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Research Article

Applied Aspects of Low-carbon and Low-alloy Steel Recrystallization

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Abstract: The efficient use of low-carbon and low-alloy structural steels in Russia depends on the degree of structure fineness. The most acceptable method of providing the fine-grain structure is the recrystallization annealing. The main purpose of annealing is to build a uniform structure providing for better workability of steel products and higher level of mechanical properties thereof. It becomes possible as a result of recrystallization in solid state to correct such a significant defect of steel structures as the coarse-grained structure obtained as a result of overheating. The possibilities of passive flux-gate test method have been studied to check shaping the fine-grained structure in the course of recrystallization annealing.

Keywords: Cold plastic deformation, materials technology, non-destructive testing

INTRODUCTION

One should not forget about the development of production of low-carbon and low-alloy structural steels on the background of growing interest to AHSS (Schaeffler, 2004). The low-alloy steels are used for manufacturing critical welded structures working under pressure, at impact loads, at low temperature conditions (down to -70°C) or high temperature conditions (up to 580°C), in various aggressive environments. The structures made of these steels are used in heavy, chemical and oil machine-building, in shipbuilding, in water engineering, etc.

The maximum ultimate strength of these steels gets mainly determined by the carbon content and is attained at full hardenability after hardening and low-temperature tempering (ASTM A36/A36M, 2004). The low-alloy low-carbon structural steels comprise normally less than 0.18% of carbon. As the carbon content grows up to 0.38-0.45%, the hardness and strength of the hardened low-tempered steel increases. In case of further carbon content increase the hardness of the hardened low-tempered steel continues to increase, the tensile strength decreases, while the ductile type of fracture gets replaced with a brittle one.

The most acceptable method of attaining the fine-grain structure for the low-alloy low-carbon structural steels is the recrystallization annealing, which technology for obtaining microstructure with a specified size of grains includes a preliminary plastic deformation of steels and the subsequent annealing thereof.

The main purpose of annealing is the formation of a homogenous steel structure providing for better workability of articles and higher level of mechanical properties. As a result of recrystallization in solid state it becomes possible to correct such an existing defect of the steel structures as the coarse-grain structure obtained as a result of overheating. In this connection the possibilities of passive flux-gate test method have been studied to check for shaping the fine-grain structure in the process of recrystallization annealing.

The addition of alloying elements increases mechanical properties of the steel and, in particular, reduces the threshold of cold brittleness. In case of grain grinding the strength of hardened low-tempered steel increases, i.e., increases its yield point, yield stress at various deformation values, ultimate strength, hardness and fatigue strength. As a result, a possibility will appear to reduce the weight of structures, ensure required reliability and durability thereof.

Presently, there is no universally accepted theory of recrystallization at annealing. Both the recrystallization kinetics and the theory of the recrystallization centers forming are insufficiently investigated. In this connection the relevancy and unlikelihood of the above subject are beyond all doubts. There is a need for further new substantial approaches and assumptions. Paying special attention to the experimental results the authors see the purpose of this study in substantiating emergence of the fine-grain structure in the structural low-tempered steel after recrystallization annealing.

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MATERIALS AND METHODS

Materials: The following were chosen for experimental research: Low-carbon steel 08ps and low-alloy steels 09G2S and 10HSND. This choice was conditioned by the fact that these steels:

- Are widely used in various industries
- Have good plasticity characteristics in the field of both standard and low temperatures
- Allow expanding the obtained regularities to all materials with similar composition and properties and giving substantiated recommendations for them.

Steel 08ps: After continuous annealing steel 08ps features ferritic matrix with equiaxed grains, basically the areas of fine-grained perlite appear instead of structurally free cementite. The microstructure of low-carbon sheets for deep drawing consists basically of ferrite and cementite; uniform distribution of cementite in the basic ferritic component ensures good steel predisposition to drawing.

Steel 09G2S: It possessing 0.09% of carbon, up to 2% of manganese and less than 1% of silicon and since the total amount of additives varies around 2.5% is low-alloyed. The stability of properties in wide temperature range helps use parts made of this grade in the temperature range from -70 to +450°C. Since the carbon quantity in steel is low, its welding is quite easy, except that the steel is not get hardened and is not get overheated in the process of welding due to which no reduction of plastic properties or increase of its grain size do not take place. The absence of liability to tempering brittleness and lack of its ductility reduction after tempering can be attributed to advantages of using this steel.

Steel 10HSND: The greatest difficulties during welding steel 10HSND are related to providing the required impact ductility of seam metal and thermal influence area in the vicinity of alloyage boundary. Low resistance to brittle destruction can become a result of significant enlargement of austenitic grain and intragranular structure, formation of Widmannstatten pattern and ferritic fringes at the grain boundaries, high brittleness of metal ferritic matrix, development of high-temperature chemical inhomogeneity.

