ISSN 0031-918X, The Physics of Metals and Metallography, 2015, Vol. 116, No. 1, pp. 109–114. © Pleiades Publishing, Ltd., 2015.
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STRENGTH
AND PLASTICITY

Enhancement of Impact Toughness of Structural Steels upon Formation of Carbide-Free Bainite

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Received April 24, 2014; in final form June 20, 2014

Abstract—Mechanical properties of chromium–nickel–molybdenum steels with the carbon contents of 0.1 to 0.4% after slow continuous cooling in the bainitic range have been determined, and the structure has been investigated. It has been shown that, at a carbon content of about 0.10–0.15% and upon additional alloying with silicon and aluminum after such a heat treatment, in steels, the structure of carbide-free bainite is formed and a substantial enhancement in the impact toughness is observed compared to bainite containing carbide precipitates. The enhancement in the level of toughness is related to the presence in carbide-free bainite of an appreciable amount of retained austenite enriched with carbon.

Keywords: bainitic steels, continuous cooling, carbide-free bainite, retained austenite, strength, impact toughness

DOI: 10.1134/S0031918X15010068

INTRODUCTION

Nowadays, the problem of employing bainitic steels to manufacture vital parts and constructions is topical both in Russia and abroad. These steels frequently possess a set of enhanced mechanical and service properties, are rather technologically effective, and are characterized by reduced cost upon economical alloying. Manufacturers of railroad rails are interested in transitioning to bainitic steels, since the possibilities of further improving the service characteristics of rails of pearlitic steel proved to be exhausted. This generated a need to create alternative sorts of rail steel, the quality of which would be higher than that of pearlitic steels. The practice of using tube steels likewise shows that it is impossible to achieve requisite functional characteristics when the ferritic–pearlitic structure is formed therein. The high strength properties of these steels are provided by heat-treatment regimes in which ferritic–bainitic, purely bainitic, or bainitic–martensitic structures are formed.

In recent years, extensive data have been gathered on the intermediate transformation of supercooled austenite [1–4] and properties of bainite of structural steels [2–5]. The bainitic structure is of a complex nature and can markedly change its morphology depending on the content of carbon and alloying elements in steels and cooling conditions.

A manifestation of the multiformity of the bainitic structure depending on the alloying and features of heat treatment of steels is the appearance of a structure of so called carbide-free bainite representing a combination of low-carbon bainitic ferrite and high-carbon retained austenite [2–4]. The structure of the α phase and morphology of retained austenite in carbide-free bainite are determined by the transformation temperature and degree of alloying of steels. Carbide-free bainite can be upper and low; in any case, carbide precipitates are absent in it, and almost all carbon that resides in the steels is in retained austenite. The carbon content in retained austenite can exceed the average carbon content in steels by several times. It is known [3, 6, 7] that the presence of finely dispersed bainitic ferrite in the structure without the precipitation of cementite-type carbides in combination with stable retained austenite ensures that a set of high-strength, tough structural steels will be obtained.

Despite the a fairly large body of data concerning features of the carbide-free bainitic structure and its properties, a number of problems remain unexplained, among which the possibilities of obtaining a carbide-free bainitic structure in medium-alloyed structural steels upon slow continuous cooling and mechanical properties of this structure are important.

As a rule, upon isothermal quenching, steels alloyed with silicon are used, including 38KhS, 35KhGSA, and 60S2 steels, in which the intermediate transformation occurs in two stages [4, 8]. At the first stage, a low-carbon bainitic ferrite is formed, and the retained austenite enriched with carbon is still present. The occurrence of the second stage is connected with

Table 1. Chemical composition of the investigated steels in wt %

Steel	C	Cr	Ni	Mn	Si	Mo	V	Al	S	P
40Kh2N2MA	0.41	1.37	1.52	0.50	0.36	0.25	–	–	0.014	0.025
40Kh2N2MYu	0.37	1.59	2.01	0.78	0.52	0.36	–	1.27	0.017	0.018
27Kh2N2SM	0.27	1.75	1.96	0.36	0.93	0.40	–	–	0.015	0.010
18Kh2N2SM	0.18	1.78	2.10	0.34	0.98	0.43	–	–	0.013	0.010
15Kh2N3MF	0.16	2.21	3.28	0.35	0.26	0.66	0.22	–	0.024	0.012
14Kh2N2GMF	0.14	2.05	2.33	0.76	0.21	0.38	0.17	–	0.026	0.016
10Kh2N3GM	0.10	2.23	2.68	0.91	0.44	0.34	–	–	0.022	0.012

the precipitation of the carbide phase and a reduction in the amount of retained austenite. The precipitation of carbides during the intermediate transformation can be delayed upon alloying with silicon, as well as with aluminum [1, 3, 5]. Isothermally quenched steels with the carbide-free bainitic structure are characterized by a high level of crack resistance and toughness [3, 9–11], whereas carbide precipitation is accompanied by a sharp decrease in the resistance to impact fracture [10].

