure.

Figure 5. Split that occurred during cold heading of a bolt.

material does not have the needed ductility for cold heading.

Spheroidised AISI 1541 and AISI 4037 steels are widely used for bolt manufacturing. The medium-to-high carbon steels, high-alloy tool steels, and spring steels are supplied in spheroidised condition to ensure that such steels with this microstructure facilitates good machining, increase tool life, and ensure better response of the finished product in subsequent hardening operations.

High carbon steels used commercially in the form of cold-drawn wire as patented wire or piano wire, have the highest strength of any available metallic material, excepting only filamentary whiskers. Approximately 160,000 tons per year[9] of medium carbon steel is spheroidised for fasteners application alone. Table 1[5,8,10,11-23,25-28] shows various steel grades used so far in the research on spheroidisation as well as a utility product.

4. DISCUSSIONS

4.1 Mechanical Properties of Spheroidised Steel

Spheroidisation of pearlite affects mechanical properties, generally reducing strength and increasing ductility. Hardness does not begin to decrease until the first stage of spheroidisation has occurred in large proportion of the pearlite colonies, but thereafter, decreases progressively with further progression of the spheroidisation sequence until a reasonably uniform system of spheres has developed, whereafter, it remains constant and the overall changes are comparatively small.

The minimum hardness obtained (140 HV for the 0.1 % *C* steel compared to 180 HV for the 0.8 % *C* steel) was somewhat greater than that for a low-carbon steel in which the cementite was also fully spheroidised. The hardness of steels with this type of structure is determined principally by that of the ferritic matrix, which is affected slightly by the cooling rate from the A_1, temperature because this cooling rate determines the amount of carbon retained in solution in the ferrite. This is the main reason for the hardness differences just referred to.

However, the presence of the cementite spheres increases hardness slightly in proportion to the volume fraction present this also would have contributed. Sherby[10], *et al*. have shown that the room temperature yield strength of warm rolled 1070 steel was about 1172.15 MPa, a three-fold increase in yield strength compared with that of the original material consisting of a pearlite structure.

4.2 Effect of Alloying Elements on Spheroidisation

Alloying elements enable a steel to have a wide variety of microstructures after heat treatment that cause a wide range of properties to be obtainable. These interact with *Fe*, *C*, and other elements in the steel, resulting in changes in the mechanical, chemical, and physical properties of steel. Alloying depends on the amount of alloying elements introduced and the character to their interaction with the main elements of the steel, *ie*, *Fe* and *C*.

The literature points out that for research, the preference has been given to pure steels from medium-to-high carbon range may be because the alloying elements influence the critical points of iron and steel and also the distribution of the alloying elements give the steel an entirely different structure than its parents *Fe-C* structure.

As to the character of their distribution in steel, alloying elements may be divided into two groups. One group contains elements that do not form carbides in steel such as *Ni*, *Si*, *Co*, *Al*, *Cu* and *N*. The other group contains elements that form stable carbides in steel, such as *Cr*, *Mn*, *Mo*, *W*, *V*, *Ti*, *Zr*, and *Nb*.

Table 1. Composition of steels used for spheroidisation[15,8,10,11-23,25-28]

1. Unalloyed engineering steel with 0.66 per cent *C* (5) [high carbon steel products]

C	*Si*	*Mn*	*P*	*S*	*Al*	*Cr*	*N*
0.66 %	0.19	0.73 %	0.027	0.007	0.010	0.135	29 PPM

2. Bearing steel SAE 52100 wt per cent (11) [ASTM A295:1992)

C	*Si*	*Mn*	*P*	*S*	*Al*	*Cr*	*Cu*	*Mo*	*Ni*
1:01	0.24	0.34	0.01	0.008	0.03	1.43	0.14	0.03	0.12

3. (12)

	C	*Si*	*Mn*	*P*	*S*	*Cr*	*Mo*	*Ni*
0.3 % *C*, 1 % *Cr*, steel	0.33	0.22	0.76	0.013	0.02	0.97	0.22	0.10
Commercial eutectoid steel	0.83	0.20	0.24	0.013	0.012	0.15	0.015	0.16

4. (13)

AISI –1045
AISI – 4135
Eutectoid 0.8 *C* – 1.0 *Cr* – 0.16 *Mo* Steel.

