OPTIMIZATION OF LOW-TEMPERATURE THERMO-MECHANICAL TREATMENT ON 54SiCr STEEL FOR SPHEROIDIZATION OF CARBIDES

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Abstract

In accordance with the current trends of economic savings efforts are also being made in the field of heat treatments to find new procedures leading to a reduction of manufacturing costs [1-3]. One option is the ASR process (Accelerated Spheroidization and Refinement) [4]. This is a progressive method of thermo-mechanical treatment with incremental deformation at a temperature around Ac1. Application of ASR leads to a spheroidization structure with distributed carbides in significantly shorter times than with conventional heat treatments. The experiment deals with the optimization of the ASR process on 54SiCr steel with ferrite-pearlite initial microstructure including pearlite of lamellar morphology. The influence of strain and cold deformation on breaking the lamellar pearlite structure at a temperature of 700 °C was determined. Then the influence of the length of the hold after deformation at temperatures of 680 and 700 °C was described. It was found that increasing holding time from 100 – 1000 s at the deformation temperature has a positive influence on the recrystallization and distribution of spheroidized carbides. The recrystallized structures with ferrite and uniformly distributed spheroidized carbides were obtained after gradual adjustment. Hardness of this structure was only about 260 HV10 in comparison with the initial lamellar structure with 283 HV10.

Keywords: carbide spheroidization, thermo-mechanical treatment, 54SiCr, ASR

1. INTRODUCTION

Spheroidization of the structure of steels with lamellar pearlite morphology is one method for improving formability and machinability of a semi-product to be used for cold forming or machining. Soft annealing is the traditional method for attaining globular pearlite morphology. The long holding time at or below the Ac1 temperature is characteristic for this kind of heat treatment. The length of this holding time presents a significant energy burden which is the main reason for the replacement of this process with a more effective one, for example ASR (Accelerated Spheroidization and Refinement) [5,6]. This progressive method of low temperature thermo-mechanical treatment achieves at least the same results as in the case of soft annealing though with distinctly shorter times. This is achieved thanks to strain energy introduced at temperatures near Ac1. This introduced strain energy supports the carbide spheroidization process and also the refinement of the ferrite matrix.

2. EXPERIMENT

The main aim of the experiment was to optimize the parameters of the ASR process. The influence of the cold deformation before the heat treatment and also the influence of the holding time during the heat treatment on the pearlite spheroidization and the structure refinement were observed. The resulting structures were analyzed with laser confocal and scanning electron microscopy. The mechanical properties were measured using hardness testing and the tensile testing.

2.1 Experimental material

The experiment was performed on spring steel 54SiCr with an increased silicon content. This steel has an initial ferrite-pearlite structure with lamellar pearlite morphology. The yield strength of the initial structure is 561 MPa, the ultimate strength is 964 MPa, the ductility A5mm is 23% and the hardness HV 10 is 283.

Because of the design of the carbide spheroidization process it is necessary to know the Ac1 temperature. This value was checked using dilatometric measurements for the different heating rates – 5, 20 and 30 °C/s, the corresponding temperatures for those speeds were A_{c1} = 707, 711 a 720 °C (**Tab. 1**).

Tab. 1 Chemical composition 54SiCr (ČSN 41 4260) [w. %] and Ac1 temperatures for different heating rates

C	Mn	Si	Cr	Ni	Cu	P	S	A_{c1} [°C]		
								5°C/s	20°C/s	30°C/s
0.5–0.6	0.5–0.8	1.3–1.6	0.5–0.7	max. 0.5	max. 0.3	max. 0.035	max. 0.03	707	711	720

2.2 The experimental programme

The whole ASR process was gradually optimized in several steps. In previous research it was found that the best deformation temperature for spheroidization and ferrite grain refinement in the case of 54SiCr steel is 700°C with holding time 10 sec. The deformation is in two steps - tensile/compression (φ = 0.3+0.54). For the support of the spheroidization and the structure recrystallization a holding time of 100 s was included. The yield strength 614 MPa, ultimate strength 924 MPa, ductility A5mm 14% were obtained after this heat treatment [7].It was necessary to find the effects of the other parameters on the development of the spheroidization and refinement of the structure, which would lead to further influences, shortening and understanding of the entire ASR process. The influence of the strain energy imparted into the material in the cold state on the breaking of the lamellar perlite structure was observed in the following experimental steps. Further, the effect of the temperature holding inserted after the heat deformation in support of the carbide spheroidization and the recrystallization of structures was evaluated. The thermo-mechanical treatment process was performed on a thermo-mechanical simulator which enables accurate measurement and strict regulation of the parameters.