Medium-carbon chromium–nickel–molybdenum steels of types 40Kh2N2MA, 35Kh2NMFA, and 38KhN3MFA, which possess an enhanced stability of austenite in the pearlitic range, are widely used for heavily loaded vital parts. However, during production, when large parts are oil-quenched, bainite is inevitably formed at their central sections, which leads to a reduction in the impact toughness.

In this work, the effect of the carbon content and alloying with silicon and aluminum on the possibility of providing a high level of impact toughness in the bainitic structure was investigated in chromium–nickel steels after continuous cooling at a rate of approximately 5 K/min which is characteristic of cooling of central sections of rather massive parts. To do this, it was necessary to exclude the formation of carbides in the process of intermediate transformation of supercooled austenite, to ensure that a carbide-free bainitic structure is obtained, and to estimate the mechanical properties of steels with different types of bainite.

EXPERIMENTAL

The structure and properties of alloyed steels whose chemical composition is presented in Table 1 were investigated. To obtain the bainitic structure, workpieces of the steels under study were heated to 870°C with 30 min of holding. Then, the samples were cooled with a furnace at the constant rate $V = 5$ K/min.

The structure of the steels was examined by the electron-microscopic method on a JEM-200 CX microscope using foils cut from corresponding samples prepared according to the conventional procedure. The fracture surface of the steels was investigated after different heat-treatment regimes on a Quanta-200 scanning electron microscope. The amount of retained austenite was measured by the magnetometric method. Mechanical properties were determined at room temperature via the static tension of fivefold samples with a 5-mm diameter of the working part. The impact toughness was determined on type-I samples according to GOST (Russian State Standard) 9454-78. To determine the retained-austenite lattice parameter, a line $(311)_\gamma$ was taken on a DRON-3 diffractometer in the Fe $K\alpha$ radiation. These data were employed to calculate the carbon content in retained austenite according to the procedure in [2].

RESULTS AND DISCUSSION

In 40Kh2N2MA commercial steel, after cooling at a rate of $V = 5$ K/min from a temperature of 870°C, the globular grained bainitic structure that usually arises in the steel under isothermal conditions at temperatures 400–450°C is formed. Electron-microscopic investigations showed that the bainitic structure differs in a wide range. In this structure sections, both globular and lath in shape, and a considerable amount of cementite-type carbides precipitated both inside and along boundaries of bainitic ferrite crystals were observed (Fig. 1a). The amount of retained austenite is small. This structure possesses a low impact toughness of 0.3 MJ/m^2, with the level of strength being about 1100 MPa (Table 2).

It is obvious that, in alloyed steels that contain about 0.4% C, it is difficult to retard carbide precipitation upon continuous cooling with rates characteristic of cooling of the middle part of massive details. It was assumed that, in order to produce carbide-free bainite that yields an enhancement in the impact toughness of the material, it was necessary to decrease the carbon content in it.

To test the validity of this assumption, a series of specially melted chromium–nickel–molybdenum steels with a reduced carbon content (10Kh2N3GM, 14Kh2N2GMF, and 15Kh2N3MF grades) in which the bainitic structure is formed upon slow cooling with a furnace ($V = 5$ K/min). Mechanical properties of these steels and a 40Kh2N2MA steel heat-treated in