Method: In order to carry out investigations the plates 30 mm wide, 150 mm long and 2 mm thick have been cut out of the sheets of structural steels 08ps, 09G2S and 10HSND across the rolling direction that have been subject to fractional cold plastic deformation to a degree ε = 50% (ε-degree of plastic deformation). The samples have been cut out of these plates for subsequent recrystallization annealing at temperatures of 20°C to 800°C and conducting metallographic examinations. Apart from this, in order to assess the influence of equilibrium structure on the magnetic properties of steels, some samples have been subjected to high-temperature annealing at 900°C and 1050°C after the cold plastic deformation.

The beginning and end of recrystallization have been determined by passive flux-gate test method through measuring the strength of stray magnetic fields (H_p) at the tested samples by means of stress concentration magnetometric gauge with dual-channel flux-gate test transducer and by means of microstructural analysis.

THE MAIN PART

A number of process operations in the course of making steel articles, in particular, in case of hot plastic deformation (forging, stamping, etc.) is inevitably related to heating to high temperatures (about 1000°C and higher), which can in some cases result in overheating, formation of coarse-grain structure and sharp drop of the impact strength. In order to correct this defect the annealing operations get effected; heating to the temperature only slightly (by 30°-50°C) exceeding the critical points brings about the formation of fine austenite grains and then, in the course of subsequent cooling-to fine grains of perlite and ferrite or perlite alone. Thus, the application of annealing helps change the original coarse-grain structure of overheating and increase resistance of steel to dynamic loads.

It has been determined in the course of studying kinetics of the process grain growth that the grains of steel of different grades feature different tendency to growth as a result of heating, which is greatly influenced by the steel chemical composition. So, in case of alloying by small quantities of vanadium or titanium (0.1-0.4%) steel attains low tendency to grains growth at heating. However, not only alloying determines the properties of high-quality steels: it is important to pay attention to their internal structure.

The low-carbon and low-alloyed structural steels may feature both the coarse-grain and the fine-grain deformed original microstructure determining mechanical properties thereof and differing significantly in different parts of the structure, zones and areas of welded joints. The works (Crisan *et al*., 2012a, 2012b) devoted to physical fundamentals of shaping impact strength of the said steels, substantiating selection of criterial values thereof show that in some cases steel selected in accordance with requirements of regulatory documents fails to ensure reliable operation of the steel structures from the point of view of view of brittle failures.

The increase of carbon content in steels complicates the welding technology and complicates the possibilities of providing equal in strength welding connection without defects, while the alloying additives in the low-alloy steels can increase the probability of forming crystallization cracks. In this respect the authors recommend not only compare the actual values of the steel impact strength with standard values but append them with the analysis of serial curves of the impact strength and a share of ductile component in the fractures of the impact samples as well as by means of metallographic analysis (AISI, 2011; Schafer, 2008; Yu and Schafer, 2003).

As compared with the other steels the low-carbon steels feature the best weldability. The required plastic properties of heat-affected zone metal are ensured during welding and, therefore, it is not needed normally to apply special technological measures to prevent formation of hardening structures. Nevertheless, investigations of welded metal structures show that one of the main reasons for damaging them are the fatigue cracks at places of welded connections, which feature structural non-uniformity (in welded seam zone-cast structure, in heat-affected zone-coarse-grain and fine-grain) (Stirnemann, 2006). Apart from this, concentrations of stresses in the elements of steel structures can entail emergence of dangerous plastic deformation and emergency situation.

One of the most important characteristics of structural steels is the temperature of ductile-brittle transition, which considerably depends on the original structure of metal: the smaller is the size of grains (crystallites), the higher is the impact strength of steel (Lieurade, 2008).

The conducted multiple experimental investigations show that the strength of annealed metals and alloys tested at quite low temperatures increases with the grains refinement, when the return processes are complicated (Gourdet and Montheillet, 2003; Gao *et al*., 1999). The investigations have shown that the fine-grain structure of metals significantly influences the structural strength. So, the yield point, yield stress at various deformation values, ultimate strength, hardness and fatigue strength of a significant number of metals and alloys increases in case of refining the size of grains in the interval from 10 to 1 μm (Li *et al*., 2014). The iron and other metals with the body-centered cubic lattice are prone to ductile-brittle transition at definite tensile test temperature and low deformation speeds. The sample collapses without forming a neck with low plasticity indices at temperatures below the threshold of brittleness (Wang *et al*., 2010).

In so much as the limits of ductility and strength, hardness, fatigue strength and impact strength increase at low temperatures with the grain size decrease, the provision of fine-grain structure has an independent importance for enhancing the strength properties and impact strength of the new-generation metals (Pakiela *et al*., 2011; Cahn, 1996). The analysis of methods of providing structure with different degree of fineness has shown that the most acceptable method of obtaining such a structure for low-carbon and low-alloy structural steels is the recrystallization annealing (Gordienko *et al*., 2010). The recrystallization of metals and alloys is divided into the primary (processing recrystallization), collecting and secondary one. Figure 1 shows the temperature influence on the strength (ultimate strength, yield point) and plasticity of metals after cold plastic deformation.