5. (14)

	C	*Si*	*Mn*	*P*	*S*	*Al*	*Cr*	*Mo*	*Ni*	*V*
AISI-1080 steel	0.76	0.17	0.60	0.015	0.04	0.02	0.06	0.01	0.06	0.02
Pure *Fe-C* alloy	0.79	0.01	0.01	0.002	0.02	0.005	0.01	--	0.02	---

6. (15)

	C	*Si*	*Mn*	*P*	*S*
AISI 4037	0.37	0.25	0.8	0.006	0.015

7. (16)

0.44 *C*	0.7 *Mn*	0.1 *Cr*					
C	*Si*	*Mn*	*P*	*S*	*Al*	*Cr*	*N*
0.44	0.22	0.67	0.022	0.017	0.031	0.12	0.006

8. (17)

C	*Si*	*Mn*	*P*	*S*	*Cr*	OPPM
0.74	0.71	0.03	0.007	0.006	<0.005	65
0.81	0.02	0.02	<0.005	0.003	<0.005	10
0.79	<0.02	0.05	<0.005	<0.005	<0.005	13

9. (18)

C	*Cr*	*Si*	*Mn*
1 %	0.99 %	0.23 %	0.34 %
1.4 %	1.35 %	0.12 %	0.45 %
0.6 %	0.61 %	0.08 %	0.6 %

10. (19)

C	*Si*	*Mn*	*P*	*S*	*Cr*	*Ni*
0.796	0.009	0.004	0.002	0.001	0.003	0.001

11. (10) 1070 commercial grade high carbon steel.

12. (20)

High purity eutectoid steel										
C	*Si*	*Mn*	*P*	*S*	*Al*	*Cr*	*Ni*	*Cu*	*V*	*Mo*
0.796	0.009	0.004	0.002	0.001	0.003	0.001	0.011	0.0002	0.002	0.003
Commercial grade eutectoid steel										
0.8	0.27	0.75	0.013	0.031	0.005	0.01	0.02	0.06	0.02	0.01

13. (8)

C	*Si*	*Mn*	
0.42	0.2	1.4	(Hot rolled steel sheets) SAE 1541
0.35	0.2	1.4	Steel SAE 15B 37H
0.30	0.2	0.8	Steel STKM15A

14. (21)

	C	*Si*	*Mn*	*P*	*S*	*Al*
AISI 1541	0.37	0.17	1.31	<0.003	0.012	0.02

15. (22) (Cold rolled thin strip high carbon steel)

	C	*Si*	*Mn*	*P*	*S*	*Al*	*Cr*	*Cu*	*Ni*	*N* (ppm)
AISI 1075	0.75	0.22	0.61	0.014	0.001	0.026	0.17	0.03	0.02	140
	0.70	0.22	0.59	0.02	0.001	0.044	0.10	0.07	0.03	67
	0.73	0.21	0.66	0.02	0.001	0.045	0.11	0.07	0.06	189
AISI 1095	1.03	0.17	0.41	0.017	0.003	0.000	0.20	0.02	0.02	124
	0.96	0.19	0.42	0.015	0.001	0.022	0.17	0.09	0.06	68
	0.96	0.19	0.42	0.015	0.001	0.022	0.17	0.09	0.06	68
	0.96	0.17	0.43	0.019	0.001	0.02	0.17	0.11	0.07	171
	1.01	0.21	0.39	0.021	0.001	0.00	0.18	0.10	0.07	132

16. (23)

1090								
1020								
1070								
304L								
309S								
	C	*Si*	*Mn*	*P*	*S*	*Cr*	*Cu*	*Ni*
1017	0.17	0.006	0.52	0.007	0.024			
1015	0.15	0.3	1.43	<0.004	0.004	0.018	0.029	<0.006
1045	<0.02	0.054 Mo	<0.002 Sn	0.0034 O	0.0058 N			

17. (25) Steel U8 (0.82 % *C*)
Steel 45 (0.43 % *C*)

18. (26) Pure *Fe*-*C* alloy of eutectoid composition

19. (27) 0.81% *C*

20. (28)

C	*Cr*	*Ni*	*Co*	*Cu*	*V*	*Mo*
0.24	0.00X	N.F.	N.F.	0.00X	0.00X	0.00X
0.42	0.00X	0.002	0.075	0.00X	0.00X	0.00X
0.79	0.0221	0.004	N.F.	0.00X	0.00X	0.00X

Another goal of spheroidisation is to produce a uniform fine structure with finely dispersed carbon after quenching. Since fine plate pearlite transforms more easily to globular pearlite as found, the 0.8 per cent *C* steel is mostly spheroidised and it is recommended that normalisation should be carried out prior to softening treatment. Refinement of the structure subjected to softening is achieved only above the point A_1. In practical applications, this type of annealing represents an intermediate treatment, and therefore, no strict requirements are imposed on the mechanical properties of annealed materials.

