Materials Science Forum *Online: 2012-01-03*
ISSN: 1662-9752, Vols. 706-709, pp 2770-2775
doi:10.4028/www.scientific.net/MSF.706-709.2770

Rapid Spheroidization and Grain Refinement Caused by Thermomechanical Treatment for Plain Structural Steel

Bohuslav Mašek[1,a], Hana Jirková[1,b] and Ludmila Kučerová[1,c]

[1]Research Centre of Forming Technology, University of West Bohemia in Pilsen, Faculty of Mechanical Engineering, Pilsen CZ-30614, Czech Republic

[a]masekb@vctt.zcu.cz, [b]hstankov@vctt.zcu.cz, [c]skal@vctt.zcu.cz

Keywords: rapid spheroidization; carbide morphology; thermomechanical treatment

Abstract. The cold formability of ferritic-pearlitic steels is one of the base parameters for material choice for different forming parts. One of the key factors is the pearlite morphology, which is strongly dependent on chemical composition and previous treatment history. The carbides in pearlite occur mainly in the lamellar form. One of the ways of improving the ductility along with formability is the change of lamellar carbides to globular carbides. This can be conventionally done by soft annealing, which is characterised by long processing times and high energy costs. This paper presents a new processing modification which can lead on the one hand to significant shortening of carbide spheroidization times and on the other hand to intensive refinement of grain size even for low-carbon steels. Low temperature thermomechanical treatment with variation of the heating temperature around A_{c1} and incremental deformation was examined on low carbon plain RSt-32 steel. After the thermomechanical treatment conditions were optimized, the refinement of the ferritic grains from an initial 30 μm to circa 5 μm took place, and the time necessary for carbide spheroidization was shortened from several hours to several seconds.

Introduction

Cold forming of components is used in a wide range of applications, not only in the engineering industry. Improved formability of semi products is conventionally obtained by heating until soft. This also increases ductility and machinability. Because of the long time necessary for the origination of spheroidization structures, this process is very demanding in terms of energy costs. It is therefore necessary to search for new, lower-energy methods with faster heating times. [1-2].

The annealing time is determined by the carbon content and the alloying elements which lower the speed of diffusion of carbon in the ferrite or stabilize the cementite. The initial structure also plays a very significant role. The precipitation and clustering of carbides is more rapid from bainite or martensite than spheroidization of lamellar pearlite. In some cases it is necessary to extend the annealing time to several dozen hours [3].

Spheroidization structures exhibit better cold formability because of their lower yield point which is influenced by the morphology and distribution of ferrite and carbide. Spheroidization may be carried out as follows [4]: isothermal annealing at a temperature just below A_{c1}, heating to just above A_{c1} with subsequent slow cooling in a furnace or holding just below A_{c1} alternate heating and cooling just above and below A_{c1} .

The main aim of the experiment was to develop a new, energetically economical technological process for a low-temperature thermo-mechanical treatment with incremental deformation for low-alloyed RSt37-2 steel. The new process is called ASR (Accelerated Spheroidization and Refinement) and is characterised by annealing times many times shorter than traditional methods and a resulting spheroidization structure with more even distribution of carbide.

Experimental programme

RSt37-2 (S232 JRC) steel was used in the experiment. It is an unalloyed construction steel (Tab.1) after cold drawing with a rod diameter of 18mm. The initial structure is ferrite-pearlite, the pearlite having a lamellar morphology (Fig. 1, Fig. 2). Image analysis showed a 9% share of pearlite and average ferrite grain size of 30μm.

Tab. 1: Chemical composition of RSt37-2 (S232 JRC) steel [wt.%]

C	Mn	Si	Cu	P	S	N
0.08	0.65	0.16	0.05	0.022	0.023	0.004

Mechanical properties of the steel in the initial state were found by tension testing and hardness measurement. The semi-product had an ultimate strength of 516MPa, yield strength 449MPa, ductility 20% and hardness 201 HV10. After impact testing on mini samples, notch toughness was found to be 77J/cm^2.

The experimental programme was designed primarily to clarify the influence of thermomechanical factors on the spheroidization of carbides and refining structures. The effects of the intensity of the deformation together with the effects of various heating and treatment temperatures were investigated. Conventional treatment in a furnace was also carried out to compare the results.