Let us give consideration to every type of recrystallization.

Primary recrystallization: This is the process of forming and growth of new non-deformed grains due to the deformed grains surrounding them. The motive force of recrystallization is the increased internal energy accumulated by the metal at cold plastic deformation (Raji and Oluwole, 2013).

The loss of metal strength takes place in the process of recrystallization, which is explained by the removed distortion of crystalline lattice and sharp decrease of dislocations concentration. The least heating temperature, when the recrystallized grains appear, is referred to as the temperature of recrystallization beginning. This temperature is not constant for this metal or alloy. It depends on the duration of heating, degree of preliminary cold plastic deformation, metal purity, pre-deformation size of grains and other factors. In case of heating the deformed metal the mechanical properties change along with the change of its structure (Singh, 2012).

An insignificant strength degradation is observed in the interval of temperatures corresponding to return process, at that plasticity characteristics increase to some extent. The strength indices sharply decrease and plasticity strongly increases in the field of initial recrystallization temperature. The primary recrystallization brings about a full removal of hardening provided at plastic deformation and shaping the fine-grain structure.

Collective recrystallization: Beginning from certain temperature the plasticity smoothly decreases, which is explained by the formation of excessively coarse grains due to the other neighbouring grains, i.e., the collective recrystallization begins. As a result of primary recrystallization the structure remains unstable, since the new recrystallized grains feature longer extension of boundaries, which brings about an increase of grain-boundary (surface) energy. The coarsening of grain provides for metal transition to more stable condition due to the fact that the total extension of boundaries decreases and, accordingly, the surface energy decreases. The coarsening of grain takes place as a result of atoms transition from one grain to the other one, bigger grains grow on the account of smaller ones.