Influence of the cold deformation

The first part of the experiment verified the possibility of breaking the lamellar pearlite by incremental cold deformation. For this purpose three strategies for treatment with compression were designed; (φ = 0.2), tensile (φ = 0.17) and tension/compression (φ = 0.17+0.3) deformations. Heating to 700°C (20 °C under A_{c1}) followed after the deformation. The heating rate was 30°C/s and the holding time at this temperature was 100 s. To supplement this optimization step, the combination of cold compression deformation (φ = 0.2) and tensile/compression deformation (φ = 0.3+0.54) at 700 °C was tried (

Tab. 2). It was mainly determined how the hot deformation is able to support the defragmentation of pearlite and refinement of ferrite grains. The larger compression component was chosen to delay fragmented cementite bodies and their uniform distribution in the ferrite matrix. For the precise description of the influence of cold deformation only the variant with hot deformation was tried. After 10 s holding at 700°C the tension/compression deformation (φ = 0.3+0.54) was inserted.

Tab. 2 The influence of the cold deformation change, the influence of hot deformation

Cold deformation		Heating temperature [°C]	Holding time [s]	Hot deformation			Mechanical properties			
Number of deformation steps	φ [-]			Number of deformation steps	φ [-]	Holding after deformation [s]	$R_{p0,2}$ [MPa]	R_m [MPa]	A_{5mm} [%]	HV10
1(compression)	0.2	700	110	-	-	-	678	947	22	273
1(tension)	0.17	700	110	-	-	-	-	-	-	275
2 (tension / compression)	0.17+0.3	700	110	-	-	-	-	-	-	293
-		700	10	2 (tension/ compression)	0.3+0.54	100s	614	924	14	262
1(compression)	0.2	700	10	2 (tension / compression)	0.3+0.54	100s	598	879	18	265

Influence of the holding time at the deformation temperature

In the next step of the experiment the influence of the holding time after hot deformation was examined. The holding time length should result in homogenous dispersion and spheroidization of the defragmented carbides and recrystallization of the deformation structure. The effect of the holding time was verified in a two-step logarithmic tension/compression deformation φ = 0.3+0.54 at 700 °C because this regime had the best results in the previous part of the experiment. The length of the holding time was between 100 and 1000s (**Tab. 3**). The same strategy was also verified on the regimes with the decreased heating and deformation temperature – 680 °C. To verify the influence of the holding time after deformation, a regime without a holding time was also performed. The deformation was followed by air cooling.

Tab. 3 The influence of the holding time at the deformation temperature and decrease of the heating temperature

Temperature of deformation [°C]	Heating rate [°C/s]	Holding time [s]	Number of deformation steps	φ [-]	Holding time after deformation [s]	Mechanical properties			
						$R_{p0,2}$ [MPa]	R_m [MPa]	A_{5mm} [%]	HV10
700	30	10	2 (tension/ compression)	0.3+0.54	100	614	924	14	262
700	30	10		0.3+0.54	300	603	924	13	273
700	30	10		0.3+0.54	500	554	853	15	265
700	30	10		0.3+0.54	1000	546	852	14	257
700	30	10		0.3+0.54	-	-	-	-	297
680	5	10		0.3+0.54	100	580	925	9	293
680	5	10		0.3+0.54	1000	541	865	15	273

3. DISCUSSION OF RESULTS

Influence of the cold deformation

In the case of the regime with the compressive cold deformation φ = 0.2 and the following heating to 700 °C and the holding time 110 s the ferrite-perlite structure was obtained. The lamellar morphology remained and only a small degree of their spheroidization and fragmentation was observed (**Fig. 1**). The hardness HV 10 of this structure was 273. This treatment achieved a yield strength of 678 MPa, and an ultimate strength of 947 MPa.