The structures were analysed using optical microscopy, laser scanning confocal microscopy (LSCM) and scanning electron microscopy (SEM). The softening of the structures was determined by measuring the hardness.

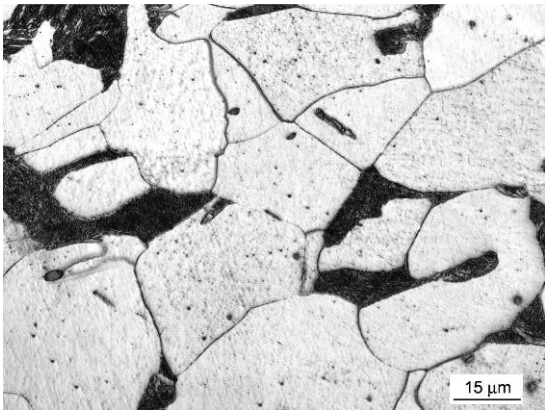

Fig. 1: Initial state: ferrite-pearlite structure, LSCM

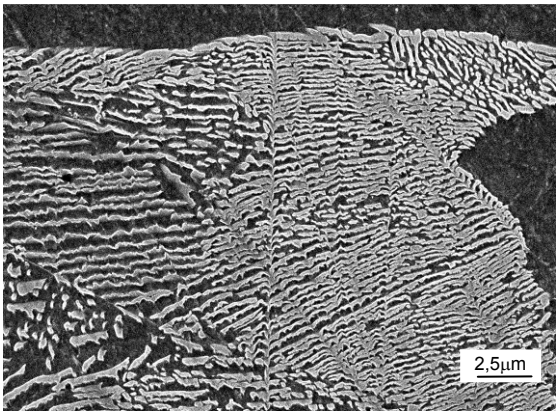

Fig. 2: Initial state: detail of lamellar morphology of pearlite, SEM

Setting phase transformation conditions. For a suitable choice of parameters for thermomechanical treatment, the phase transformation temperatures must be known. For rapid carbide spheroidization, this means primarily the transformation temperatures during heating, i.e. A_{c1}.

Dilatometric measurement was used to accurately find A_{c1} and A_{c3}. It was carried out at two different heating rates; 0.05°C/s a 30°C/s (Fig. 3). With slow heating, A_{c1} was found to be 727°C and A_{c3} was 844°C. For cooling rates of 30°C/s, A_{c1} was 50 °C higher, i.e. 777°C.

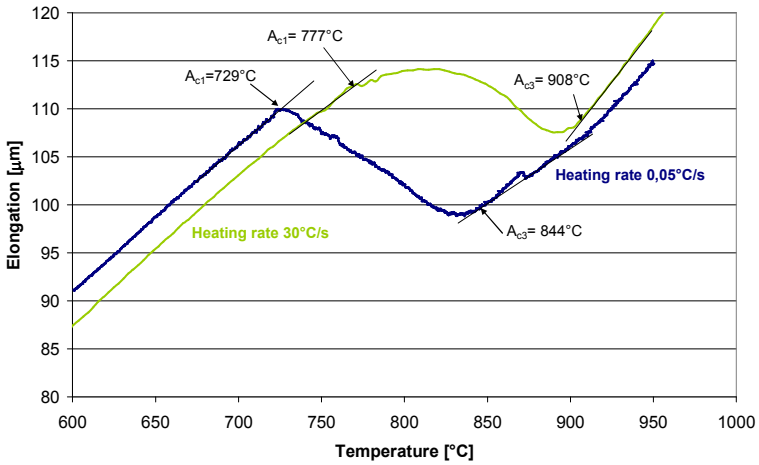

Fig. 3: Determination of A_{c1} and A_{c3} by dilatometric measurement

JMatPro was used to calculate approximate temperatures for the initiation of ferrite formation (869°C) and pearlite formation (709°C).

Accelerated Spheroidization and Refinement. In order to shorten the time for carbide spheroidization, a range of variations of the ASR process parameters was tested with heating temperatures just below A_{c1} with integrated deformation. This combination was selected with the intention of shortening the heating time and refining the structure. Tests were carried out using material-technological modelling on the FORTECH thermomechanical simulator and on real material samples.