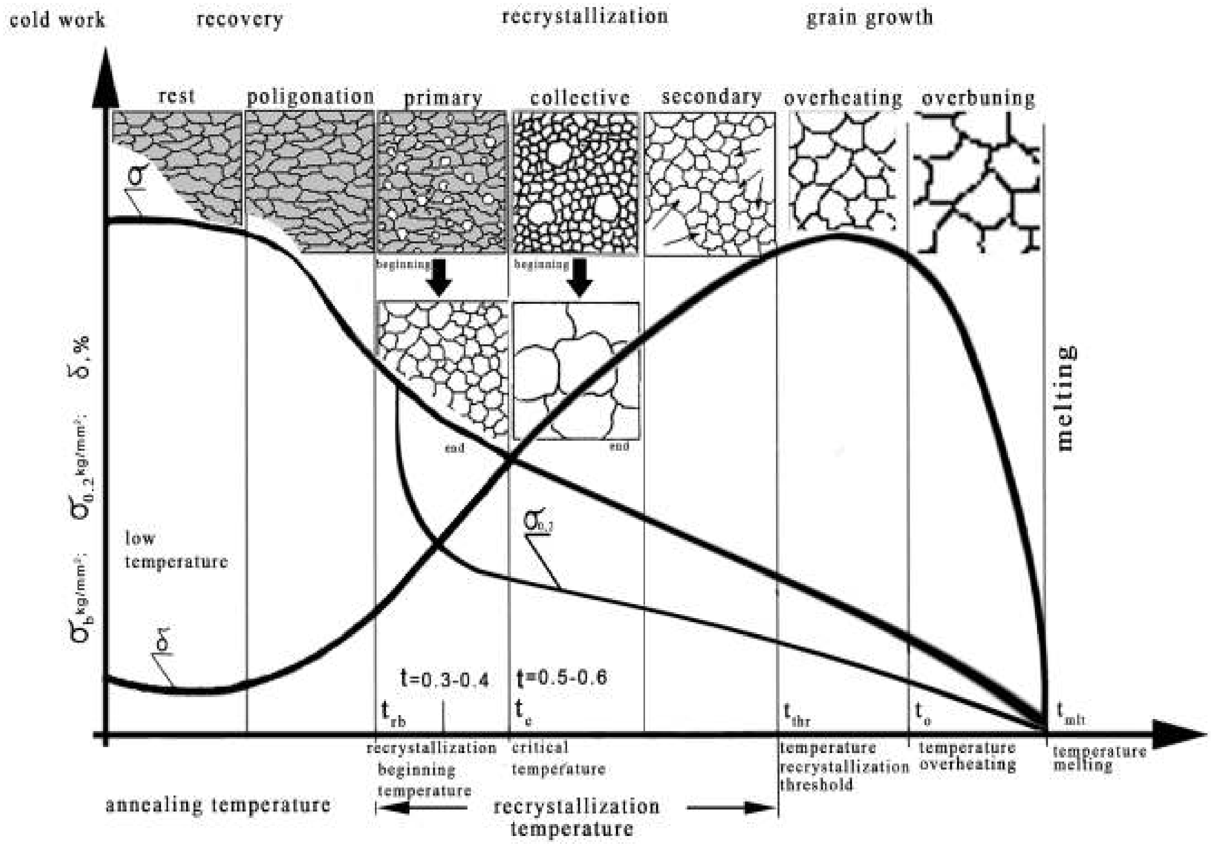
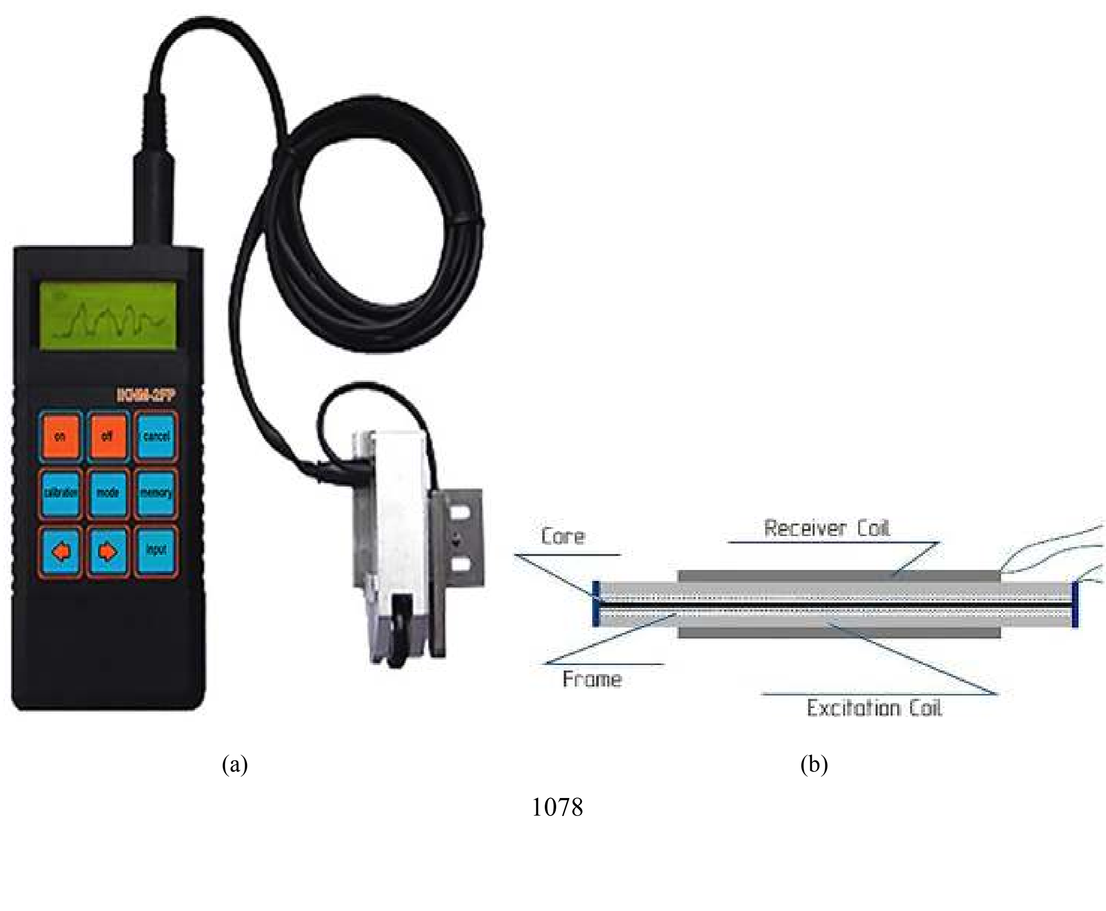
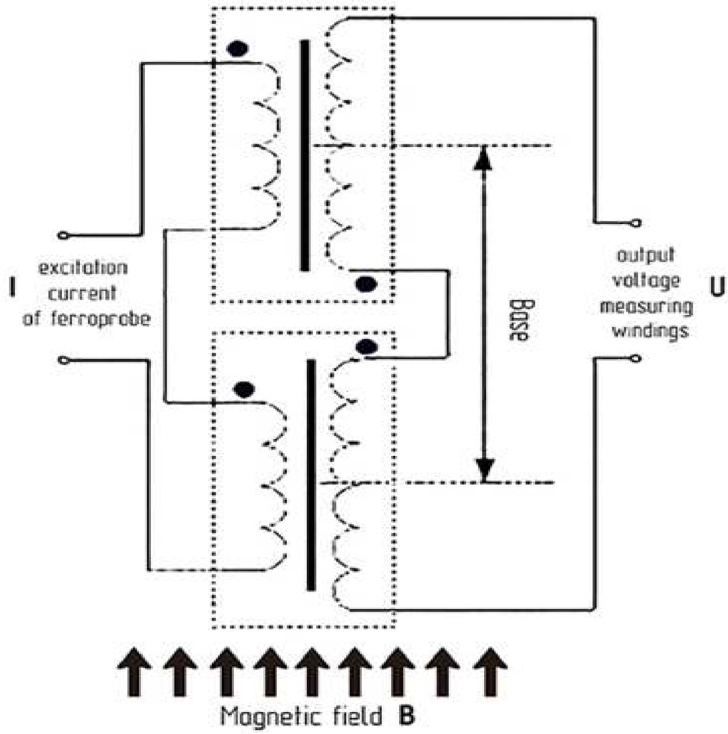


