Bainite austenitization in 51CrV4 spring steel: accelerated cementite spheroidisation

J Dlouhy, D Hauserova and P Motycka
COMTES FHT a.s., Prumyslova 995, 334 41, Dobrany, Czech Republic, EU
E-mail: jaromir.dlouhy@comtesfht.cz

Abstract. Spheroidisation is well studied process in steels with pearlitic structures. Bainite as initial microstructure for spheroidisation treatment is not so frequent. The article describes rapid carbide spheroidisation of bainitic structure of 51CrV4 spring steel. The experimental steel was treated in quenching dilatometer capable of rapid temperature changes. Isothermal austenitization was studied at different temperatures with respect to its kinetics and microstructural features. Special attention was paid to the morphology of growing austenite grains and carbide morphology during their dissolution in austenite. Rapid partial austenitization was repeatedly applied to achieve accelerated carbide spheroidisation. This phenomenon is known for pearlitic structures. The article shows that bainite can be spheroidised in similar way as pearlite. Accelerated carbide spheroidisation can be applied as replacement of conventional time-consuming spheroidisation annealing.

1 Introduction

Spring steels are one of the steel groups, where spheroidisation annealing is widely used. Examined steel belongs to the group of low alloyed steel with medium carbon content. Spheroidisation treatment is performed to decrease hardness, yield strength and increase ductility for technological reasons.

Conventional way to spheroidise carbides in steel is so-called “soft annealing”. This procedure employs tendency to minimize carbide/ferrite (or carbide/austenite) interface area [1]. The area minimization leads to formation of spherical carbides and their coarsening via mechanism of Ostwald ripening. This change of carbide shape and size brings steel structure closer to thermodynamic equilibrium. Sufficient temperature and time is necessary for successful spheroidisation which is usually defined as 95% of carbides in spheroidal form. However, morphological criteria are rarely set in engineering practice and the only criterion for spheroidisation annealing is the maximal permissible hardness of the treated material.

Soft annealing typically comprises of several hour soaking at spheroidisation temperature. This temperature is usually slightly below the \( A_1 \) temperature in case of hypo- and eutectoid steels and slightly higher than \( A_1 \) temperature in case of hypereutectoid steels. The main objective to choose the temperature is keeping the carbides in the matrix, whereas ferritic or austenitic, without dissolving them completely. The material is than cooled down slowly (usually in furnace) in order to retain globular carbides without austenite decomposition into lamellar pearlite. Whole soft annealing lasts several hours, even more than 24 hours in case of large batches (in order of 10 or 20 tons).

There is significantly faster way to spheroidise carbides in the structure. It was developed for spheroidisation of lamellar pearlite in low alloyed bearing steel 100CrMnSi6-4 [2, 3]. The principle
of so called “Accelerated carbide Spheroidisation and Refinement” (ASR) is repeated austenitization and divorced pearlite transformation [4]. Three cycles are sufficient for complete spheroidisation of lamellar pearlite. Austenitization is in ASR process rapid, performed by i.e. induction heating in rate in order of tens degree per second. Ferritic matrix is austenitized and cementite lamellae only partially dissolved [5, 6]. The lamellae undergo fragmentation at the advancing ferrite/austenite front. Cementite remnants act as nuclei for cementite growth during subsequent cooling and austenite decomposition. Thus divorced pearlitic transformation occurs and no new cementite particles form during cooling.

ASR process produces spherical carbides in ferritic matrix in significantly smaller size (ca 3-times) than conventional soft annealing. This fact is reflected by the term “Refinement” in ASR title. Finer dispersion of carbides is highly beneficial for subsequent hardening [7]. Smaller carbides dissolve at higher rate than coarse ones. Lower quenching temperatures can be applied to gain the same hardness in comparison with soft annealed material. Finer dispersion means also shorter average distance of the particles. It causes more effective pinning of austenite grain boundaries during austenitization for quenching. Smaller austenite grain leads to finer martensite and higher hardness after hardening in comparison with soft annealed material.

Presented article describes application of ASR principle to the bainitic microstructure of spring steel 51CrV4. Alloying by chromium and vanadium slows down the kinetics of austenite decomposition. Thus bainitic structure can be often found in hot rolled semiproducts before spheroidisation treatment. The aim of experimental program was to investigate ability of bainite to be spheroidised via ASR process. The optimal parameters for ASR were set and dilatometric study of austenitization was performed.

2 Materials and methods

Experimental steel was grade 51CrV4, used widely for spring production. The chemical composition of the steel is in the table 1. The steel was delivered in form of hot-rolled bars 21 mm in diameter, air cooled after rolling, without any subsequent thermal treatment.

Table 1. Chemical composition of the experimental steel.

| Element | C  | Mn  | Si  | Cr  | V   | Cu  | S   | P   | Fe  |
|---------|----|-----|-----|-----|-----|-----|-----|-----|-----|
| wt. %   | 0.51| 0.96| 0.27| 1.07| 0.14| 0.02| 0.017| 0.015| bal.|

Heat treatment was performed in quenching dilatometer Linseis L78 RITA. It enables dilatometric analysis of metallic cylindrical samples from 3 to 5 mm in diameter and typically 10 mm in length. Samples are heated by induction heating and cooled by gas flow. Maximal controlled cooling and heating rate is 200°C/s. Dilatometers chamber was evacuated and filled with argon. Specimens for heat treatment in the dilatometer were prepared in form of cylinders 4mm in diameter and 10 mm in length. These samples enables microstructuralanalyse, hardness measurement but also preparation of micro-tensile specimens [8, 9].

