JOURNAL OF ENGINEERING
annals OF
FACULTY OF ENGINEERING HUNEDOARA
TOME VI (year 2008), FASCICULE 1, (ISSN 1584 – 2665)

ANALYSIS OF MICROSTRUCTURE AND MECHANICAL PROPERTIES OF HSLA STRIP STEEL AFTER COLD ROLLING AND ANNEALING

[1.]Marcel JANOŠEC, [1.]Ivo SCHINDLER, [1.]Vlastimil VODÁREK,
[2.]Emerich MÍSTECKÝ, [2.]Martin RŮŽIČKA

[1.]VŠB – TECHNICAL UNIVERSITY OF OSTRAVA, FACULTY OF METALLURGY AND MATERIALS ENGINEERING, OSTRAVA, CZECH REPUBLIC
[2.]NOVÁ HUŤ – VÁLCOVNA ZA STUDENA, SPOL. S R.O., OSTRAVA, CZECH REPUBLIC

ABSTRACT:
Influence of graduated deformation and parameters of annealing on the resulting microstructure and mechanical properties of microalloyed steel was investigated. The experiment was based on combination of cold rolling, recrystallization annealing, mechanical testing, metallographic examinations, SEM and TEM analyses. It was confirmed that by a suitable combination of size of previous cold deformation and parameters of the following recrystallization annealing it is possible to influence a complex of mechanical properties of particular strips.

KEYWORDS:
HSLA Steel, Cold Rolling, Annealing, Microstructure, Mechanical Properties Testing

1. INTRODUCTION

A significant part of hot rolled sheets and strips is subjected to process of cold rolling, when recrystallization cannot be realized due to low forming temperatures. Hence, structural changes have to come into existence, in which grains forming the basic matrix of the material are gradually stretched in the direction of the principal deformation and at the same time the directional arrangement of the crystallographic lattice is developed. So the deformation, structural and crystallographic texture is formed. Besides changes in the grain character also a "banding" arrangement of other structural phases, such as inclusions, carbides or pearlitic blocks, is formed. Character of all these microstructural changes will basically result in values of mechanical properties.

In the case of microalloyed steels the resulting mechanical properties influenced are to a great extent by the character of released precipitates because another mechanism of so called dispersion strengthening [2, 3] is added to standard strengthening mechanisms. In the course of processing of HSLA steels the changes of distribution, size and/or shape of precipitates [1, 4, 6] occur, which finally influences significantly the level of not only strength but also plastic properties.

The aim of this work was to investigate impact of various cold reduction size in combination with recrystallization annealing on microstructure and mechanical properties of investigated microalloyed steel. For a deeper understanding of development of mechanical properties the microstructure of samples was evaluated by use of both optical and electron microscopy.

2. METHODOLOGY

A large testing programme of a strip steel grade S 460 MC, microalloyed by vanadium, titanium and niobium, was realized. Chemical composition of the studied HSLA steel is presented in Table 1.

TABLE 1. CHEMICAL COMPOSITION OF THE INVESTIGATED STEEL (WT. %)

C	Mn	Si	P	S	Al	V	Ti	Nb	N
0.08	1.36	0.18	0.018	0.008	0.022	0.033	0.030	0.067	0.0053

The experiment was based on combination of cold rolling, recrystallization annealing, mechanical testing, metallographic examinations and electron microscopy. The initial material was in the form of pickled cuts of the hot rolled strip with thickness of 3.9 mm.

Samples in the form of stripes with dimensions 3.9 x 25 x 500 mm were cold rolled in several passes with the total height reduction 5 to 75 %. Particular partial strains were realized at room temperature in the housingless, hydraulically prestressed laboratory mill stand [5]. Annealing in a laboratory vacuum resistance furnace in the protective atmosphere consisting of 90 % of nitrogen and 10 % of hydrogen followed. Parameters of applied annealing mode are: speed of temperature increase up to an intermediate dwell – 120 °C/h; temperature of the intermediate dwell – 600 °C; time of intermediate dwell – 2 h; speed of slow temperature increase – 15 °C/h; temperature of the dwell – 650 °C; time of dwell – 6 h.