Fig. 1: Influence of heating temperature on metal structure and properties after cold plastic deformation [σ: Standard maximum] metal strength or temporary failure resistance; $\sigma_{0,\ 2}$: Strength, to which plastic deformation corresponds 0, 2% δ; Plastic deformation; T_{mlt}: Absolute melting temperature)



(a) (b)



(c)

Fig. 2: External view of IKNM–2FP instrument (a) and diagram of flux-gate transducer (b, c)

Secondary recrystallization: If some of the new grains have preferential conditions for growth, this recrystallization stage is referred to as the secondary one. In this case the grains growing at a big rate can be conventionally considered as germinal centers. A multiplicity of fine grains and a small quantity of very coarse grains appear as a result of the secondary recrystallization. If different grain composition appears at the secondary recrystallization, the plasticity of metals and alloys decreases (Hosford, 2012).

Thus, in the process of recrystallization annealing one can obtain both the fine-grain and coarse-grain structures. It proceeds from consideration of the recrystallization types that the primary one is the most acceptable in order to provide the fine-grain structure, while the collective or secondary recrystallization is the most acceptable for providing the coarse-grain structure (Weng, 2009).

The evaluation of structural condition and mechanical properties of metals and alloy with the use of magnetic methods of control provokes presently a special interest of the scientists amidst an essential versatility of metal structures, growing number of steel grades, improvement and development of new technologies with the aim of acquisition of special physical and mechanical characteristics of metals. These methods are based on the analysis of relation of magnetic and structural parameters in ferromagnetic materials (Gordienko, 2013). One of them is the method of passive flux-gate test nondestructive testing, which has made an effective claim about itself at evaluating the structural state of low-carbon steel 08ps and low-alloy steels 09G2S and 10HSND, being subject to recrystallization annealing.

Method of passive flux-gate test: The implementation of passive flux-gate method of testing is effected by means of IKNM-2FP instrument (magnetometric indicator of stresses concentration) with a dual-channel flux-gate transducer presented in Fig. 2.

Structurally, the instrument consists of the measuring unit with storage batteries, flux-gate transducer and connecting cable. The instrument features small size, it is provided with autonomous power supply, it is simple in operation and adjustment, it makes it possible to make measurements in hard-to-reach locations. The principle of instrument operation is based on registration of strength of stray magnetic field (H_p) at the object surface to be tested in case of its magnetization in weak magnetic field of the Earth (Rayleigh field) and revealing any abnormal behavior of stray magnetic field in the area of stresses concentration.

RESULTS AND DISCUSSION

Results: Figure 3 shows a dependence of the magnetic field strength on the temperature of recrystallization annealing for steels 08ps, 09G2S and 10HSND.

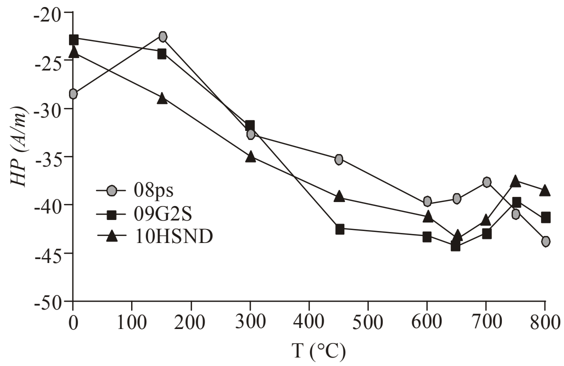


Fig. 3: Dependence of stray magnetic field H_p strength on temperature of recrystallization annealing for steels 08ps, 09G2S and 10HSND

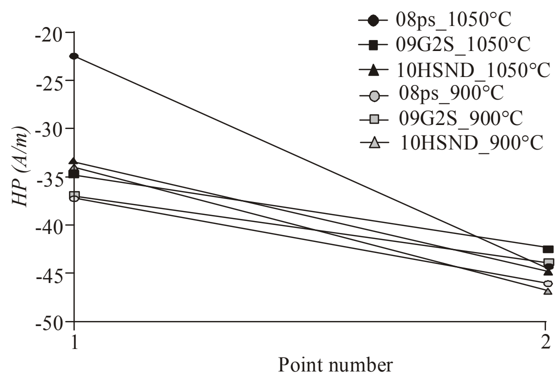


Fig. 4: Variation of stray magnetic field H_p strength in samples of steels 08ps, 09G2S and 10HSND after annealing at 1050°C (continuous line) and 900°C (broken line); axis 1: Before annealing, axis 2: After annealing