In order to obtain a suitable carbide morphology, even distribution and intensive refining of grains, it was necessary to optimize the range of parameters. The most important of these was the range of heating temperatures, size of deformation and length of isothermic holding after deformation (Tab. 3).

In the first phase of the experiment the heating temperature was 740°C with a 10s hold and heating rate of 30°C/s [5]. After the hold there followed tension deformation $\varphi = 0.3$ at a strain rate of $3s^{-1}$, after which there was compression deformation in the range of 0.3 to 1.7 at a strain rate of $3s^{-1}$ (Tab. 3). The high intensity of the deformation led to instability of the form of the sample. Therefore the influence of slower deformation was tested at a strain rate of $0.3s^{-1}$. The effect of diffusion on the resulting carbide morphology and the recrystallization structure was ascertained by inserting a 300s hold after forming. In the second phase, the influence of lowering the treatment temperature by 40°C to 700°C was observed (Tab. 3).

Tab. 3: Variants of parameters for ASR treatment

Heating temperature [°C]	Hold time [s]	Heating rate [°C/s]	Forming	True strain φ tension+compression [-]	Strain rate [s^{-1}]	Hold after forming [s]	Air cooling [s]	HV10 [-]
740	10	30	without forming	0	0	-	75	157
			2 step forming	0.3 + 1.7	3	-		166
				0.3 + 1.7	3	300		121
				0.3 + 0.8	3	300		143
				0.3 + 0.3	3	300		141
				0.3 + 1.7	0.3	300		124
700				0.3 + 1.7	3	-	69	181
				0.3 + 1.7	3	300		122
				0.3 + 1.7	3	500		118

Comparison with traditional heat treatments. In order to compare the results achieved using ASR with traditional methods, two further tests were carried out. First, soft annealing at a temperature of 700°C and then, after a two hour hold, cooling in a furnace; and secondly normalization at a temperature of 900°C also with a two-hour hold but with cooling in open air.

Results and discussion

Traditional heat treatment. Traditional soft annealing in a furnace gave rise to a ferritic structure with spheroidized cementite at the sites of the original lamellar pearlitic formations (Fig. 4) with hardness of 99 HV10. Normalization annealing achieved relatively even distribution of pearlitic areas, however the cementite remained in lamellar form. Both annealing methods led to a reduction in hardness of approximately 100 HV10, i.e. roughly half the hardness of the initial state.

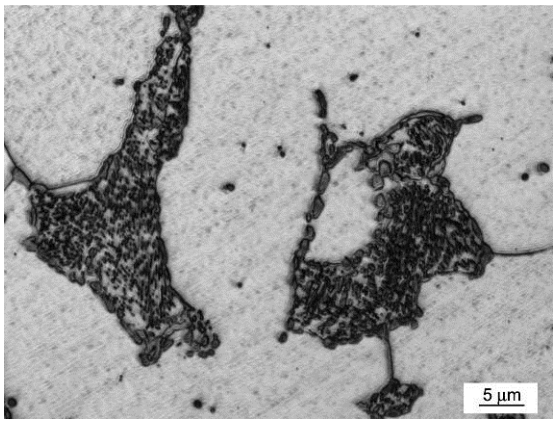

Fig. 4: Soft annealing: 700°C/2h., LSCM

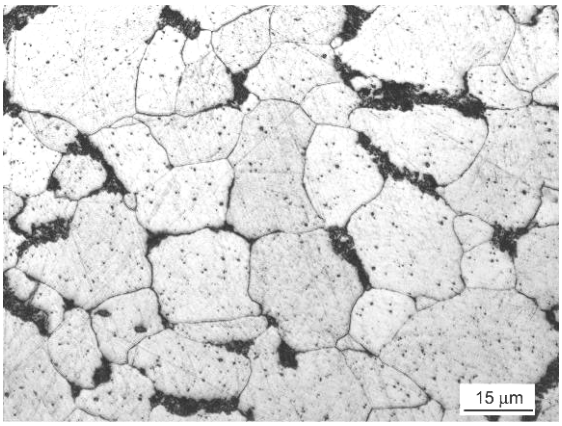

Fig. 5: ASR: 740°C/10s – without deformation, LSCM

Accelerated Spheroidization and Refinement. The first step was to determine the morphology of the carbide and hardness of structures after heating to 740°C with a 10s hold (Tab. 3, Fig. 5). After cooling a ferritic-pearlitic structure with partially spheroidized cementite was observed. There was no significant refining of the structure when compared with the initial state. Annealing lowered the hardness from 201 HV10 to 157 HV10.

