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FORMATION OF IDENTICAL FINE GRAINED MICROSTRUCTURES WITH HIGH IMPACT RESISTANCE IN AS CAST AND AS HOT ROLLED CONVENTIONAL LOW ALLOY STRUCTURAL STEELS

I.Tkachenko, K. Tkachenko, V.Miroshnichenko

Priazovsky State Technical University; University str., 1, Mariupol, 87500, Ukraine

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Introduction

Casting and hot deformation are currently among the main steel product manufacturing processes. The most considerable alloy steel quality problems arising from their use are as follows [1-3]: strong nonuniformities in spatial distributions of chemical elements and structure components, coarse grained microstructures and, as a consequence, bad steel product performance in as received conditions. So, a number of additional treating operations are used to improve the performance. Hot deformation or heat treatment after casting, regulated cooling or heat treatment after hot deformation are the typical ones. Nevertheless, most of the above problems, such as chemical and structural nonuniformities, not enough fine austenite grains and reduced impact resistance are still remaining very actual [4].

Purpose of the research is to show possibility of considerable refining microstructures and improving the performance of as cast and as hot rolled alloy steel products by means of proposed cooling regime.

Materials and Methods

Investigations were conducted using 34CrMo4 and E36 steels, respectively, in as cast and as hot rolled conditions. The steels have industrially obtained microstructures and properties which enough clear illustrate the above actual quality problems. Chemical compositions of the investigated steels are given in Table I. The impact test sample billets of the sizes 20x20x60 mm were used for the research. In order to obtain guaranteed coarse grained initial microstructures, all the billets were preliminary annealed at T =1100 ^{0}C, 40 min with furnace cooling. To model various cooling conditions after crystallization or hot deformation of a steel product the following finishing heat treatment was applied: austenitizing at T=1000 ^{0}C, 30 min with further furnace isothermal holding within the interval 700…900 ^{0}C, 0,5…5 hours with final calm air cooling.

Table I. Chemical compositions of the investigated steels (weight %)

Steel grade	C	Mn	Cr	Si	Al	Mo	V	Nb	S	P
E36	0.16	1.42	0.09	0.36	0.043	-	0.062	0.031	0.022	0.031
34CrMo4	0.35	0.82	0.98	0.32	0.054	0.28	-	-	0.032	0.035

The steel sample characterizations included: optical metallography, room temperature Mesnager impact test, SEM fractography.

Results and Discussion

Initial microstructures of the investigated steels, just after the annealing, are shown on Figure 1a,b. Common feature of the structures is extremely inhomogeneous spatial distributions of ferrite grains and pearlite colonies. The high levels of the above non-uniformities are also confirmed by wide hardness scattering ranges: 77…82 HRB for E36 steel and 76…93 HRB for 34CrMo4 steel. The average ferrite grain size corresponds to 5…6 ASTM G.

As it seen from Figure 1c-k, isothermal holding at optimal conditions [5] during the cooling at finishing heat treatment provides considerable changes in the initial (annealed) microstructures. Practically full microstructure regeneration has been reached for the both steels by forming identical, homogeneously distributed, fine (9…10 ASTM G), generally equiaxed ferrite grains and pearlite colonies. Hardness scattering ranges in the case are as follows: 88…90 HRB for 34CrMo4 steel and 84…87 for E36 steel.