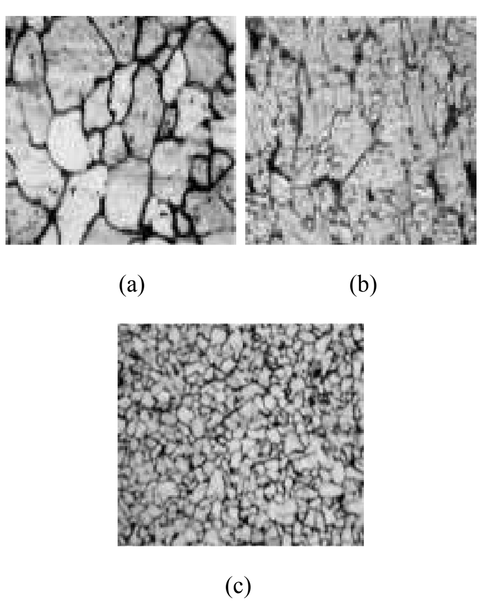


Fig. 5: Variation of structure of steels 08ps during recrystallization annealing, x400; *a*: As-delivered state; *b*: After rolling at ε = 50%; *c*: After annealing at 700°C

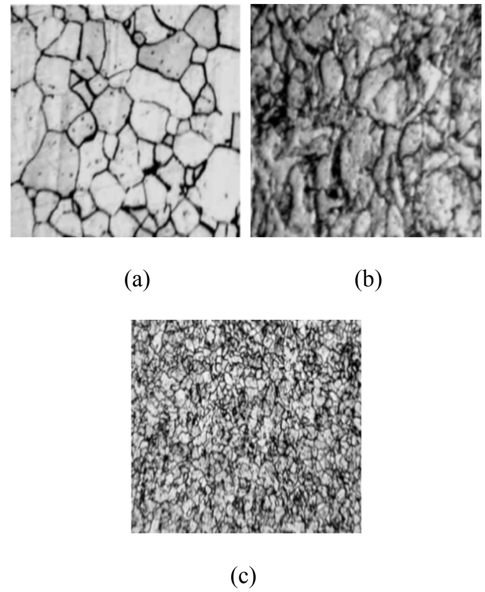


Fig. 6: Variation of structure of steels 09G2S during recrystallization annealing, x400; *a*: As-delivered state; *b*: After rolling at *ε* = 50%; *c*: After annealing at 725°C

Figure 4 presents a change of structure of steels under study 08ps, 09G2S and 10HSND after recrystallization annealing at 900°C and 1050°C.

Figure 5 shows variation of structure of steel 08ps during recrystallization annealing.

Figure 6 shows variation of structure of silicon-manganese-based steel 09G2S after recrystallization annealing.

As Fig. 3 shows a sharp reduction of magnetic field strength (H_p) values for all steels under study is observed in the range of temperatures from 150°C to 300°C. As the heating temperature rises in excess of 300°C, a further reduction of H_p values takes place but with lower intensity. The reduction of H_p values stops in the range of temperatures from 600°C to 650°C and then a certain rise can be observed.

The increase of temperature of annealing for the deformed steel from 900°C to 1050°C changes the value of H_p as compared with the original state (Fig. 4). At that, the increase of annealing temperature irrespective of the steel grade, contributes to stabilizing H_p values and approximating them to the values commeasurable with the strength of magnetic field of the Earth (±40 A/m = 0.5 Gs).

According to data of metallographic investigation the beginning of recrystallization for steel 08ps is observed at 550°C, for steels 09G2S and 10HSND it is observed at 600°C. The temperature of recrystallization end for steel 08ps at 700°C (Fig. 5), for 09G2S and 10HSND -at 725°C (Fig. 6). The fine-grain structure with grain size of 8 μm for steel 08ps, 6 μm for steel 09G2S and 5 μm for steel 10HSND is shaped in the process of primary recrystallization. Further increase of annealing temperature brings about an increase of grains size. It should be noted that as the degree of steel alloying, increases, more fine-grain equiaxed structure is shaped, which ensures isotropy of mechanical properties (Campbell, 2008).

Discussion: In the course of steels structure investigation the problems appear that are related to insufficient clarity of recrystallization kinetics (Bhadeshia and Honeycombe, 2007; Callister and Rethwisch, 2014). One of them concerns an issue, whether the metals get crystallized in the course of deformation or in the wake of hot deformation? According to authors a significant reduction of H_p values at temperatures from 150°C to 300°C (Fig. 3) is probably related to the course of the first stage of return, the rest, in steels. As a result of the rest, a number of pin hole defects (interstitial atoms and vacancies) gets reduced through annihilation at the edge dislocations. The number of distortions of crystalline lattice also drops. According to Shackelford and Alexander (2001) no structural adjustments of dislocation structure take place in this case.