The next step was to carry out an intensive, incremental double tension-compression deformation just before air-cooling (Tab. 3). This led to defragmentation of the carbidic lamellae and thus to a very fine ferrite-pearlite structure with very pronounced texture (Fig. 6). Ferrite grain size was about 1 µm. Scanning electron microscopy showed that pearlite colonies occurred with a large portion of spheroidization of cementite (Fig. 7). Hardness values reached 166 HV10.

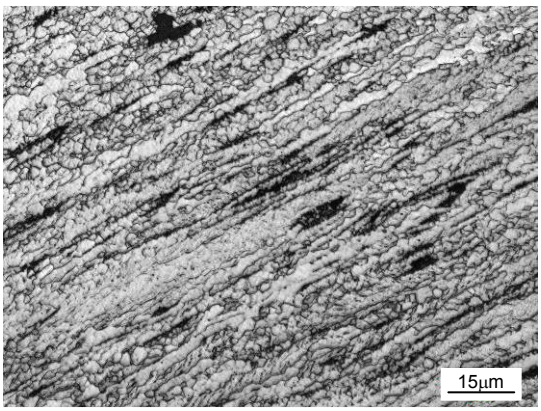

Fig. 6: ASR: 740°C/10s - tension+compression (φ = 2.1), LSCM

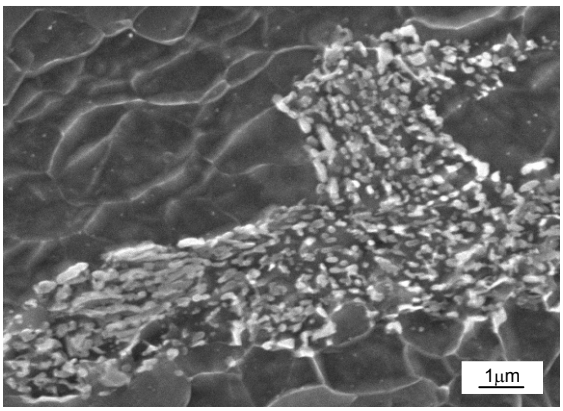

Fig. 7: ASR: 740°C/10s - tension+compression (φ = 2.1), detail SEM

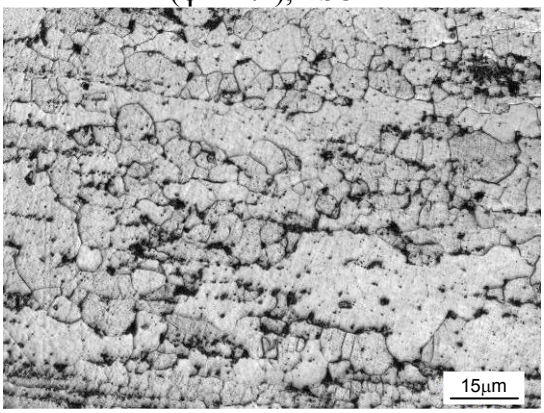

Fig. 8: ASR: 740°C/10s - tension+compression (φ = 2.1), hold 300s, LSCM

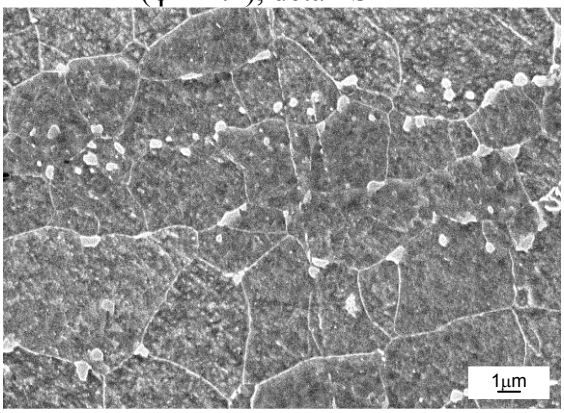

Fig. 9: ASR: 740°C/10s - tension+compression (φ = 2.1), hold 300s, SEM

To assist the process of recrystallization and improve the conditions for spheroidization of the carbide, a 300s hold was included in the next step after tension-compression deformation. This hold caused a coarsening of ferrite grains and localized spheroidization of carbide and more even diffusion of them in the ferrite matrix (Fig. 8, Fig. 9). Changes to microstructure led to significant lowering of hardness values to 121 HV10, i.e. about 27% lower than for the variant without holding.

