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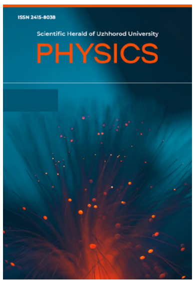

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Study of hardening and structure of maraging powder steel grade PS-H18K9M5TR (18%Ni+9%Co+5%Mo+1%Ti+1%Re+66%Fe)

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Abstract

Relevance. High-strength steels are increasingly in demand in modern industry for various applications. Maraging steels are the primary material in the manufacture of most aircraft parts as well as machine-building components. This type is low-carbon and is rich in nickel, which forms martensite when cooled as well as demonstrates properties such as high hardness, wear resistance, etc. The hardening process is the main factor affecting the functional properties of maraging steel. At certain temperatures, austenite has the ability to transform into various kinds of phases. However, the shortcoming that lies in the presence of some impurities limits the established types of improvement technologies, leading to the search for innovative methods to improve the characteristics of steel without losing any of the desired properties. Good qualities appear in maraging steels mainly after treatment with a solution at a temperature of about 1000°C and during aging at a temperature of about 490°C.

Purpose. Thus, the purpose of this research paper is to analyze the structure of maraging steel powders and study the thermal effect on its properties.

Methodology. In this paper, powder steel was pressed by spark plasma sintering technology at a pressure of 60 MPa to a powder compact and heated at a temperature of 1100°C for 180 s at a rate of 20°C/s, after which the samples underwent phase and elemental analysis, their hardness was measured, the value of which amounted to about 60 HRC.

Results. The results of this scientific research demonstrate the presence of a variety of precipitates. The presence of impurities such as Co, Ti, and Re led to an improvement in strength due to martensitic phase transformation and precipitation hardening, as well as slowed down the diffusion process.

Conclusions. In addition, tasks for further research on the issue of manufacturing maraging steels by the additive manufacturing method were identified. This technology enables obtaining strong maraging steels based on a powder mixture with the required characteristics

Keywords: spark plasma sintering, laser processing, additive manufacturing, heavy-duty steel, heat treatment

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Introduction

Various branches of engineering require the refinement of high-strength steels. Maraging steels are low-carbon high-strength steels. Their structure and characteristics with good mechanical properties provide resistance to impact loads. High-alloy maraging steels with high strength and processability as well as good fracture toughness are popular in various areas of activities (for example, in the aerospace industry, mechanical engineering, various types of structures) [1; 2]. Despite the low carbon content, high strength values are due to the Ni-martensitic matrix as well as the presence of significant dislocation density, subsequently formed martensitic metamorphosis, atoms of a chemical compound between elements in the form of a phase of variable composition or intermetallic compound. The deposition of such compounds is one of the most effective ways of hardening maraging steels. However, it should be emphasized that the high percentage of Ni with the combined presence of retained austenite sharply decreases the steel's strength. Ni is an element that is widely used as an impurity, with Mo, Cu, Ti and others following it. During aging, the metastable state has an increased free energy, and therefore tends to decay with deposition of phases that give strength: Fe_2Mo, Ni_3Ti (Mo), etc. An increase in the content of impurities of various kinds leads to an increase in the volume of precipitated phases and greater dispersion strengthening, despite the fact that a shortage of such elements leads to the search for new ways to improve the functional characteristics of steels without losing such properties as ductility, brittleness and toughness.

At high temperatures, Fe has a face-centered cubic lattice (FCC), while at low temperatures it has a body-centered cubic lattice (BCC). A feature of maraging steels is martensitic hardening, i.e., intermetallic compounds are deposited in Fe-Ni martensite with negligible carbon content during aging, which hardens the steel. As reported by L.F. Van Swam, R.M. Pelloux & N.J. Grant [3], such steel is typically heat-treated using a one-hour solution annealing at 820°C followed by cooling to room temperature to form Fe-Ni martensite. The results of the maraging steel research by T.A. Chernyshova & T.V. Lyulkina [4] show that rapid hardening of maraging steels significantly affects the nature of phase metamorphoses, structure and functional characteristics of steels. Z.-F. Hu & Ch.-Xu. Wang [5] report grain refinement after heat treatment. However, hardness tests show that the mechanical properties of maraging steel do not depend significantly on grain size. Thus, the preparation of the austenitic phase in the martensitic matrix has a beneficial effect on the strength and ductility of the steel. In their paper, J.M. Pardal, S.S.M Tavares, V.F. Terra, M.R. da Silva & D.R. dos Santos [6] propose a model for the aging of maraging steel within the temperature range of 440-560°C using the following equation:

$$\Delta H = (kt)^n \tag{1}$$

where: k is the rate constant depending on temperature; n is the exponent that is weakly dependent on temperature; ΔH is the increase in hardening volume; t is the aging time.

In detail, the hardening process consists of quenching and aging, or of quenching, cold working and natural aging. Higher strength properties are achieved through hardening, deformation and aging [7]. During rapid quenching, a martensitic transformation occurs due to the shift of FCC to BCC, creating a microstructure with a high density of internal defects. When a quenched supersaturated solid solution is reheated to a certain temperature, the precipitates are formed and their number increase [8]. Morphology, dimensions and concentration of precipitates mainly depend on the chemical composition and hardening. It is worth to consider cases of lattice mismatch, which will lead to the formation of precipitates in the dislocation regions, which in turn weakens the ability to distribute precipitates throughout the matrix. In addition, there is the potential to regulate the concentration and number of precipitates by adjusting the solution treatment conditions [9].

Research journals lack information about the study of powders obtained by spark plasma sintering. Therefore, the purpose of this research is to study the structure after sintering of a maraging powder mixture and to analyze the heat treatment on its properties.

Materials and Methods

Maraging powder steel containing 18% Ni, 9% Co, 5% Mo, 1% Ti, 1% Re was selected the object of study. This steel belongs to class C maraging steel, which usually contains about 18% Ni as well as contains alloying elements such as Co, Mo and Ti. Powders are obtained by gas atomization, which is a polarization method for the production of powder steel. When sprayed, spherical particles with a relatively round shape are usually formed. As part of this process, the assimilation of the alloy occurs, which is subsequently excited by a gas flow at an ultrahigh speed. In the course of this, the liquid metal is distributed into droplets with further solidification in the form of continuous powder grains. The method for pressing powder mixture in this paper is the technology of spark plasma sintering by applying 60 MPa to the powder compact and heating it at a temperature of 1100°C for 180 s at a rate of 20°C/s. This method was chosen due to good compaction as well as high relative density. Figure 1 shows a schematic representation of the SPS (spark plasma sintering) technology unit, which includes graphite molds, into which the powder mixture is poured between stampings. An image of the powder mixture is shown in Figure 2, 3 shows sintering results.

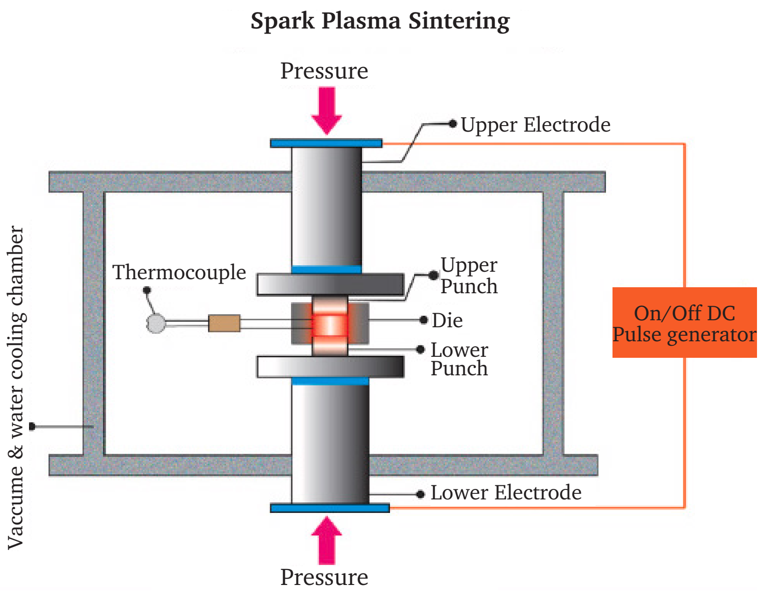

Figure 1. SPS technology unit diagram

Source: [10]