The authors suppose that in case of increasing the temperature of heating in excess of 300°C the reduction of H_p values happen due to diffusion processes activation. At that, redistribution of dislocations, annihilation thereof and forming-up excessive dislocations of the same sign into vertical dislocation walls occur, which results in sub grains formation: the polygonization process is in progress. According to Montheillet (2004) they become larger due to dislocation boundaries movement, which brings about the reduction of defects density.

As it was stated before, the kinetics of recrystallization and formation of recrystallization centers provokes many questions due to insufficient knowledge about it. It is considered that recrystallization begins normally at the boundaries of grains at increasing the temperature of annealing. Hence, the presence or absence of recrystallization depends basically on the energy of deformation of the boundaries of grains required for origination of new grains (Panov *et al.*, 2013). However, such a finding needs clarification. The authors suppose that the beginning of primary recrystallization is characterized by the formation of recrystallization centers in those areas of deformed grains, where the density of dislocations is increased and the crystalline lattice features the worst distortions. They grow as a result of reattachment (diffusion) of atoms thereto from a deformed environment, at that, the boundaries of recrystallization center migrate towards the deformed environment.

The development of recrystallization process are normally accompanied by the structural adjustments of the dislocation structure and reduced density of dislocations down to 10^6-10^8sm^{-2}, which entails a removal of effective obstacles on the way of displacing dislocations. A destruction of the rolling texture due to structural changes taking place in the process of annealing and shaping of the new equiaxed grains with low density of dislocations increases the mobility of domain walls and decreases the magnetic field strength (H_p). The end of monotonous lowering of H_p from the annealing temperature testifies to termination of the primary recrystallization. A certain rise of H_p curve at 750°C is probably related to a partial phase recrystallization of steels. A further heating temperature increase up to 900°C and 1050°C brings about the progress of collective and secondary recrystallizations, which will result in the formation of more equilibrium coarse-grain structure with increased grain-size difference (Lartigue-Korinek and Carry, 2013).

It should be noted that according to data of metallographic research carried out by the authors the beginning of recrystallization for steel 08ps is observed at 550°C, while for steels 09G2S and 10HSND it is observed at 600°C. In case of magnetic testing not only the recrystallization beginning gets recorded but the return processes as well, which testifies to high sensitivity of the magnetic method.

CONCLUSION

The study of recrystallization of low-carbon and low-alloy steels 08ps, 09G2S and 10HSND helps come to the following conclusions:

- Alloying of the hardened low-tempered steel (with carbon content of 0.38-0.45%) increases resistance to brittle failure, which helps use it as a reliable structural material. In case of further carbon increase additional difficulties appear for retaining reliability of the said steel (hardness continues to increase, tensile strength decreases, while ductile fracture is replaced with a brittle one). Moreover, even an insignificant amount of ferrite and perlite in the hardened steel structure brings about a sharp decrease of the impact strength in the low-tempered state. The most reasonable way to increase the structural strength is the provision of steels featuring the superfine grain down to 10 μm.
- Preliminary cold plastic deformation and the subsequent recrystallization annealing are the most acceptable methods of obtaining the fine-grain structure in low-carbon and low-alloy structural steels.
- Creation of a homogenous fine-grain structure ensures better workability of articles and higher level of mechanical properties of structural steels 08ps, 09G2S and 10HSND.
- Solid-state recrystallization results in the possibility of correcting such an essential defect of steel structures as the coarse-grain structure acquired as a result of overheating.

- Registration of quite an early stage of finishing the primary recrystallization in structural steels 08ps, 09G2S and 10HSND makes it possible to attain the fine-grain equiaxed structure, which becomes more particulate in the course of increasing the degree of alloying.
- At that it is possible to use rather high sensitivity of the stray magnetic field (H_p) strength depending on the temperature of recrystallization annealing for checking quality of low-carbon and low-alloy steels.
- The capabilities of passive flux-gate test method to monitor shaping of fine-grain structure in the process of recrystallization annealing have been studied.

REFERENCES

AISI, 2011. North American Specification for the Design of Cold-formed Steel Structural Members. American Iron and Steel Institute, Washington, DC.

ASTM A36/A36M, 2004. Standard Specification for Carbon Structural Steel. ASTM International, West Conshohocken, PA.

Bhadeshia, H. and R. Honeycombe, 2007. Steels: Microstructure and Properties. 3rd Edn., Elsevier, Amsterdam.

Cahn, R.W., 1996. Recovery and Recrystallization. In: Cahn, R.W. and P. Haasen (Eds.), Physical Metallurgy. 4th Edn., North-Holland Publishing Co., Amsterdam, pp: 2399-2500.

Callister, D.W. and D.G. Rethwisch, 2014. Materials Science and Engineering: An Introduction. 9th Edn., John Wiley & Sons, Hoboken, NJ.

Campbell, F.C., 2008. Elements of Metallurgy and Engineering Alloys. ASM International, Materials Park, OH.