Microstructure of the samples was investigated on metallographic section prepared in longitudinal direction of the samples. Sections were prepared by mechanical grinding and polishing, microstructure was revealed by etching in 3% Nital solution. Sections were observed by optical microscope ZEISS Observer Z1m and scanning electron microscope (SEM) JEOL JSM 7400F. Hardness was measured by method HV10 on automatic hardness tester Struers Durasan 50.

ASR was performed as 3 cycles heating to temperatures from 750°C to 800°C. Every hold lasted 15 seconds. The regimes are shown in figure 1. Heating rate was 50°C·s⁻¹, cooling rate was 30 °C·s⁻¹ to the temperature 730°C and 3 °C·s⁻¹ to the 650°C or to the ambient temperature after the third heating cycle.

Isothermal austenitization was performed at temperatures from 750°C to 780°C. Samples with interrupted austenitization were prepared. The isothermal austenitization was stopped by quenching...
at moment with estimated amount of austenite in the structure reached 25 vol.%, based on the dilatometric record of austenitization. Metallography investigation of carbide morphology at ferrite/austenite interface was performed.

![Figure 1](image1.png)

**Figure 1.** Regimes of ASR treatment performed in quenching dialtometer. Regimes labelled after the austenitization hold temperature.

3 Results and discussion

2.1 ASR via cyclic heating.

Initial microstructure of the bars was bainitic with hardness 345 HV10. Microstructure was homogeneous (figure 2), composed of ferritic matrix and carbides, emphasizing plate-like structure of the matrix (figure 3).

![Figure 2](image2.png)

**Figure 2.** Microstructure of initial state observed in optical microscope.

![Figure 3](image3.png)

**Figure 3.** Microstructure of initial state observed in SEM in detail.

The microstructure after thermal cycles between 750°C and 650°C did not change in terms of carbide morphology. However, the hardness decreased rapidly from 345 HV10 to 287HV10 (table 2). This could be explained by recovery and recrystallization of the ferritic matrix. ASR treatment was carried out successfully by thermal cycling to the 760°C. Carbides were almost completely spheroidised. Only traces of original elongated carbides were observed. Also formation
of new pearlitic lamellae during the last cooling occurred, as seen in the figure 4. This sample exhibited the lowest hardness due to the most complete carbide spheroidisation. Carbide globules size was from 100 to 300 nm.

Higher austenitization temperatures lead also to carbide spheroidisation. However carbide dissolution advanced too much in some areas, that new pearlite was formed there. This happened probably due to lack of undissolved carbides necessary for divorced pearlitic transformation. Thus, regular pearlitic transformation occurred with formation of cementite lamellae (figure 5). There were also visible martensite islands in the structure for samples T 780 and T800. Austenite in these areas was so stable that cooling rate 3 C·s\(^{-1}\) was higher than critical cooling rate for martensitic transformation. Austenite stability was increased by amount of dissolved carbon and alloying elements concentrated in carbides, mainly chromium. Hardness of samples rose with rising amount of new lamellar pearlite.

Table 2. Hardness and carbide morphology after cyclic heating. Regimes labelled after the austenitization hold temperature.

| Regime | Initial state | T 750°C | T 760°C | T 770°C | T 780°C | T 800°C |
|--------|---------------|---------|---------|---------|---------|---------|
| HV10   | 345           | 287     | 254     | 265     | 301     | 350     |
| carbides | bainitic      | bainitic | spheroidised, traces of new lamellae | spheroidised, ca. 5% of pearlite | spheroidised, ca. 30% of pearlite | pearlite, ca 20% spheroidised carbides |

Spheroidised carbide particles size decreased slightly with increasing austenitization temperature of ASR treatment. Globules diameter was in range of 50 to 200 nm in case of sample T800.

2.2 Dilatometric analyse of the austenitization

Isothermal austenitization was observed via sample dilatation. Figure 6 shows austenitization progress at temperatures from 750°C to 780°C. Curve for 750°C reveals reason why no carbide spheroidisation was observed after regime T 750. 15 second holds were too short to austenitize the sample. ASR based on reverse austenitization and divorced pearlitic transformation did not take place.
Samples with interrupted austenitization were prepared. Austenitization was stopped by rapid cooling of the sample at point, where ca 25vol.% of austenite was estimated to be present in the structure (according to curves from figure 6). Growing austenite was turned to martensite and the carbides “froze” in state they were at the beginning of the rapid cooling.

Figure 7 shows structure of samples with interrupted austenitization at temperatures 750°C and 780°C. Metallographic sections were etched by Nital. Martensite is etched at significantly slower rate than ferrite and carbides are not etched at all. Thus ferrite is etched deeply, revealing 3D shape of initial bainitic carbides. Martensite is etched only slightly showing surface relief reflecting individual martensite crystals.

There are clearly visible undissolved carbides in the growing austenite (turned to martensite). Carbides retained in austenite at temperature 780°C are smaller and seem to have higher spatial density. This corresponds with finer carbide globules observed after ASR performed at higher temperature.
4 Conclusion
Accelerated carbide Spheroidisation and Refinement (ASR) was successfully applied to the bainitic structure of 51CrV4 steel. Hardness dropped from initial 345 HV10 to 254 HV10. Vast majority of carbides was spheroidised. The spheroidisation regime comprised in three heating cycles to 760°C for 15 sec with intermediate cooling to 650°C.

Results showed that ASR process can be applied to the bainitic structure. The mechanism of carbide fragmentation and globules formation seems to be the same like in the case of pearlitic initial structure.

Spherical carbides with size from 100 to 300 nm were formed. Formation of finer carbides (from 50 nm to 200 nm) was observed after temperature cycling to higher temperatures; however lamellar pearlite also formed during cooling. Promotion of divorced pearlitic transformation can be achieved by prolonging the time of intermediate cooling. It is way to prevent formation of lamellar pearlite.

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