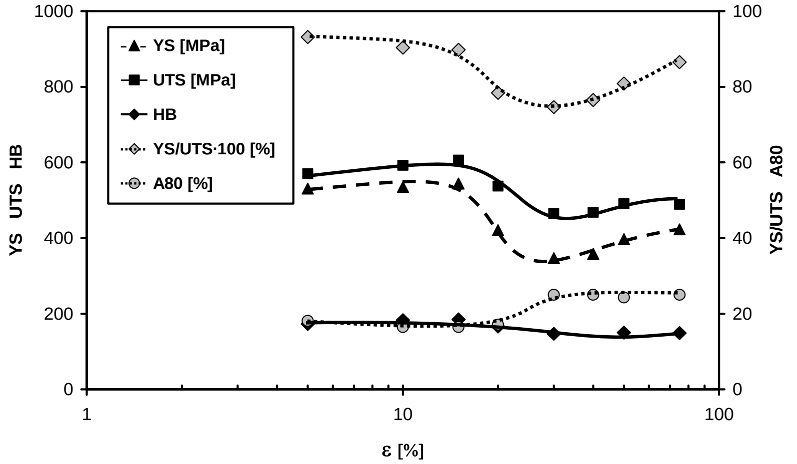


Figure 1. Mechanical properties of annealed samples

The annealed samples underwent the tensile test at the room temperature and the Brinell hardness test (a ball of diameter 2.5 mm). The gained results – hardness HB, yield stress YS [MPa], ultimate tensile strength UTS [MPa] and the ratio of YS to UTS, as well as elongation A80 [%], were summarized in graph in Figure 1 in dependence on cold deformation size (i.e. relative height reduction) before annealing – ε [%].

3. DISCUSSION OF RESULTS

As it is apparent from relationships in Fig. 1, strength properties are slowly increased with the increasing reduction size. Maximum values of YS and UTS were reached approximately after deformation ε = 15 %. A relatively steep decrease follows, which is alternated again by an increase of strength variables. Development of plastic properties is not so complicated, but the trend of elongation A80 corresponds to development of strength properties.

Samples for evaluation of the structure by optical microscopy were taken from central parts of rolled out products (in the perpendicular section, parallel with the direction of rolling). The structure was evaluated on selected samples after annealing, but - for comparison - also on the initial – non-cold deformed sample. It may be seen from Figure 2 that microstructure after hot rolling was created by ferrite, with occurrence of pearlite and very fine grains (ferritic grain size G = 12–13). Nevertheless, not all ferritic grains were equiaxed.

Microstructures of cold deformed samples after annealing may be seen in Figure 3. The selection of samples was based on the known fact that mechanical properties are essentially influenced by a character of microstructure. The structure was therefore evaluated for those reduction values in which significant changes of values of mechanical properties occur.

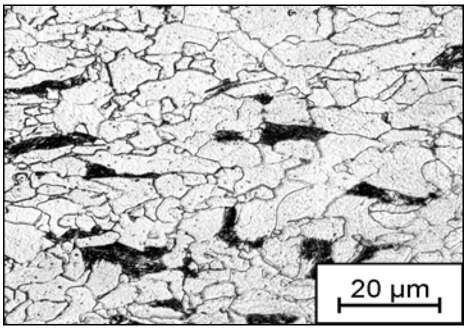
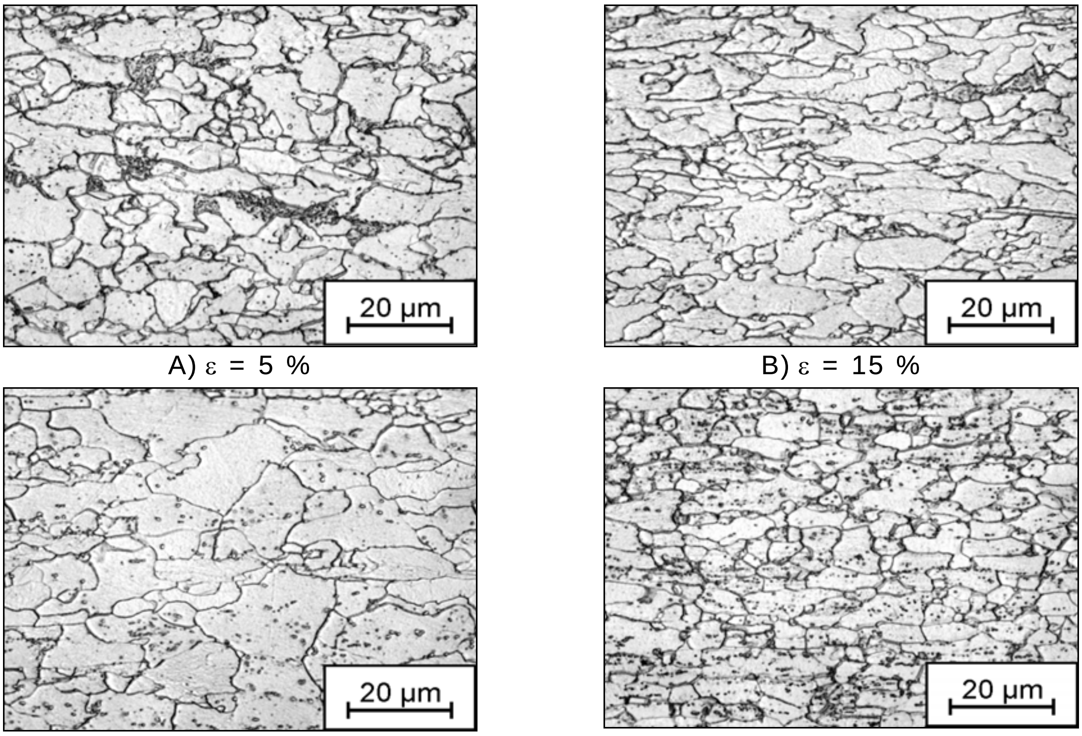