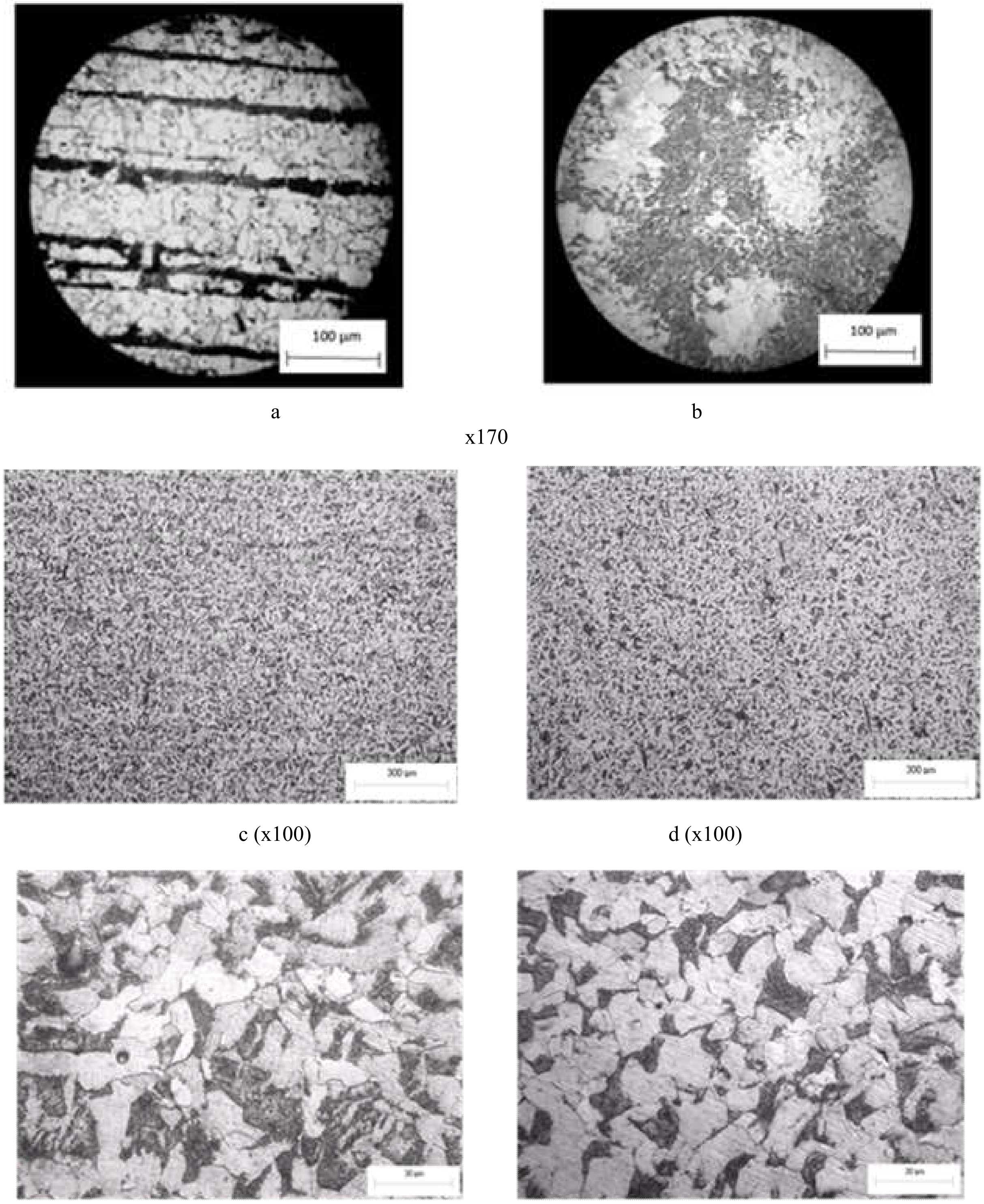
Some novel features of the obtained microstructures distinguishing them from the known ones should be outlined: predominantly quasi-polyhedral with curved interfaces morphology of the ferrite grains in 34CrMo4 steel; mainly non-polyhedral, branched form of the grains and colonies in E36 steel; presence of ferrite grains divided by specific type of interior boundaries in both the steels (see Figure 2). The revealed interior boundaries are not as good observed metalographicaly as the ordinary intra-phase surfaces, due to probably their less decorating by solute atoms. Hence, misleading in real ferrite grain size evaluation is possible especially for fine microstructures of the revealed type by using the ASTM standard evaluation scales.

Results of the impact characterization for all the samples are collected in Table II. Pair comparison of the data before and after the optimal finishing heat treatment for each steel shows over about twice increasing the impact resistance.

Unprecedented growth (over three times) reached for the as cast 34CrMo4 steel impact resistance should be particularly emphasized.

General view of the fracture surfaces for the both steels after the optimal finishing heat treatment and annealed as cast 34CrMo4 steel, for comparing, is given on Figure 3. As it seen, the fracture surfaces for the optimally heat treated steels are very similar and include ~80 % ductile and ~20 % brittle both trans-granular fracture. Details of the ductile fracture surface regions are shown on Figure 4 a,b. It should be noticed practical absence of the second phase particles on the surfaces for the both steels. According to [7] it particularly means dominant role of the surfaces separating matrix phase crystals in the micro-void nucleation process. So, it may be supposed that the distance between a pair of the nearest fracture cup centers, which is less than a typical metallographic ferrite grain size, in average corresponds to actual size of a ferrite crystal. This assumption is in accordance with the above metallographic observations of the interior boundaries existence within the ferrite grains. Namely such boundaries are, probably, the main void nucleation places.