Crisan, A., V. Ungureanu and D. Dubina, 2012a. Behaviour of cold-formed steel perforated sections in compression. Part 1: Experimental investigations. Thin Wall. Struct., 61: 86-96.

Crisan, A., V. Ungureanu and D. Dubina, 2012b. Behaviour of cold-formed steel perforated sections in compression: Part 2: Numerical investigations and design considerations. Thin Wall. Struct., 61: 97-105.

Gao, W., T. Sakai and H. Miura, 1999. Modeling the new grain development under dynamic recrystallization. In: Sakai, T. and H.G. Suzuki (Eds.), Proceeding of the 4rth International Conference on Recrystallization and Related Phenomena. Japan Institute of Metals, Tsukuba City, pp: 659-664.

Gordienko, V., 2013. Investigation of influence by the cold plastic deformation of metals on magnetic intensity of scattering. World Appl. Sci. J., 23(13): 74-79.

Gordienko, V.E., E.G. Gordienko, O.V. Kuz'min *et al*., 2010. Opredelenije zon i stepeni plasticheskoj deformacii metalla passivnym ferrozondovym sposobom[Determining areas and the degree of plastic deformation of the metal using passive fluxgate method]. Vestnik Grazhdanskih Inzhenerov B. Civil Eng., 1(22): 37-42.

Gourdet, S. and F. Montheillet, 2003. A model of continuous dynamic recrystallization. Acta Mater., 51: 2685-2699.

Hosford, W.F., 2012. Iron and Steel. Cambridge University Press, New York.

Lartigue-Korinek, S. and C.P. Carry, 2013. Creep and High Temperature Plasticity: Grain Boundary Dynamics. In: Priester, L. (Eds.), Grain Boundaries and Crystalline Plasticity. John Wiley & Sons, London, pp: 358.

Li, D.Z., Y.C. Liu, T.X. Cui J.M. Li, Y.T. Wang *et al*., 2014. The effect of thermo-mechanical processing parameters on microstructure and mechanical properties of a low carbon, high strength steel. Steel Res. Int., 85(3): 307-313.

Lieurade, H.P., 2008. Fatigue Strength of Welded Joints. In: Blondeau, R. (Ed.), Metallurgy and Mechanics of Welding. John Wiley & Sons, London, pp: 207-238.

Montheillet, F., 2004. Moving Grain Boundaries during Hot Deformation of Metals: Dynamic Recrystallization. In: Fischer, F.D. (Ed.), Moving Interfaces in Crystalline Solids. CISM Courses and Lectures N° 453, Springer, Wien, New York, pp: 203-256, ISBN: 3211274049.

Pakiela, Z., M. Lewandowska and K. Kurzydlowski, 2011. The Effect of Microstructural Features on the Mechanical Properties of Nanocrystalline Metals. In: Li, J.C.M. (Ed.), Mechanical Properties of Nanocrystalline Materials. Pan Stanford Publishing, London, pp: 213-244.

Panov, D.O., Y.N. Simonov, P.A. Leont'Ev, A.I. Smirnov and L.T. Zayats, 2013. A study of phase and structural transformations of hardened low-carbon steel under conditions of multiple intense heat effect. Metal Sci. Heat Treat., 54(11-12): 582-586.

Raji, N.A. and O.O. Oluwole, 2013. Recrystallization kinetics and microstructure evolution of annealed cold-drawn low-carbon steel. J. Crystall. Process Technol., 3: 163-169.

Schaeffler, D.J., 2004. Introduction to advanced high-strength steels-part I: Grade overview. Stamp. J., 16(11): 434-439.

Schafer, B.W., 2008. Review: The direct strength method of cold-formed steel member design. J. Constr. Steel Res., 64(7/8): 766-778.

Shackelford, J.F. and W. Alexander, 2001. CRC Materials Science and Engineering Handbook. 3rd Edn., CRC Press, Boca Raton, FL.

Singh, S.B., 2012. Mechanisms of Bainite Transformation in Steels. In: Pereloma, E. and D. Edmonds (Eds.), Phase Transformations in Steels: Fundamentals and Diffusion-controlled Transformations. Woodhead Publishing, Cambridge, pp: 385-416.

Stirnemann, L.K., 2006. Behavior of arc spot weld connections subjected to combined shear and tension forces. M.S. Thesis, University of Missouri-Rolla, Rolla, MO.

Wang, C.Y., J. Shi, W.Q. Cao and H. Dong, 2010. Characterization of microstructure obtained by quenching and partitioning process in low alloy martensitic steels. Mater. Sci. Eng. A, 527(15): 3442-3449.

Weng, Y., 2009. Ultra-fine Grained Steels. Springer-Verlag, Berlin, Heidelberg.

Yu, C. and B.W. Schafer, 2003. Local buckling tests on cold-formed steel beams. J. Struct. Eng-ASCE, 129(12): 1596-1606.