Figure 2. Microstructure after hot rolling



A) ε = 5 %

B) ε = 15 %

C) ε = 30 %

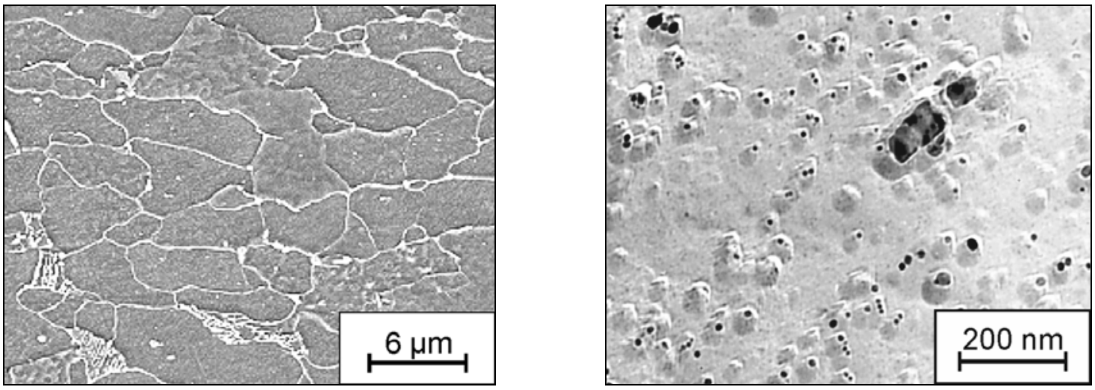
D) ε = 75 %

Figure 3. Microstructure after cold rolling and annealing

Generally it may be stated that the microstructure of samples after cold rolling and annealing is essentially in all cases created by ferrite and a small quantity of pearlite. The character of ferritic grains, as well as the form and distribution of pearlitic formations in basic ferritic matrix, is influenced by the cold reduction size and parameters of the applied annealing mode. The higher cold deformation resulted in higher spheroidization of pearlitic formations. The uniform and equiaxed structure with relatively fine grains is reached only after the highest cold reduction rate (Fig. 3d). The deformation size of ca 30 % (Fig. 3c) in combination with the used annealing mode results in a pronounced coarsening of recrystallized grains. With regard to the Hall-Petch equation [3] it is possible to explain the decrease of strength properties or yield stress in graph in Fig. 1 by means of Fig. 3c. When deformations up to 15 % are used, no significant crumbling of pearlitic formations (they are well distinguished in particular after using of smaller deformations – Fig. 3a) occurs and the chosen annealing temperature is insufficient for recrystallization (see Fig. 3b – showing the structure which is strengthened by deformation and characterised by corresponding high values of YS and UTS).

For a deeper understanding of the development of mechanical properties, which is documented by graph in Fig. 1, the selected samples were evaluated by use of the electron microscopy. A scanning electron microscope (SEM) was used for identification of minority phases. The precipitation processes (or differences in size, quantity and distribution of precipitates) were evaluated with use of a transmission electron microscope (TEM).