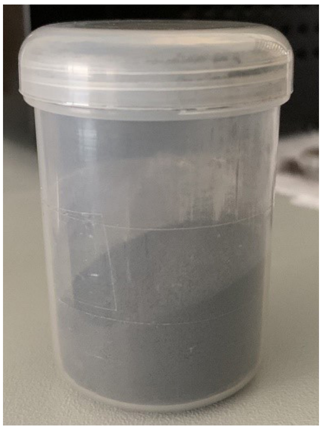

Figure 2. Image of the powder mixture before sintering

Figure 3. Image of powdered steel after sintering

To study the microstructure before observation, the samples were etched in a Fry's reagent solution ($FeCl_3$ + $CuCl_2$ + HNO_3 + HCl + ethanol + H_2O) and then examined using scanning electron microscopy (SEM). To study the characteristics, a Difrey-401 diffractometer was used to obtain phase and elemental analysis. The phases are established by comparing and matching the diffraction angles and intensity values of the diffraction peaks with well-known template X-ray patterns obtained from open sources. In the cubic system, the a_{hkl} lattice parameter for diffraction from (h, k, l) defined by the diffraction angle θ_{hkl} is calculated as follows:

$$a_{hkl} = \frac{(h^2+k^2+l^2)^{1/2}}{\lambda/2sin\theta_{hkl}} \quad (2)$$

where: λ is the X-ray wavelength.

The share of austenite in the linear model varies depending on temperature, ranging from the beginning and end of austenite occurrence (617°C and 674°C respectively). The transformation of austenite to martensite is calculated using the Koistinen-Marburger phase transformation model:

$$f_{martensite} = f_{austenite}[1 - \exp\big(-0.011(M_s - T)\big) \quad (3)$$

where: f is the volume fraction of the phase; Ms is the initial temperature, at which martensite appears.

The following section is divided into three main parts, which discuss important aspects for this research. To begin with, the issue of the hardening effect on the structure and functional characteristics of martensite-containing steels was considered. For comparison, studies are given where the authors carried out different types of heat treatment of steels, the microstructure, phase transformations and properties of which were subsequently considered. The second part analyzed an innovative method for the production of maraging steels using laser technologies for powder mixtures. The results of the influence on the structure and properties of steels produced using this technology are presented. The third part analyzes the effect of chemical composition on the structure and mechanical properties of maraging steels. The research papers cited as examples can be used as a basis for further research.

Results and Discussion

Below are the sampling areas of initial powder and sintered powder steel (Fig. 4). The data obtained, presented in Table 1, confirm the composition of the powder mixture.

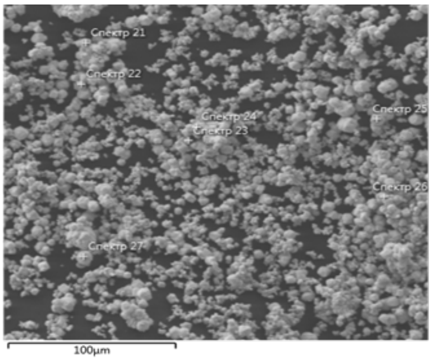

Figure 4. Selective sampling region

Table 1. Elemental analysis of the initial powder

Spectrum number	Element content, atomic fraction, %					
	Fe	Ni	Co	Mo	Ti	Re
1	67	15	8	7	1	1
2	68	13	6	4	1.3	0.8
3	69	18	9	3	1.5	0.9
4	61	20	4	4	0.9	0.7
5	62	18	8	5	0.85	1.2
6	64	19	9	6	0.9	1.1
7	63	18	10	3	1.1	0.95
8	66	17	7	5	1.2	0.9

During phase analysis, it was noticed that diffusion reactions slowdown, which in turn affects the formation of phase inhomogeneity throughout the volume of the material obtained. The Rockwell hardness of the samples was also measured, the value of which amounted to 60 HRC.

