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DEVELOPMENT OF FINE GRAINED STRUCTURE LOW CARBON STEEL USING ARB TECHNOLOGY

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ABSTRACT
The paper analyses methods of grain refinement and demonstrates development of ultrafine grains structure and properties of low carbon steel after ARB deformations. ARB technology was experimentally verified. True strain has archived the value around 9. Basic relations between magnitude of deformation, grain refinement and resulting mechanical properties were described. Development of structure was verified on low carbon steel. Obtained grain size was around 0,3 μm. Properties obtained by tensile test did not achieve the expected value.
Keywords: ARB technology, low carbon steel, structure and mechanical properties

1. INTRODUCTION
The fact that strength (hardness) of material increases with decreasing grain size in its structure was known from the early fifties of the last century, when famous Hall-Petch relationship was formulated

$$Re = \sigma_o + k.d^{-1/2} , \quad (1)$$

where Re - yield value, σ_o - stress necessary for overcoming of Peierls-Nabarr friction stress, resistance of dissolved foreign atoms, resistance of precipitates from solid solution and lattice defects, k the constant, the measure of which is the value of shearing stress necessary for release of accumulated dislocations, d - grain size.

It follows from the equation (1) that material yield value increases with decreasing grain size. This phenomenon is a driving force for research and development of high-strength structural materials, particularly of steels. It turns out that refining of grain can lead to increased drawability of metallic materials. On condition of identical strengthening mechanism refining of grains down to the level of nanometers can bring enormous increase in material strength.
It can be calculated that for grain sizes between 10 – 20 nm the yield value approaches the theoretical material strength. Validity of the relationship (1) has been proved experimentally, with the exception of its validity for large grains and for very fine grains - approx. below 10 nm [1].
Fine-grain materials are characterised by high density of grain boundaries and other interfaces, which leads to a notion of validity of functioning of high-temperature deformation mechanisms respecting

the role of grain boundaries into the zone of lower temperatures. For example at significantly lower homological temperatures the ultrafine-grain materials („nano-crystalline“) materials will be deformed by processes, which are controlled by diffusion along grain boundaries. There appears a possibility of production of plastic ceramics, super-plastic behaviour of metals at low temperatures, diffusion creep of pure copper at room temperature [2].

2. GRAIN REFINEMENT METHODS

Several methods are used for grain refinement, such as phase transformation, re-crystallisation, forming of duplex alloys and distribution of phases in duplex alloys. In case of the first two methods – phase transformation and re-crystallisation the mechanism of these processes is based on formation of nuclei of new grains inside the grains of initial structure.

In the third method – deformation of duplex alloys, both phases disintegrate and coagulate. Process in both phase sis accompanied by re-crystallisation, which brings another contribution into overall grain refinement.

In case of the fourth method the initial structure is not an equilibrium microstructure. It can be e.g. martensite, or over saturated solid solution. Distribution of metastable phase to two equilibrium phases leads to formation of ultra-fine grain duplex structure. Very often several of these methods are used simultaneously. Diagram in Fig. 1 show four grain refinement methods mentioned above.

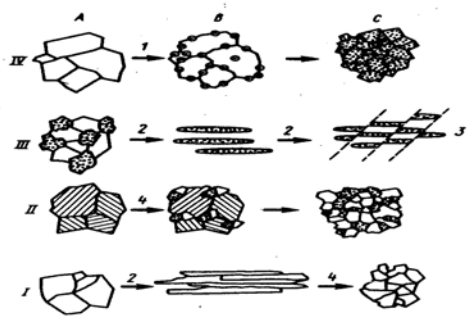


Figure 1. Basic mechanisms of grain refinement
I – re-crystallisation; II – distribution of phases in alloys with duplex structure; III – non-homogenous deformation of alloys with duplex structure; IV – phase transformation;
A, B, C- initial, intermediary and final microstructure
1 - Heating cooling; 2 – deformation; 3 – shear planes; 4 – annealing

2.1 Grain refinement by re-crystallisation

Re-crystallisation is a universal method for grain refinement – unlike grain refinement methods described above, which are suitable only for alloys, in which transformation arise or for alloys with duplex microstructure. The results obtained during last years declare influence of size of individual structural particles on the course of re-crystallisation. There are two types of effect of particles on re-crystallisation:

1) Fine particles (with diameter much smaller than 1 μm) inhibit nuclei and slow down growth of re-crystallised grains as a result of blocking of walls of dislocation cells and sub-grain boundaries.
2) Coarser particles (with diameter larger than 1 μm) create places of nuclei for re-crystallisation. During deformation deformed zones are formed around non-deformable particles and formation of nuclei of re-crystallised grains occurs inside these deformed zones. It is possible to use two types of re-crystallisation for grain refinement. Both are connected with use of particles for creation of fine grain.