Occurrence of cementite particles on ferritic grain boundaries was confirmed by the phase analysis in structure of the sample after hot rolling. Inside grains (or on their boundaries, as the case may be) occurrence of complex particles of carbonitrides, or carbides of niobium and titanium (Fig. 4) was proved. The ratio of titanium to niobium in these particles is very variable. It may be supposed that stability of the mentioned precipitates is higher than in the case of Nb(C,N) or NbC. Very fine particles of MX type are relatively uniformly released inside ferritic grains. Their size reaches several tens of nanometers at the maximum.

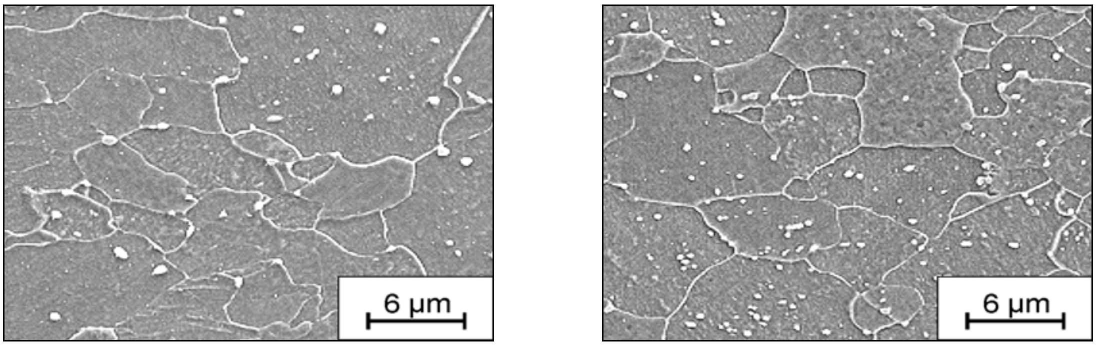


A) SEM B) TEM

Figure 4. microstructure and precipitates after hot rolling

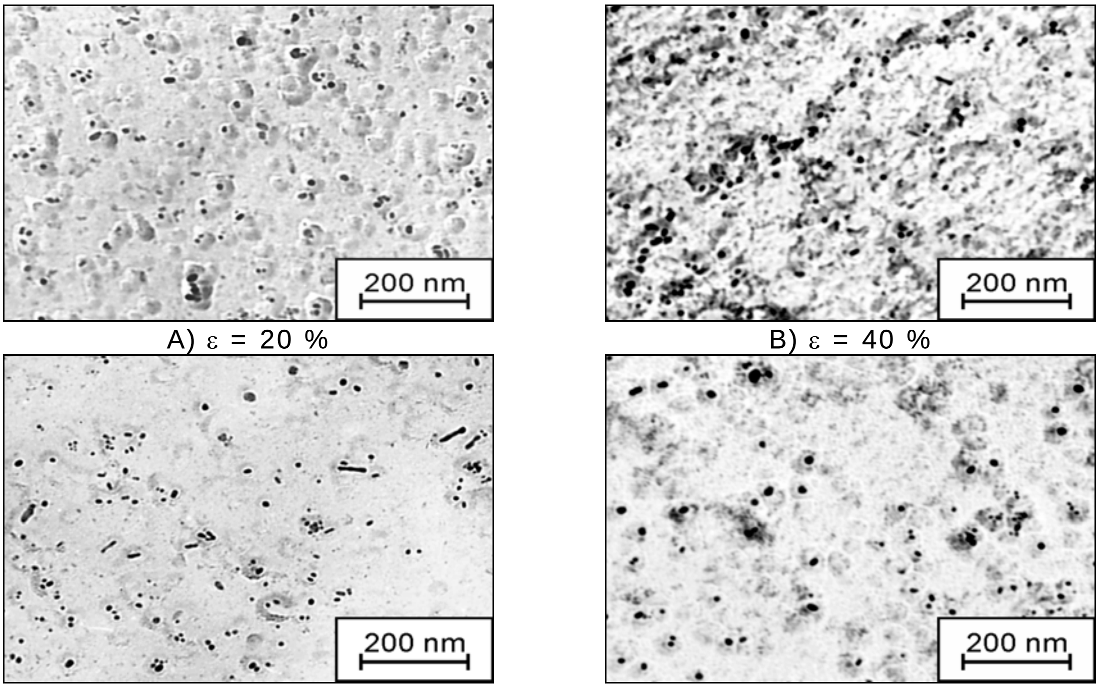
With regard to products of solubility of particular carbides and nitrides of microalloying elements in austenite and ferrite it may be presumed that fine precipitates are created by vanadium carbides, in which a smaller quantity of niobium can be solved. It is evident that these particles precipitated during cooling of the material after hot rolling because due to solubility of vanadium carbides in ferrite and austenite their precipitation can be expected only at temperatures below 900 °C.