Researching on pure and commercial grades of steel, it was found that the commercial steel exhibits higher strength and lower ductility at the same temperature when compared with high purity grade eutectoid steel, and this difference is probably due to the higher content of both soluble and insoluble impurities in the commercial grade products.

Vedula[28], *et al.* experimented on spheroidisation of cementite in *Fe-C* alloys over ranges of carbon content, temperature, and time. This work is also being carried out for the same reasons on pure steels. The high purity steel eutectoid, chosen by Harrigan[19] was to try to minimise effects on diffusion rate and other complicating factors caused by alloying elements and impurities.

4.3 Effect of Hydrogen Content

The spheroidisation treatment is by far the most time-consuming phase of bolt manufacture. Commercial spheroidisation of coils usually takes from 10 h to 24 h, depending on the alloy and the size of the load. Brien[9], *et al.* have surveyed commercial spheroidisation practice by interviewing eight companies, among these, four were steel producers that spheroidise their own product before shipping to bolt manufactures. One company used to simply buy steel wire, cold-reduces, and spheroidises it before selling to bolt manufacture; the other three companies were the bolt manufactures who used to spheroidise the wire themselves before cold heading.

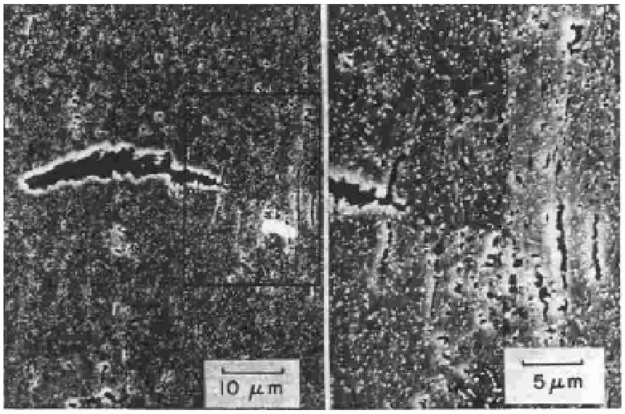
Working on AISI 1541 and AISI 4037, they found that the problem mentioned by producer that the AISI 1541 steel was more difficult to spheroidise, was genuine and was due to its high *Mn* content. Thus grade AISI 4037, which is considered easier to spheroidise, is used extensively in industrial application. Thus kinetics, of spheroidisation is affected by its composition.

Lone[22], *et al.* while working on spheroidised low-carbon steel found that the normal fracture mode was somehow accelerated by the presence of hydrogen, in the composition with no change in the microscopic features of the fracture process and hydrogen caused a shift from a normally ductile fracture mode to a more brittle fracture mode. Thus, hydrogen causes ductility losses in low-and medium-strength steel and causes common hydrogen-related phenomena as fisheyes, snowflakes, silver steak, checks, and tears at specimen surface as shown in Fig. 6.

Working on 1020 steel, Seabrook[23], *et al.* found that the presence of hydrogen increased engineering tensile strength by 4.2 x 107 N/m^2 or about 10 per cent, yet the fracture strength was reduced by 27.78 x 107 N/m^2 or about 35 per cent. Bernstien and Azou[24] noted that hydrogen had little effect on the flow properties of mild steel but lowered the fracture stress and fracture strain. Experimenting on high purity iron with carbon contents varying from 20 ppm to 80 ppm, Bernstein[24] suggests that the degree of hydrogen-induced ductility loss increases with increasing carbon content. This trend is supported by his experiments on 304 L stainless steel tested in gaseous hydrogen where ductility-reducing effect of hydrogen increased with the increasing strength level of the material, as shown in Figs 6 (a) and 6 (b).