Additional information about fracture mechanisms in the steels and the microstructure parameters controlling their impact resistance, may be obtained by the fractography analysis of the brittle fracture regions of the samples (Figure 4 c,d). As it seen, this fracture type for both the steels should be classified as quasi cleavage. According to [7], such a fracture is typical for steels after the thermal improvement which provides them with complex microstructures, comprising martensite type matrix phase crystals together with hardening particle precipitates. One of the specific features of such fracture type is less quasi cleavage facet sizes than real cleavage plane ones, corresponding to the equilibrium metallographic ferrite grains may be formed in the same steel under the same austenitizing conditions.



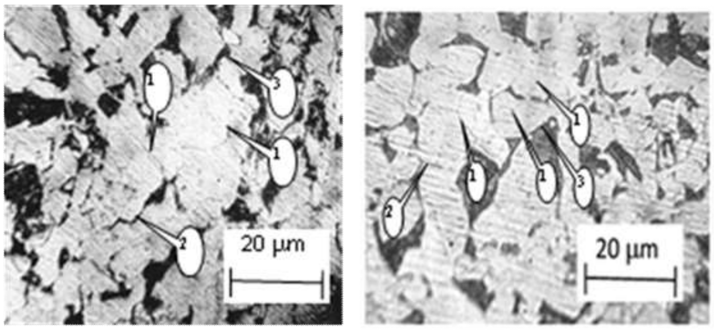
a b

x170

c (x100) d (x100)

e (x1000) k (x1000)

Figure 1. Microstructures of the hot rolled E36 (a,c,e) and cast 34CrMo4 (b,d,k) steels after different heat treatments: preliminary annealing (a,b); optimal finishing heat treatment (c,d,e,k)



a b

Figure 2. Typical microstructure regions of E36(a) and 34CrMo4(b) steels with various types of the ferrite grain boundaries: interior (1), ordinary intra-phase (2) and inter-phase (3), after the optimal finishing heat treatment

Table II. Mesnager impact toughness (J/cm^2) at +20 ^{0}C for the investigated steels after various heat treatments

Thermal treatment regime	Steel grade	
	E36	34CrMo4
Annealing	142	30
Annealing + Optimal finishing heat treatment	281	104

As it follows from the above metallographic and fractography data obtained in the work, after the proposed finishing heat treatment there are no ferrite crystals of non-equilibrium morphology within the both steel microstructures (See Figure 1) as well as the second phase particles, able to effect the fracture propagation (See Figure 4). So, it may be concluded that a size of the ferrite grain regions separated by the revealed interior boundaries is the microstructure parameter controlling the steel quasi cleavage fracture. Another conclusion is that such interior boundaries are expected to be the high angle ones, because of their strong barrier effect on the cleavage crack propagation. Besides, stratification resistance of such boundaries, probably, controls the void nucleation in the course of the ductile fracture as well.

So, the revealed in the work, probably, high angle and practically free of solute atom segregations interior boundaries within the metallographic ferrite grains may be considered as a factor responsible for the achieved general increase of the impact resistance of the investigated steels after the proposed optimal cooling.

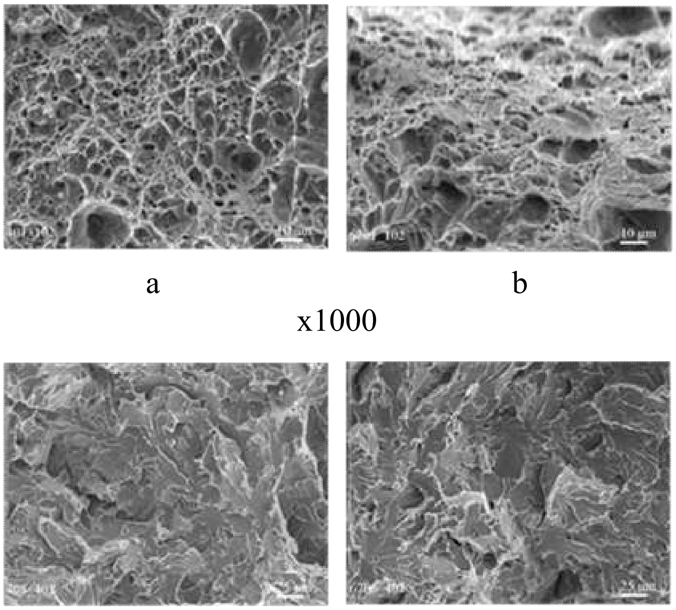
Formation of the observed alloy steel microstructures may be explained based on the following commonly accepted statements:

- atoms of chemical elements in a solid solution interact with the dislocation sub-boundaries via mutual elastic crystal lattice distortion fields [8] and the grain boundaries[6];
- grain boundary diffusivity of solute atoms exceeds the volume one in over one order of magnitude[4];
- grain boundaries and dislocation sub-boundaries are the most preferable places for new phase nucleation [5,8-10].