The size of the deformation used is quite large for some technical applications. On the boundaries of the test bodies, where the nominal values of deformation were lower, it was clear that ASR is less intense. Therefore two treatment variants were tested where the size of the deformation in the second step was gradually decreased from $\varphi = 1.7$ to 0.8 and then to 0.3. The total intensity of deformation in these variants corresponded to a total deformation of $\varphi = 1.1$ and $\varphi = 0.6$. Lowering the total size of deformation resulted in a re-growth of hardness by about 24% compared to the previous strategy. The actual size of the second deformation had no significant influence and for both strategies hardness values were approximately 142 HV10. After treatment, both variants showed larger pearlitic formations with lamellar pearlite morphology (Fig. 10).

Further lowering of the strain rate from $3s^{-1}$ to $0.3s^{-1}$ was tested whilst maintaining the intensity of deformation $\varphi = 2.1$ (Tab. 3). This slower deformation did not result in spheroidization of lamellar pearlite, but only to a refining of the structure (Fig. 11).

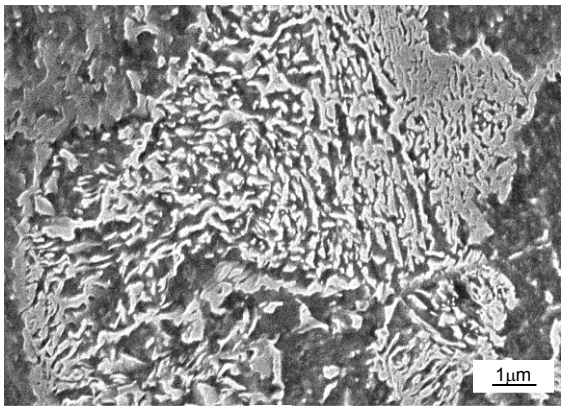

Fig. 10: ASR: 740°C/10s - tension+compression ($\varphi = 0.6$), hold 300s, SEM

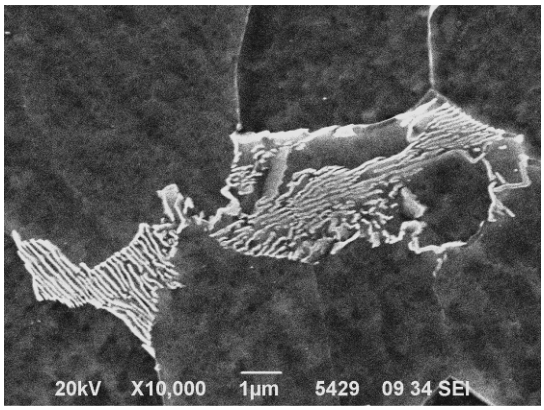

Fig. 11: ASR: 740°C/10s - tension+compression ($\varphi = 2.1$), hold 300s, strain rate $0.3s^{-1}$, SEM