Martensitic transformation theories provide specific parameters for each of the geometric and crystallographic features of the transformations assigned to a particular invariant shift system. That is, each variant of the correspondence between the lattice and its orientation is the result of the choice of an invariant lattice shift system. The high strength of maraging steels was achieved due to the martensitic γ→α transformation and martensite aging. The fatigue properties of the material are explained by its service life. That is, these properties are usually qualified as the ultimate performance indicator that determines whether a material can be developed for further use. The experiments performed show the possibility of forming structures such as martensite, ferrite, a chemical compound of martensite and ferrite-forming elements, such as oxyfer, depending on the rate of cooling of solid solution and subsequent cooling. The formation of an austenite phase at the boundary of a martensite grain plays a significant role in reducing the concentration of deformation stresses and coordinating deformation. Part of the austenite phase was retained during quenching. The maximum amount of reduced austenite is mainly observed at room temperature. The aging of the steel under study is accompanied by the formation of intermetallic compounds such as Fe3(Ni, Mo), Fe2Mo, FeMo, Ni3Ti, Ni3Mo, ŋ-Ni3Ti, as well as Fe7Mo6. That is, such compounds increase strength by accompanying the formation of segregations, metastable and stable phases, but with a sharp decrease in ductility. The sintered powder steel in the annealed state has a fully martensitic structure.

J. Tian, W. Wang, H. Li, M. Babar Shahzad, Y. Shan, Zh. Jiang & K Yang [11] talk about a method to increase the hardness of maraging steel by quenching. J.M. Pardal, S.S.M Tavares, V.F. Terra, M.R. da Silva & D.R. dos Santos [6] report that direct aging provides the stiffest state with the highest flexural strength. There are also opinions about improving the microstructure due to the transformation of martensite into austenite using thermal cycling. The distribution of elements after thermal cycling accelerates the kinetics of formation and growth of austenite grains. The transformation of martensite into austenite depends on diffusion phenomena occurring within a certain temperature range. Therefore, the stimulation of metamorphosis in the temperature range where sedimentary phenomena are not observed and the stabilization of reverse austenite at room temperature is of paramount importance for improving the functional properties of the steel. Based on the data obtained from elemental analysis, it is possible to identify an area enriched in iron, i.e., the basis of the compressed powder mixture (Fig. 5) is an iron frame. Elemental analysis also shows that in the range of at least 26 microns, there is a large amount of iron on the surface with added alloying elements. The micrographs of the samples (Fig. 6) show a small porous structure formed after sintering. In addition to the main particles, there are fractions of regular spherical shape, located mainly at the junction of large Fe grains. The shape and arrangement of the particles of this fraction allows assuming that they were formed due to the liquid phase. It should also be noted that their size does not exceed the size of small pores.