4.4 Mechnism of Spheroidisation

Ochi1[16], *et al.* in their experiment studied the spheroidising mechanism of cementite in annealing 0.44 *C* steel showed that fine cementite particles, which can become the nuclei of spheroidal cementite, reside in the austenite during soaking. The reason for this is that third elements (*Mn* and *Cr*) are concentrated in the cementite in the heating process,



(a) (b)

Figure 6. (a) Central crack propagating[22] toward the lateral surface of a hydrogen charged 1045 steel tensile specimen (b) Micrograph on the right contains a magnified area showing how the crack erects with existing voids. The tensile axis orientation is vertical.

causing the A_{cm} point around the cementite to raise locally, that might be one of the causes for preference of pure alloy for spheroidisation.

The reason for poor ductility of steels 1, 2 and 3 experimented by Chattopadhyay[17] *et al*. was mainly due to the differences in Mn: S ratio in the three steels. In all other respects, steels 1, 2, and 3 behaved identically.

The presence of either proeutectoid constituent does not affect the rate of spheroidisation; that is, carbon content has no effect. However, other alloying elements may have minor effects as does deoxidation practices, for example, aluminium-killed steels spheroidise at somewhat faster rates than do silicon-killed steels. Rate of spheroidisation is greatly influenced by deformation prior to or during heating.

4.5 Thermomechanical Treatment for Spheroidisation

Plastic deformation prior to heating has significant effects on both the mechanism and the kinetics of spheroidisation. Deformation during heating also has a significant effect, but only differences in kinetics rather than in principle, are involved The range of austenitising temperature that can produce a spheroidal transformation product, or a mixture of spheroidal and lamellar transformation products, varies with carbon content Spheroidal transformation products can be obtained over a reasonable wide range of austenitising temperatures only for steel containing more than about 1 per cent carbon for steel.

Deformation of the steel grades used for spheroidisation was accomplished by torsional straining, tension, and compression and training technique. It was found by Robbins[20], *et al*. that the torsion test has a distinct advantage over the tension test in that a large amount of deformation can be imposed on the specimen before fracture occurs. Compression straining on the other hand, has the disadvantage that barreling can complicate analyses of the influence of deformation. In addition, the true strain rate is not usually constant in a compression test due to the change in dimensions of the specimen.

SAE 52100 was a grade widely used in the manufacture of rolling element bearings. The steels 0.33C, 0.83C were chosen because of the absence of proeutectoid ferrite. With 0.33 per cent C steel, the slow transformation kinetic allows easier comparison between the undeformed and the deformed parts on the same specimen. An acceleration of the transformation after a critical deformation was observed with this steel, is a fact that has been previously worked by several researchers with other steels[29,30].

4.6 Graphitisation during Spheroidisation

It is sometimes found that cementite not only is spheroidised when steel is heated for long periods at sub-critical temperatures, but also is replaced by irregularly shaped nodules of graphite. This is known as secondary graphitisation. Hardness decreases progressively throughout the graphitisation process to value considerably lower than which would be found in the absence of graphitisation. This graphitisation commenced in this steel after quite short heating times (1 h) and continued for about 500 h, by which time, approximately 10 volume per cent of graphite was present but not all of the cementite had decomposed. The graphite volume is so large (corresponding to about 3 Wt per cent of cementite the graphite was of theoretical density) that it must concluded that the graphite nodules are porous (Fig. 7).

The change in mechanical property due to Graphitisation are manifestations of the inherent tendency in all steels for cementite to revert to the thermodynamically stable form, graphite. However, the kinetic of the reaction varies over many orders of magnitude for different steels because it is affected by many factors, some of them being ill-defined.

The tendency for graphitisation to occur is determined essentially by the silicon content in steels. Silicon content of the required amounts normally is not encountered in plain carbon steels. For graphitisation, Panqueton[12], *et al*. found that the behaviour of steel A (0.33 % C) deformed after transformation is similar to the behaviour of