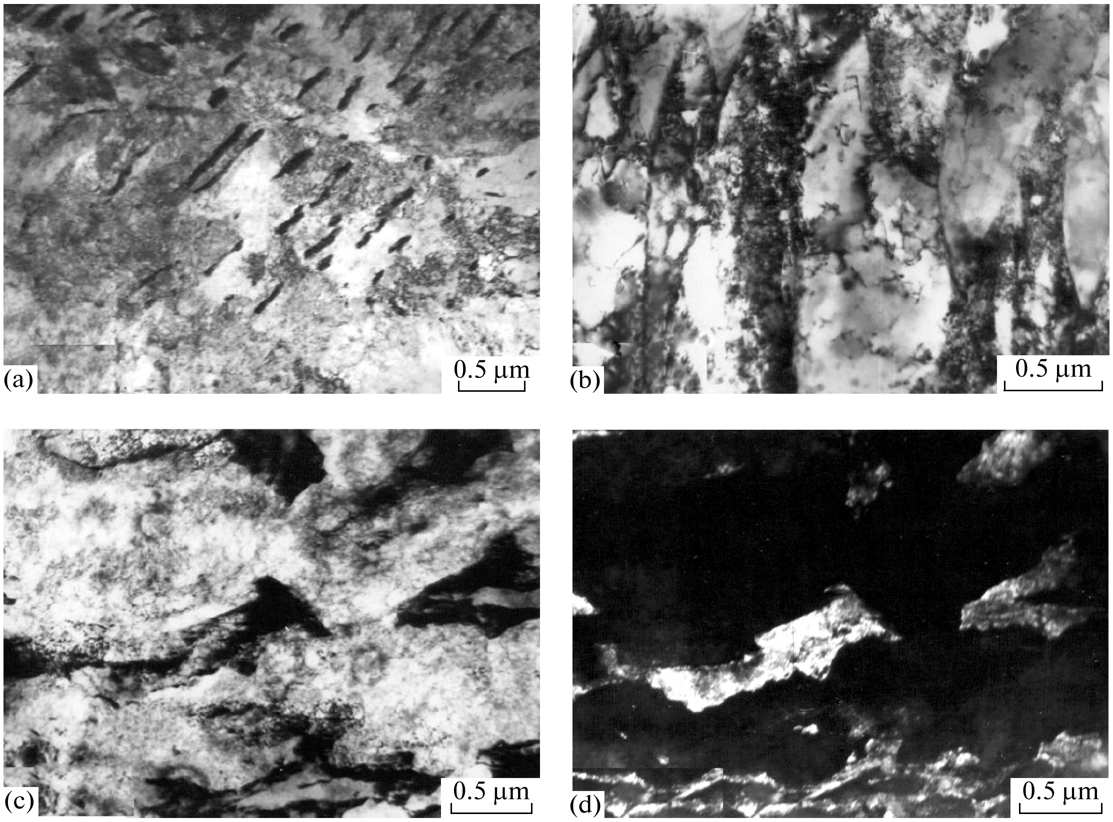

Fig. 1. Structure of (a) 40Kh2N2MA, (b) 14Kh2N2GMF, and (c, d) 10Kh2N3GM steels after cooling from 870°C at a rate of 5 K/min: (a, b, c) a bright-field image and (d) a dark-field image in reflection 002_γ.

the same regime giving the bainite formation are listed in Table 2. It can be seen that, at most of the same strength characteristics, the impact toughness of chromium–nickel–molybdenum steels with reduced carbon contents (0.1–0.15% C) is appreciably higher (approximately three- to fourfold) than the toughness of the 40Kh2N2MA steel.

Electron-microscopic investigations (Figs. 1b–1d) showed that, compared to medium-carbon steels, the distinctive feature of the bainitic structure of low-carbon chromium–nickel–molybdenum steels is the complete absence of carbon. The morphology of bainite in low-carbon steels is almost identical; bainitic-ferrite crystals, globular, and lath in shape, and retained austenite in the form of isle and film sections are observed, and this austenite contains 0.8–1.0% C. Consequently, for massive parts where bainite is inevitably formed in the center upon continuous cooling, in order to reach high impact toughness, it is necessary to use steels with a limited carbon content that yields bainitic hardenability with the formation of carbide-free bainite.