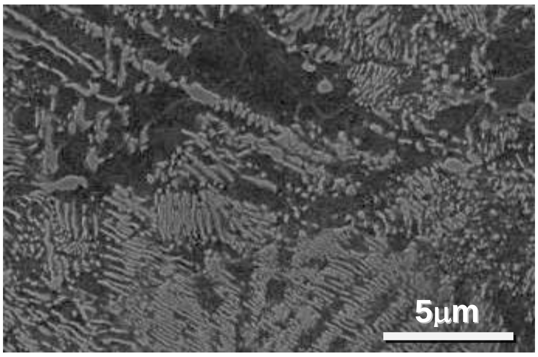

Fig. 1 Cold deformation – compression - (φ = 0.2) 700 °C - 110 s, SEM

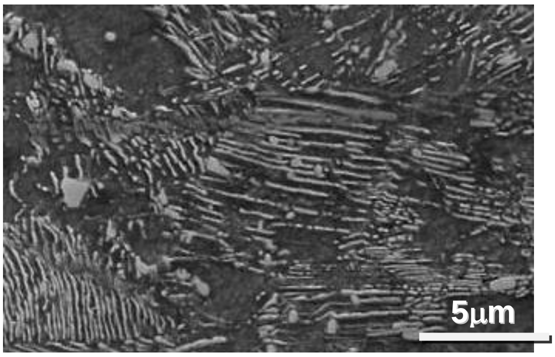

Fig. 2 Cold deformation - tension (φ = 0.17) 700 °C - 110 s, SEM

With the change of character of cold deformation from compression to tension with a value φ = 0.17 (**Fig. 2**) and the combined tension/compression cold deformation φ = 0.17+0.3 there was no observed significant change in the pearlite structure as in the case of compression with cold deformation. In the case of the two-step deformation the hardness increase to 293 HV10 was observed. These results show that the inclusion of the cold deformation before heat treatment does not contribute to the fragmentation and spheroidization of the cementite. The introduced deformation energy is not sufficient for the start of these processes during this type of low temperature treatment.

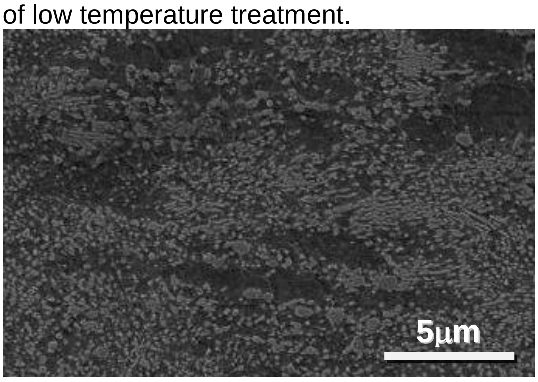

Fig. 3 Cold deformation - compression (φ = 0,2) - 700 °C - 2x def. (φ = 0.3+0.54) - 100 s, SEM

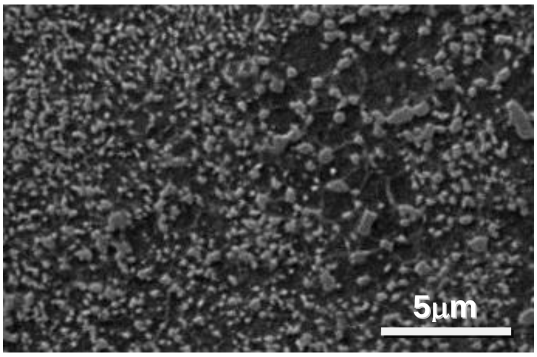

Fig. 4 Hot deformation - 700 °C - 2x def. tension/compression (φ = 0.3+0.54) - 100 s, SEM

The combination of the cold deformation (compression φ = 0.2) and the hot deformation (φ = 0.3 + 0.54) at 700 °C showed better results. With the inclusion of the deformation energy at 700 °C, the temperature increased to 730 °C and this value is higher than Ac1. This treatment caused modest dilution and distancing of the carbide particles which largely preserved the lamellar character (**Fig. 3**). The hardness also decreased to 265 HV 10. A partial change to the cementite morphology led to a decrease of the ultimate strength to 879 MPa and yield strength to 598 MPa.

In the case of the regime with only hot deformation tension/compression φ = 0.3+0.54 at 700 °C, the structure was significantly refined, fragmented and the carbides distances were bigger. The introduced deformation increased the sample temperature to 755 °C. The cementite shapes were mainly spheroid and homogenously dispersed inside the ferrite grains (**Fig. 4**). In some parts the spheroidization was not complete. The structure hardness was 262 HV 10. The significant spheroidization, ferrite grain refinement and homogenous dispersion of the carbides were observed in the entire cross section. These results led to increasing the ultimate strength to 924 MPa and yield strength to 614 MPa.