a b c

Figure 3. General view of the fracture surfaces for the 34CrMo4 steel (a,b) and E36 steel (c) after the annealing (a) and optimal finishing heat treatment (b,c)

Proceeding from the above, it may be suggested that during the proposed isothermal holding, solute atoms in austenite diffuse towards the grain and subgrain boundaries forming corresponding segregations there. Meantime, forming the segregations results in purification of an austenite subgrain interior



a b

x1000

c d

x400

Figure 4. Typical view of the ductile (a,b) and brittle (c, d) fracture surface regions for the investigated steels: 34CrMo4 (a,c) and E36 (b,d) after the finishing heat treatment.

from the solutes. So, in steels with the austenite stabilizing alloy elements, transformation of such purified austenite volumes into ferrite during the holding becomes preferable. As local concentration fluctuations on grain and subgrain boundaries are probable to occur, local nucleation of ferrite crystals is possible there according to the known mechanisms [8]. Meantime, in the case of enriching most of the boundary surfaces by the austenite stabilizing elements, further growth of the ferrite crystals away from the boundaries should be expected to develop. As a result, a group of new ferrite crystals, nucleated on the austenite grain and subgrain boundaries as substrates, can be formed within each austenite subgrain. Under such conditions, the boundaries separating the new fine ferrite crystals (grains), within an austenite subgrain, have not to be strongly decorated by segregated solute atoms. It is, evidently, in contrast with the early existing grain and subgrain surfaces surrounding such a ferrite crystal group. So, weak etching of the interior boundaries should be expected to occur.

The proposed above mechanism of the steel microstructure formation under the investigated conditions is indirectly confirmed by the latest our experimental data showing additional both the microstructure refining and the impact resistance increase as a result of decreasing the finishing treatment austenitizing temperature e.g. an average austenite grain and subgrain sizes. Undoubtedly, precise investigations are needed to specify details of the revealed phenomena mechanisms.

As to austenite volumes enriched by the stabilizing elements, they mainly are localized in close vicinities or directly on the grain and subgrain boundaries. Obviously, in dependence on the steel chemical composition, proposed isothermal holding duration and subsequent cooling conditions they can finally transform according to the CCT diagram or retain in the microstructures. So, a wide range of the steel strength properties, accompanied by both the novel type microstructures and spatially homogeneous chemical element distributions, should be expected to obtain using the proposed cooling regime in the course of any alloy steel making operation comprising high temperature austenitizing, such as: conventional casting, 3-D printing, depositing, welding, hot deformation and heat treatment.

Besides, in view of general character of the above statements for real metallic polycrystalline solid solutions, the based on them proposed mechanism of the revealed novel type alloy steel microstructure formation may be expected to develop in various metallic alloys with polymorphic phase transformations at heating and cooling.

Conclusions

1. The experimental data obtained confirm formation of highly inhomogeneous structural states in modern low alloy structural steels in as cast and as hot rolled industrial conditions together with conservation of the states after high temperature annealing.
2. Full regeneration of the industrially formed microstructures of the researched as cast and as hot deformed steels is shown as a result of the proposed cooling regime application providing formation of identical novel type microstructures there, which consist of homogeneously distributed, fine (9…10 ASTM G) equiaxed ferrite grains and pearlite colonies.
3. Dividing metallographic ferrite grains by weakly etched interior boundaries is revealed and its accordance with the fractography analysis results is shown.
4. Considerable increase was shown for the impact resistance of the investigated steels, especially of as cast 34CrMo4 steel (over three times), as a result of the proposed cooling regime application.
5. The results obtained in the work were explained by the known general effects of grain and subgrain boundaries on diffusion processes and structure formation in metallic solid solutions that allows to expect the analogous microstructure appearance in various metallic alloys. The explanation developed is indirectly confirmed by the fractography data and latest own experimental results for the researched steels. Precise investigations are needed to specify details of the mechanisms of the phenomena revealed.
6. High effectiveness of the proposed cooling regime in eliminating chemical and structural non-uniformities together with forming fine grained, novel type microstructures in low alloy structural industrial steels in as cast or hot deformed states, allows to recommend the following areas of its industrial application:

- enriching and stabilizing performance of as cast and as hot deformed bulk alloy steel industrial products;
- improving performance of as cast bulk alloy steel products to the levels of conventionally hot deformed ones or eliminating the traditional hot deformation use after casting in relevant industrial conditions;
- refining microstructures and improving performance of weld, deposited and 3-D printed alloy steels;
- microstructure and performance regeneration for recycled or renovated alloy steel products.

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