Limits in the carbon content can vary depending on the steel composition. In chromium–nickel–molybdenum steels without other alloying elements the carbon content giving the formation of carbide-free bainite is 0.10–0.15%. Alloying of steels with silicon and aluminum upon isothermal holding in the

Table 2. Effect of carbon content on amount of retained austenite A_{ret} and mechanical properties of steels after continuous cooling from 870°C in the bainitic temperature range (V_{cool} = 5 K/min)

Steel	σ_u, MP	KCU, MJ/m^2	Hardnes, *HRC*	A_{ret}, %	Carbon content, wt %		Fraction of carbon in A_{ret}, %
					in steel	in A_{ret}	
40Kh2N2MA	1110	0.30	36	6	0.41	1.0	15
15Kh2N3MF	1150	1.33	37	14	0.16	0.9	79
14Kh2N2GMF	1090	1.25	36	15	0.14	0.8	86
10Kh2N3GM	1240	1.10	38	9	0.10	0.8	72

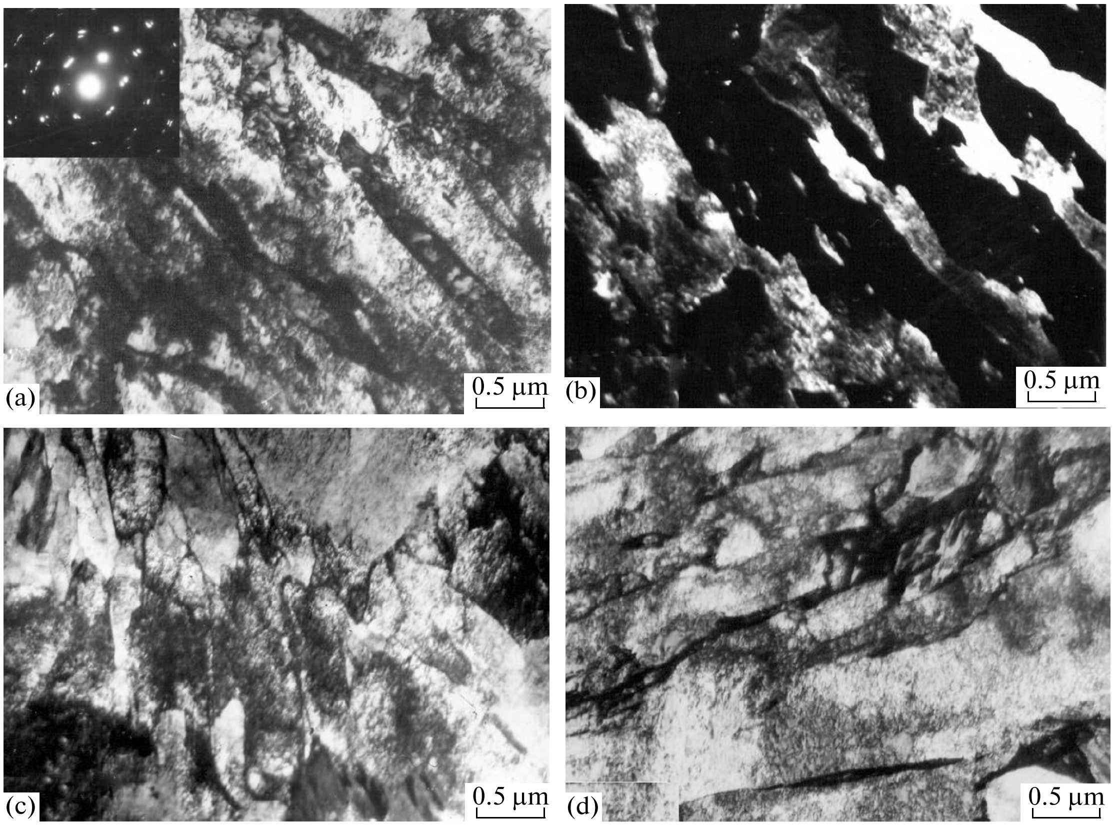

Fig. 2. Bainitic structure of investigated steels: (a) 40Kh2N2MYu; (b) 40Kh2N2MYu, a dark-field image in reflection 002_γ; (c) 27Kh2N2SM; (d) 18Kh2N2SM; (a, c, d) a bright-field image.

bainitic-transformation range retards the formation of cementite-type carbides and favors carbon enrichment of retained austenite. In this connection, it was of interest to clarify how additional alloying with silicon and aluminum reflects on the morphology and properties of the bainitic structure arising in the process of continuous cooling. For this purpose, chromium–nickel–molybdenum steels (18Kh2N2SM, 27Kh2N2SM, and 40Kh2N2MYu) that were additionally alloyed with silicon and aluminum were studied. As in the steel 40Kh2N2MA, in these steels, after continuous cooling from an austenitization temperature of 870°C, an inhomogeneous bainitic structure is formed that consists of bainitic ferrite with lath and globular morphology. However, the structure of steels alloyed with silicon and aluminum differs greatly from the structure of 40Kh2N2MA steel in that carbide precipitates are not observed in either bainitic ferrite or in retained austenite (Fig. 2). In this case, the fraction of retained austenite in the bainitic structure increased sharply. For example, in 40Kh2N2MA steel, the amount of retained austenite is 6%, whereas in 40Kh2N2MYu steel, the amount is 24%. The suppression of the carbide formation in the course of bainitic transformation favored the significant carbon enrichment of retained austenite. This can be clearly seen from the results of X-ray diffraction analysis of the investigated steels (Tables 2, 3).