Influence of the holding time at the deformation temperature

In the second experimental part the influence of the temperature holding time on the spheroidization process and structure recrystallization were observed. Because in the experimental programme it was tried to find the least energy-intensive treatment and simulated the different heating possibilities, two different heating temperatures were tried – 700 °C (heating rate 30 °C/s) and 680 °C (heating rate 5 °C/s). After 10 s holding time the two-step deformation tension/compression φ = 0.3+0.54 was performed. The different holding times at the temperatures between 0 and 1000 s were tested (**Tab. 3**). For the heating temperature 680 °C the lower heating rate was chosen due to the decrease of Ac1 temperature to 707 °C. Because the short exceeding of the Ac1 temperature during the heat treatment positively affects the spheroidization process and also recrystallization, this temperature was exceeded by inserting the deformation and the temperature were increased to 730 °C. The prolongation of the holding time at the deformation temperature from the previous 100 s to 300s did not show any changes in the structure for the regime with two-step tension/compression deformation at 700 °C. The structure contained relatively equally dispersed carbides in the ferrite matrix (Fig. 5, **Fig. 5**).

With the further prolongation of the holding time at the deformation temperature to 500 s the structure was fully recrystallized ferrite matrix containing spheroidized but less evenly distributed carbide formations (**Fig. 6**). The hardness value for this structure was 265 HV10. After the holding time of 1000 s the recrystallized ferrite matrix was obtained but this structure contained visibly coarse carbides along the ferrite grain boundaries (**Fig. 7**). This longest holding time led to the decrease of the hardness to 257 HV10. Without the holding time after the deformation, the structure was distinctly deformed and alignment is disturbed (**Fig. 8**). The hardness value increased to 297 HV10.

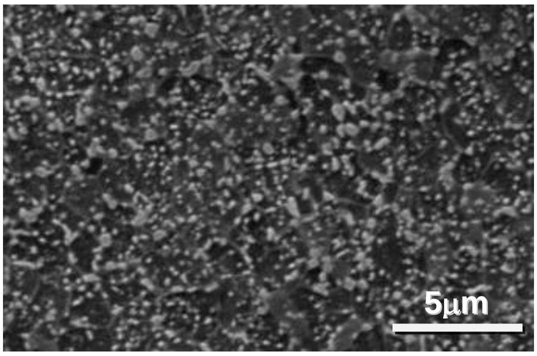

Fig. 5 Hot deformation - 700 °C - 2x def. tension/compression (φ = 0.3+0.54) - 300 s, SEM

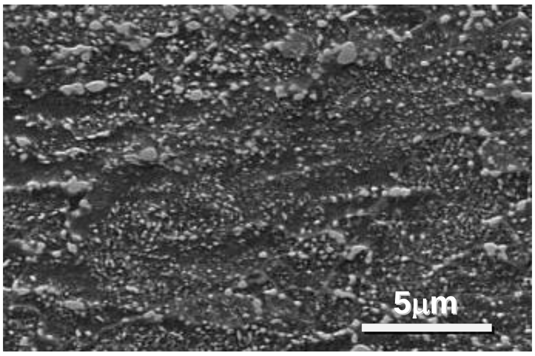

Fig. 6 Hot deformation - 700 °C - 2x def. tension/compression (φ = 0.3+0.54) - 500 s, SEM

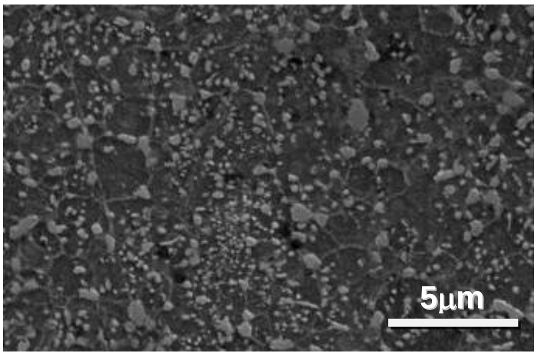

Fig. 7 Hot deformation - 700 °C - 2x def. tension/compression (φ = 0.3+0.54) - 1000 s, SEM

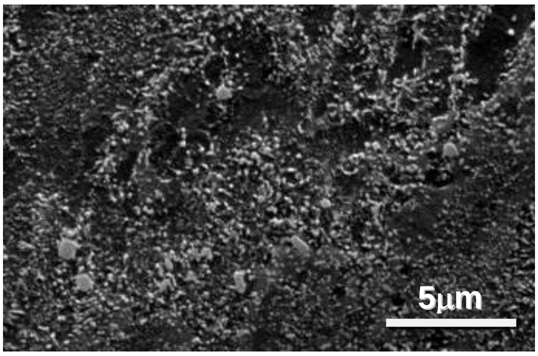

Fig. 8 Hot deformation **-** 700 °C - 2x def. tension/compression (φ = 0.3+0.54) - without holding time, SEM

In the next step the heating temperature was decreased to 680°C. In this case the two-step tension/compression deformation with the following holding time 100 or 1000 s was applied. In the case of the 100 s holding time the resulting very fine and aligned ferrite structure contained fragmented, partly spheroidized carbide formations with hardness 293 HV10 (**Fig. 9**). The increase of the holding time to 1000 s brought only partial elimination of alignment and more homogenous spheroidized cementite distribution. The hardness value decreased to 273 HV10 (**Fig. 10Chyba! Nenalezen zdroj odkazů.**).