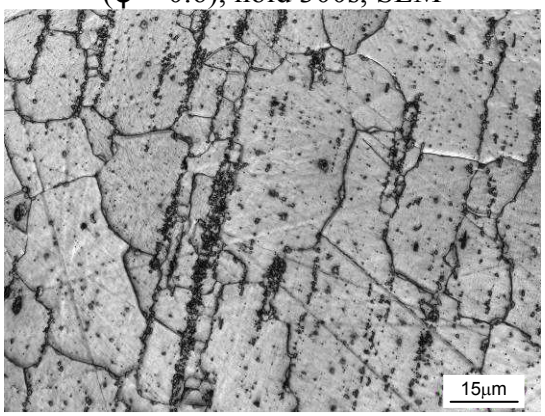

Fig. 12: ASR: 700°C/10s - tension+compression ($\varphi = 2.1$), hold 500s, LSCM

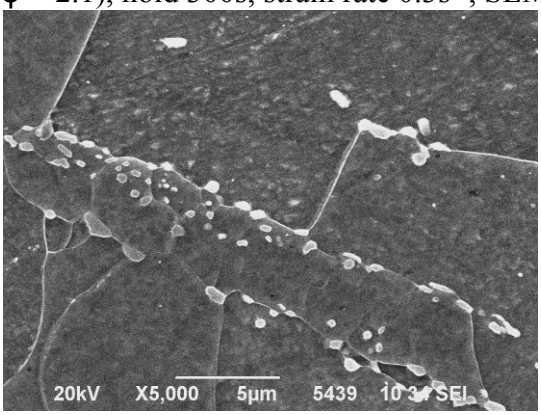

Fig. 13: ASR: 700°C/10s - tension+compression ($\varphi = 2,1$), hold 500s, SEM

In the next step towards optimization it was necessary to ascertain how the development of the structure would react to lowering the treatment temperature. Therefore a heating temperature of 700°C was selected for further experiments (Tab. 3). The previous results were taken into account when selecting the parameters for the experiment. A strategy with rapid tension-compression deformation was tested with total deformation of $\varphi = 2.1$. Treatment was carried out without holding after deformation and also with 300s and 500s holds. All three cases led to a refining of the ferrite matrix. For the strategy without holding the resulting microstructure was textured and

hardness was 180 HV10. Holding after deformation again caused recrystallization of the structure, coarsening of ferrite grains and redistribution of cementite even into the ferrite grains. Pearlite and cementite formations still to a great extent corresponded with the original texture, however they are fragmented and more dispersed (Fig. 12). In the case with the 300s hold, pearlite morphology remained lamellar with minimal signs of spheroidization. When the hold time was increased to 500s, then spheroidization of carbide occurred (Fig. 13) and there was a reduction in hardness to 118 HV10.

Conclusion

A new low-temperature thermomechanical treatment with a considerable reduction in treatment time and energetic demands was designed and tested for low-alloyed construction steel RSt37-2. This treatment, called Accelerated Spheroidization and Refinement, allows a fine grained structure with spheroidized cementite to be obtained in a very short time.

The best results were obtained by using a sufficiently fast intense incremental tension-compression deformation. The most suitable combination of parameters in the investigated cases was found to be true strain 2.1 with a hold of 300s at 740°C after completion of deformation. Lowering the size of the true strain did not lead to spheroidization of the cementite. These results are in agreement with the assumption that, in order to assist intense spheroidization, not only must the segmentation of the cementite lamellae of pearlite be performed mechanically, but also where possible, their fragments must be intensively separated.

Holding after deformation led jointly to recrystallization of structures and to their significant hardening to up to 121 HV10 compared to the initial 201 HV10. Diffusion which could occur during this hold further led to redistribution of carbide and partial removal of the deformation character of the structures. If the heating temperature was lowered by 40°C, to 700°C, the hold time had to be extended to 500s in order to achieve comparable results.

Compared with conventional annealing approaches, ASR reduced the time required for carbide spheroidization from several hours to several minutes.

Acknowledgement. This paper includes results created within the project GA ČR P107/10/2272 Accelerated Carbide Spheroidization and Grain Refinement in Steels. The project is subsidised from specific resources of the Czech Science Foundation.

References

[1] E. Karadeniz. Influence of different initial microstructure on the process of spheroidization in cold forging, Materials and Design, Vol. 29 (2008) 251-256.

[2] C. Chen-Chia. Accelerated spheroidization of hypoeutectoid steel by the decomposition of supercooled austenite, Journal of Materials Science, Vol. 21 (1986) 3339-3344.

[3] J. M. O´Brien, W. F. Hosfort. Spheroidization of Medium-Carbon Steels, Journal of Materials Engineering and Performance, Vol. 6, No. 1 (1997) 69-72.

[4] A. Kamyabi-Gol, M. Sheikh-Amiri. Spheroidizing Kinetice and Optimization of Heat Treatment paramters in CK60 Steel Using Taguchi Robust Design, Journal of Iron and Steel Research International, Vol. 17, No. 4 (2008) 45-52.

[5] Jirková, H. et al. Influence of Low Temperature Thermomechanical Treatment on Carbide Morphology of RSt37-2 Steel, Proceedings of the 21st DAAAM International Symposium Intelligent Manufacturing & Automation (2010), B. Katalinic (Eds.), 25-26.