Thus, in 18Kh2N2SM, 27Kh2N2SM, and 40Kh2N2MYu steels, the result of the intermediate transformation that occurs upon continuous cooling in a wide temperature range is carbide-free bainite that represents a ferritic–austenitic structure without carbide precipitates.

The exclusion of the carbide formation in the process of the intermediate transformation and the formation of carbide-free bainite markedly increased the resistance to impact fracture, as is evinced by mechanical properties of the studied steels (Table 3).

The impact toughness of steels alloyed with silicon and aluminum at the same and even higher levels of strength is threefold higher than in 40Kh2N2MA steel, the bainitic structure of which contains an appreciable amount of cementite-type carbides. In 40Kh2N2MA steel, as the results of fractographic investigation have shown, the dominant mechanism is the intragrain cleavage fracture (Fig. 3a) with clearly discernible cleavage facets and a river pattern inherent in this fracture mechanism. A mixed fracture (plastic fracture via coalescence of micropores and quasi-cleavage) is characteristic of steels with a carbide-free bainitic structure (Fig. 3b). The more energy-con-

Table 3. Effect of carbon content and alloying with silicon and aluminum on the amount of retained austenite A_{ret} and mechanical properties of steels after continuous cooling (V_{cool} = 5 K/min) in the bainitic range

Steel	σ_u, MPa	KCU, MJ/m^2	Hardness, *HRC*	A_{ret}, %	Carbon content, wt %		Fraction of carbon in A_{ret}, %
					in steel	in A_{ret}	
40Kh2N2MA	1110	0.30	36	6	0.41	1.00	15
40Kh2N2MYu	1220	1.00	38	24	0.37	1.45	94
27Kh2N2SM	1340	0.85	38	22	0.27	1.08	88
18Kh2N2SM	1200	0.90	38	16	0.18	1.00	89

suming fracture of steels alloyed with silicon and aluminum is caused by features of the carbide-free bainitic structure; none of rough carbide precipitates and an enhanced amount of retained austenite. The positive effect of retained austenite on the impact toughness is seemingly connected with the retardation of cracks that nucleate in bainitic ferrite. The fracture of steels with bainitic structures can be considered like the fracture of composite materials; i.e., a more solid phase yields a high strength, whereas a softer phase absorbs energy upon crack propagation.

A characteristic feature of the bainitic structure of the investigated steels is a substantial carbon enrichment of retained austenite by factors of about 2.5, 4, and 8 for 40Kh2N2MA, 40Kh2N2MYu, and 10Kh2N3GM steels, respectively, compared to the total carbon content in steel (Tables 2, 3). This enrichment is a typical sign of the occurrence of the bainitic transformation and determines the chemical composition and morphological features of formed structural constituents (bainitic ferrite and retained austenite) depending on the intermediate-transformation temperatures. As follows from Table 2, for all the steels listed in this table, the carbon content in retained austenite is of much the same value (0.8–1.0% C), and the amount of retained austenite for steels with completely carbide-free bainite and for 40Kh2N2MA steel also does not differ very significantly, i.e., from 6 to 15%. The carbon content in ferrite of all the studied steels with carbide-free bainite is approximately 0.03–0.04% C, which corresponds to its content in lower bainite. Thus, the amount of retained austenite and degree of its carbon enrichment cannot explain substantial differences in the level of impact toughness of the investigated steels. Yet, if the fraction of carbon content in retained austenite is calculated relative to the total carbon content in the steel, the picture changes significantly (Table 2, last column). It can be seen that, when carbide-free bainite is formed, the main portion of carbon (72–86%) resides in retained austenite and the steels exhibit high impact toughness. For 40Kh2N2MA steel, this fraction of carbon in retained austenite is only 15%; i.e., 85% of carbon resides in ferrite and cementite, and the impact toughness is low.