The mechanical properties were also influenced by the gradual prolongation of the holding time. At the heating temperature 700 °C with the holding time longer than 500 s the ultimate strength distinctly decreased. This value was 924 MPa with the holding time 100 s but only 852 MPa with the holding time 1000 s (**Tab. 3**). For the yield strength the same trend was observed. For the heating temperature 680 °C only two holding times were observed, the prolongation from 100 s to 1000 s caused the decrease of the ultimate strength value by about 60 MPa (**Tab. 3**).

This part of the experiment shows that to support the spheroidization of fragmented carbides it is necessary to add at least a short holding time. The pronounced increase of the holding time at the deformation temperature can remove the structure alignment but at the same time causes a coarsening of the carbides and deterioration of mechanical properties.

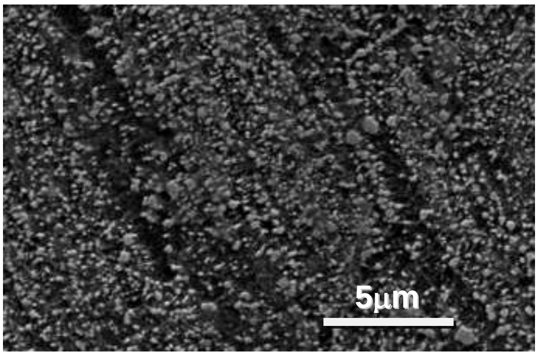

Fig. 9 Hot deformation - 680 °C - 2x def. tension/compression (φ = 0.3+0.54) -100 s, SEM

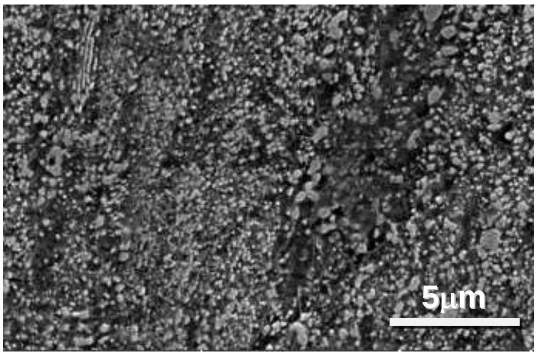

Fig. 10 Hot deformation - 680 °C - 2x def. tension/compression def. (φ = 0.3+0.54) -1000 s, SEM

4. CONCLUSION

The experiment investigated the influence of low-temperature thermo-mechanical treatment – the ASR process on the structural development in 54SiCr steel. The influence of cold deformation before the ASR process and also the influence of the holding time after deformation at the temperatures 680°C and 700°C were observed. The holding time was inserted to support the spheroidization process and refinement of the structure.

The first experimental part showed that insufficient cold deformation (compression φ = 0.2, tension φ = 0.17, tension/compression φ = 0.17+0.3) before heat treatment does not contribute to the cementite fragmentation and spheroidization. The tension/compression deformation φ = 0.3+0.54 at 700 °C after cold compression deformation φ = 0.2 caused partial change of cementite morphology. This change of structure caused a different ultimate strength of 879 MPa and yield strength of 598 MPa. The regime with the tension/compression deformation φ = 0.3+0.54 at 700 °C with the following holding time 100 s guaranteed the biggest structure refinement and the carbide formations were fully spheroidized. The value of the ultimate strength was 924 MPa and the value of the yield strength was 614 MPa.

The experiment verified that holding time at the deformation temperature is necessary to support the spheroidization of the fragmented carbide formations. This holding time affects the carbide spheroidization and also the recrystallization of the deformed structure. A ten-fold increase of holding time from 100 to 1000 s caused the coarsening of the carbides and also the ferrite matrix. The structural changes also influenced the mechanical properties, the holding time prolongation caused the decrease of the ultimate strength from 924 (100 s) to 852 MPa (1000 s) and yield strength from 614 to 546 MPa. The deformation at 680 °C showed a similar trend, the longer holding time partly supported the recrystallization process and led to a decrease of the ultimate strength by about 60MPa.

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