Discontinuous re-crystallisation – nuclei are formed and re-crystallised grains grow. In this case the key factor is high density of nuclei for re-crystallised grains. It is obvious that high density of large particles will refine grains at running discontinuous re-crystallisation. This mechanism of grain

refinement was verified on dispersively hardenable Al alloys. Mean diameter of grains was around 10 μm and alloys had high values of strength.
Continuous re-crystallisation – sub-grains grow, high-angle boundaries are formed and structure is transformed to re-crystallised structure. Nuclei of individual re-crystallised grains are not formed. Braking of discontinuous re-crystallisation by more rapid process is pre-requisite for running of continuous re-crystallisation. It is possible to expect continuous re-crystallisation in alloys with high density of fine particles, which prevent running of discontinuous re-crystallisation.

3. GRAIN REFINEMENT BY SEVERE PLASTIC DEFORMATION

Several procedures are used (ECAP, S2C2, ARB), during which severe plastic deformation accumulates in bulk of metal. Magnitude of deformation at classical techniques of forming is limited by shrinking of material cross section with growing pass reduction. Technology ARB (accumulative roll bonding) is a SPD process, at which severe deformations are obtained by rolling [3]. The principle is shown in Fig. 2. It is possible to repeat the ARB almost without any limitations.

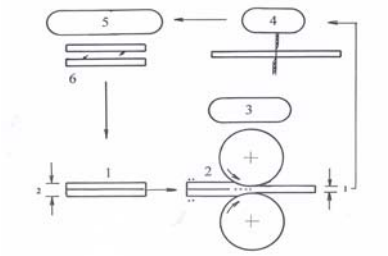


Figure 2. Principle of ARB process
1 – initial sample, 2 and 3 – rolling, 4 – transverse cutting, 5 and 6 surface finish and stratification

4. EXPERIMENTAL VERIFICATION

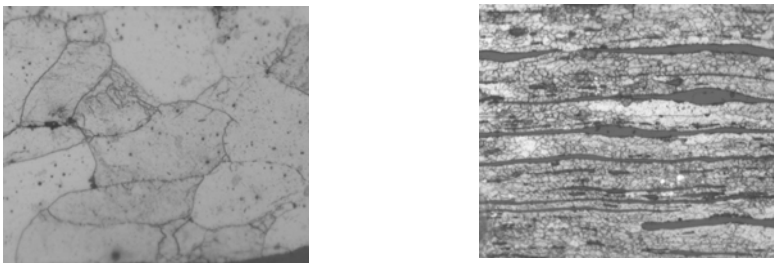
ARB process was verified in laboratory conditions on low carbon steel and on austenitic steel. Under given conditions of rolling certain problems occurred with pressure welding of individual layers in case of austenitic steel, that's why results of the experiment will not be presented in greater detail. Chemical composition of low carbon steel is given in the table 1.

Table 1. Chemical composition of low carbon steel

Chemical composition [mass %]					
C	Mn	Si	P	S	Al
0.05	0.45	0.15	0.020	0.020	0.020

4.1 Results and their analysis

Altogether 11 cycles were made at temperature of 520 °C. Grain was gradually refined with increasing temperature. Development of structure is shown in Fig. 3. Structure is non-uniform and there are areas with grain size smaller than 0,5 μm. Boundaries between grains are distinct, but irregular. Similar structure can be found in severely deformed materials, obtained by different SPD processes.



a) 500 x b) 500 x

Figure 3. Grain size after deformation e = 2,4 (a) and for e = 8 (b)

Characteristic feature of materials processed by the ARB process is their orientated structure. Photos show typical microstructure of elongated very fine grains in steel after 11 cycles. Total number of individual sheets in the packet is 2 048. It is obvious from photos of microstructures that UFG structure is not formed by sub-grains, but rather with grains with high-angle boundaries. Maximum deformation obtained by the ARB process is e = 8,8. Grains are elongated in direction of rolling. It is possible to discover very similar microstructures also in other metals with KSC structure processed by the ARB process. These microstructures resemble to lamellar structures observed in severely deformed materials (Fig.4)

Figure 4. Lamellar structure of low carbon steel after deformation e = 8.8

Analysis indicates that formation of UFG is not effected by conventional discontinuous re-crystallisation, but by continuous re-crystallisation, characterised by consecutive division of very fine grains, and by migration of grain boundaries to short distance. Mechanical properties of the sample after deformation equal to 8.8 were verified by tensile test [4]. The results are given in the table 2.

Table 2. Properties of samples after deformation e = 8.8

Direction of taking of sample	E [MPa]	Rm [MPa]	A [%]
longitudinal	209 700	288.0	0.155
	206 174	315.3	0.217
transverse	193 973	339.0	0.243
	197 518	234.0	0.12
along	-	max. 400	25

5. CONCLUSIONS

Tests made on the low carbon steel show a UFG structure. The obtained strength after severe deformation (e = 8.8) is very low. It is caused by big number of oxides in original dividing planes, which were formed at heating in oxidation atmosphere. In majority of cases the average size of grains, which occur also in the form of very fine lamellar structures, is around 0.5 μm. Next experiments have proved, that significantly finer grain is obtained that at lower temperatures. If there are created conditions for limitation of oxidation in dividing planes, it is possible to predict – subject to validity of relation given in Fig. 4.

6. ACKNOWLEDGEMENTS

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