This picture is observed for steels alloyed with silicon and aluminum (Table 3, last column). Steels with the carbide-free bainitic structure are characterized by the fact that the main portion of carbon (88–94%) is located in the retained austenite, they possess high impact toughness at much the same level of strength.

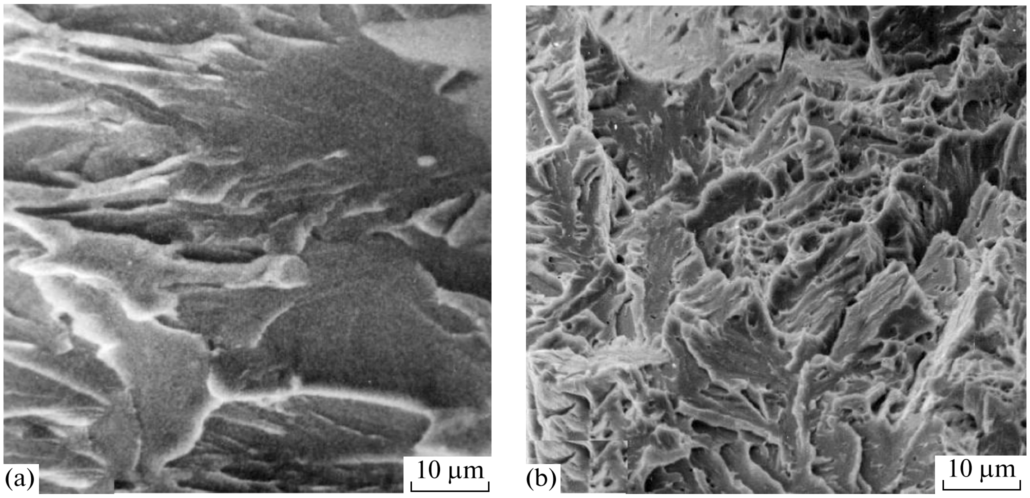

Fig. 3. Characteristic type of fracture of (a) 40Kh2N2MA and (b) 40Kh2N2MYu steels with bainitic structure.

It follows from this that, for the studied steels in which the bainitic structure is formed upon slow continuous cooling, the fraction of carbon in the retained austenite, regardless of its amount, can characterize morphological features of structural constituents of phase transformations (carbide-free bainite or bainite with carbides) and the level of impact toughness of the steel. However, a detailed determination of the interrelation of mechanical properties of the bainitic structure with features of the chemical composition of structural constituents calls for further investigations.

CONCLUSIONS

(1) Upon the development of steel compositions for massive parts where bainite inevitably forms in the center upon heat treatment, alloying should be directed toward obtaining carbide-free bainite.

(2) Alloying medium-carbon chromium–nickel–molybdenum steels with silicon and aluminum in an amount of about 1% and a reduction in the carbon content to 0.10–0.15% C make it possible to exclude the carbide formation in the course of the intermediate transformation upon continuous cooling and result in the formation of carbide-free bainite representing a ferritic–austenitic structure not containing precipitates of the carbide phase. The high impact toughness of steels with the carbide-free bainitic structure is due to the absence of carbide precipitates and an enhanced amount of retained austenite.

(3) Retained austenite in carbide-free bainite is enriched substantially with carbon and contains a noticeable portion of the total carbon content in the steel. When the carbon content in retained austenite of carbide-free bainite is more than 70–80%, the steel at nearly the same strength possesses a level of impact toughness that is three to four times higher than in steel with bainite containing carbide precipitates.

ACKNOWLEDGMENTS

Electron-microscopic investigations were performed in the Center of Colloborative Access for Nanotechnologies and Advanced Materials of the Institute of Metal Physics (Ural Branch, Russian Academy of Sciences). This work was supported by the Ministry of Education and Science of the Russian Federation within Decree 218 Development of Cooperation between Russian Institutes of Higher Education and Plants: contract no. 02.G25.31.0068 between the Ministry of Education and Science of the Russian Federation and OAO Motovilikhinskie zavody, contract no. 2013/050 between OAO Motovilikhinskie zavody and the Permskii National Research Polytechnic University, and contract no. 3s/14 between the Permskii National Research Polytechnic University and the Institute of Metal Physics (Ural Branch, Russian Academy of Sciences).

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Translated by I. Krasnov