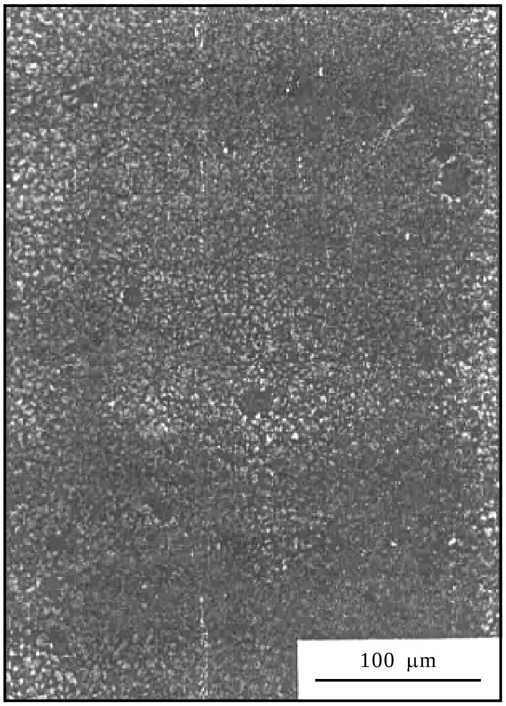


Figure 7. Graphite nodules[21] (black) observed after annealing for 100 h at 650 °C a sample of the cold-rolled AISI type 1095 steel of 0.64 mm thickness.

steel B (0.83 % *C*). Also at low range of temperature, the phenomena are similar to those observed at higher range of temperatures.

5. CONCLUSIONS

The spheroidisation of cementite in steels is carried out to improve the ductility of the lamellar pearlite to guarantee a subsequent cold deformability. Conventionally, it is achieved by a long-time soft annealing, at temperature depending on the steel grade and desired mechanical properties. It is known that in all the steels used for spheroidisation, a two-phase lamellar structure is commonly observed in metallic system, *ie*, eutectoid pearlite and eutectic alloys. The high thermal stability of some lamellar structures makes these potentially useful in high temperature applications. A literature survey was carried for steel grade for understanding the mechanism and kinetics of spheroidisation. The spheroidisation annealing heat treatment for all grades analysed here, may be the autstenitisation treatment, cooling media of lower and higher strength grades will be different, and it was found that the general nature of the structure was the same.

Carbon steels need to undergo cold forming during their production must have good formability and machining characteristics. The plain carbon steels of any grade and composition (without spheroidising treatment) as such do not posses these properties, thus, these need to undergo spheroidising annealing treatment. Today, one thinks, in terms of economy of time and money with having a product fulfilling the required properties during its use, thus on the slogan of where there is a need there is a way. The need-based steels, which are used for the above treatment are all those mentioned in Table 1. It is found that the spheroidised steel cover all the applications that use plain carbon steel up to 2 per cent carbon.

The conclusions for the composition of steels undergone for spheroidisation are:

- The experimental and theoretical values are in reasonable agreement at carbon contents from 0 to 0.4 per cent, and at the eutectoid composition, but there are significant departures between the two at other percentages of carbon contents, and the reasons for these discrepancies are:
  (a) The fraction of proeutectoid constituent in as continuously cooled steel will always be less than the equilibrium fraction with an essential requirement that a suitably sensitive steel must be used.
  (b) The material needs to be given an aging treatment after straining and before etching. *ie,* a treatments at about 200 °C for 30 min is optimum.
- A suitable steel seemingly being one with a nitrogen content in the range 0.01 per cent to 0.05 per cent little effect is observed with hydrogen and nitrogen contents less than about 0.01 per cent and a general obscuring layer of copper is deposited by etching when nitrogen content exceeds about 0.05 per cent.
- Very few steels with these contents in the required range are available now, modern steel

characteristically having nitrogen contents of the order of 0.00 per cent the nitrogen referred to must be present in solid solution, from which it follows that nitrogen-fixing element (such as aluminium) must be low.

- The spheroidised structure is very soft and readily lends itself to deformation during drawing, cold rolling, etc. Steels with a low carbon content become very soft after this annealing treatment. Thus, the globular pearlite structure is favorable in steels with a concentration of >0.5 per cent *C* with *Mn*, *Si* be kept in close control for better and quicker spheroidisation.

- For graphitisation, it is observed that the steel graphitise because of the graphite nuclei present in stock before spheroidising annealing. Also according to Mail and Well[14], iron-carbon eutectoid is at 723 °C ± 2 °C, and iron-graphite eutectoid is at 738 °C ± 3 °C. The enthalpy and Gibbs free energy is for:

Cementite H-15452 cal/g mole,
G-26410 cal/g mole/°C

Graphite H-1622 cal/g mole,
G-1.810 cal/g mole/ °C.

Cementite has 14.6-time more free energy, this fact has also contributed for graphitisation during spheroidisation.

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