The microstructure of samples after cold rolling and annealing is characterised by the occurrence of uniformly distributed globular cementite particles on grain boundaries or inside ferritic grains. It is a result of spheroidization of pearlitic formations, crumbled in cold deformation. Precipitates in these samples can be found in a relatively small quantity on grain boundaries and inside ferritic grains in the form of carbonitrides or carbides of niobium (Fig. 5 and 6).



A) ε = 20 % B) ε = 50 %

Figure 5. SEM analysis of microstructure of samples after cold rolling and annealing



A) ε = 20 % B) ε = 40 %

C) ε = 50 % D) ε = 75 %

Figure 6. TEM analysis of microstructure of samples after cold rolling and annealing

Fine, in more detail unspecified, particles of MX type, the mean size of which is mildly larger than in the case of the sample after hot rolling, occur in a greater extent inside ferritic grains. It may be assumed that they are vanadium carbides, in which a smaller quantity of niobium can be solved. Unfortunately, these particles are too small for the X-ray microanalysis. Most of them were probably present in the initial semifinished product in the state after hot rolling; a lesser portion of them could originate in the course of annealing after cold rolling. A share of fine particles, which precipitate during annealing, was dependent on vanadium and niobium contents, which surpassed the solubility value of these elements in ferrite at the applied annealing temperatures. The precipitates that were present in the material before cold deformation coarsened during subsequent annealing and/or changed their morphology.

The described facts are demonstrated by photos of the microstructure in Fig. 6. Annealing after reduction size of 40 % (Fig. 6b) resulted in increase in number of precipitates and at the same time in coarsening of some of them, or their distribution into bands (streaks) in the structure. The degree of deformation of 50 % resulted in the origin of particles or their clusters in the form of stick formations (Fig. 6c). The sample that was annealed after reduction of 75 % (Fig. 6d) exhibited relatively intensively coarsened precipitates, which had exclusively globular character. The surface density of particles in photo 6d (the greatest degree of cold reduction) is in comparison with photo 6a (reduction size only 20 %) significantly smaller. With regard to size of precipitates in particular samples it may be judged that the driving force for growth of precipitates during annealing is represented by cold deformation. Their mean size increases and frequency of their occurrence in the matrix decreases with the growing degree of the former deformation.

4. CONCLUSIONS

The experiment proved that by a suitable combination of reduction size and annealing it is possible to influence to a great extent the complex of mechanical properties of the investigated microalloyed steel.

Values of strength properties may be influenced by the described way in the range of approximately 100 MPa, which enables - related to applications in practice - to use the obtained results in formation of technological procedures of forming and heat treatment in cold rolling mills.

ACKNOWLEDGEMENTS:
This work was accomplished in the framework of solution of the project MSM6198910015, supported by the Ministry of Education of the Czech Republic.

REFERENCES

[1] GHOSH P., BHATTACHARYA B., RAY R.K., Comparative study of precipitation behaviour and texture formation in cold rolled-batch annealed and cold rolled-continuous annealed interstitial free high strength steels, Scripta Materialia, 8, 56, 2007.
[2] GINZBURG V.B., Metallurgical Design of Flat Rolled Steels, Marcel Decker, New York, NY, 2005.
[3] GLADMAN T., The Physical Metalurgy of Microalloyed Steels, Institute of Materials, Cambridge, 1997.
[4] HONG S.J., JUN H.J., KANG K.B., PARK C.G., Evolution of precipitates in the Nb-Ti-V microalloyed HSLA steels during reheating, Scripta Materialia, 8, 48, 2003.
[5] http://www.fmmi.vsb.cz/model/
[6] JUN H.J., KANG K.B., PARK C.G., Effect of cooling rate and isothermal holding on the precipitation behaviour during continuous casting of Nb-Ti bearing HSLA steels, Scripta Materialia, 11, 49, 2003.