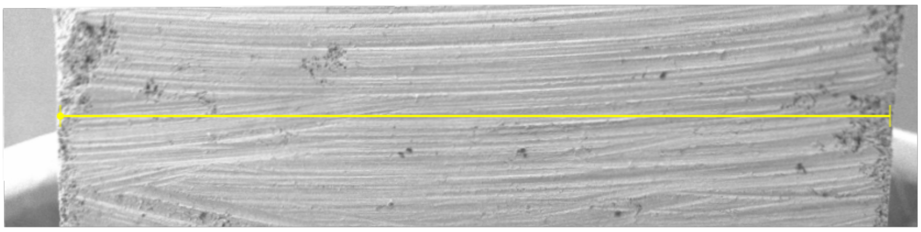

Figure 5. Image of a cut of pressed powder steel

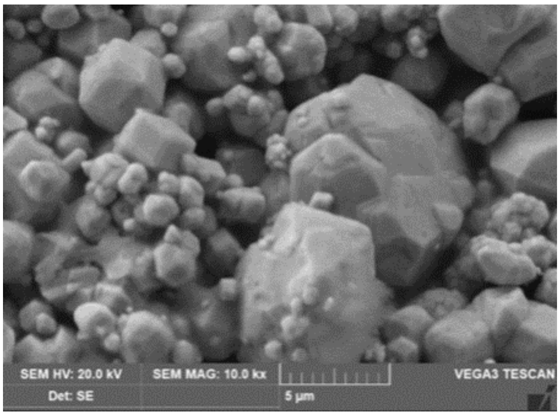

Figure 6. Sample micrography

Thus, the basis of the microstructure of the hardened 18% maraging steel is martensite with a low carbon content and a high content of nickel and cobalt. Aging at low temperatures (<450°C) occurs due to ordered and coherent phases, and will also be followed by the propagation of dislocations, which play an important role in increasing hardness and strength during aging. However, the propagation of dislocations can lead to the appearance of precipitates, such as Ni_3Ti (Mo), and an increase in their concentration. Hardening at high temperatures (above 850°C) leads to the increase in grain size and ductility. Therefore, it is necessary to harden maraging steels at 800-850°C in air, followed by aging within the temperature range from 480°C to 520°C.

A detailed analysis of the steel microstructure is the most important indicator in describing the material for the correct definition of purpose and application. Also, mechanical properties directly depend on the nature and features of the microstructure. The chemical composition can affect the change in phase stability. Alloying powder steel with cobalt led to an increase in the aging effect. Titanium and aluminum, in turn, also influenced the aging process in the future. M.A. Cerra Flore, Ú.C. Pereira, J.L. Cardoso, F.J. Santos Oliveira, W.S. Araújo, G.F. Ribas, H.F. Gomesde Abreu & M.J. Gomes da Silva [12] obtained results indicating a decrease in the electrochemical corrosion resistance of maraging steels in relation to the amount of content of certain elements. The dissolution of alloying elements in iron occurs due to the replacement of Fe atoms by impurity atoms. Changing the dimensions of the α-lattice leads to a change in properties, i.e., morphology mainly depends on the chemical composition. For example, doping with substances such as Mo, Ti and Ni can increase the density. The content of Ni and Ti is necessary for the formation of intermetallic phases that cause aging. The presence of a high content of Ni, Si, or Mn compared to Cr, Mo, and W strengthens the single-phase region γ to room temperature, i.e., contributes to martensitic transformation, which hardens the steel. Ni stabilizes the γ-solid solution, while reducing the transformation temperature $\gamma \rightarrow \alpha$. The addition of refractory Re to the overall chemical composition can increase the hardness after heat treatment. In turn, Re has the ability to reduce the self-diffusion coefficient, which mainly leads to high thermal stability [13]. For example, in the paper of A. Fedoseeva, I. Nikitin & N. Dudova [14; 15], Re was added to the martensitic steel and the results show that this hardened the steel. At that, the presence of Ti negatively affects the processibility of the alloy. Re also gives the microstructure a hierarchical appearance, which consists of austenite grains in the form of blocks with martensite laths. The absence of Ti leads to the absence of precipitates, more specifically, the nickel-based intermetallic compound of the Ni_3Ti type, which, in turn, is the main hardening precipitate and dissolves in the γ'-phase [16; 17].

S. Dehgahi, H. Pirgazi, M. Sanjari, R. Alaghmandfard, J. Tallon, A. Odeshi, L. Kestens, M. Mohammadi, M.H. Ghoncheh & B. Shalchi Amirkhiz [18; 19] reported an increase in the proportion of the austenite phase after heat treatment by increasing Ti, where it promotes the formation of austenite in the presence of Ni and Mo. The presence of titanium (TiO_2) or molybdenum (MoO_3) oxides gives the steel additional protection. It has also been found that ductility was improved in samples with a high Ti content by developing the copper texture and fibers that facilitate the movement of dislocations. The reversible kinetics of γ formation, stimulated by the addition of Ti, has the greatest strengthening effect due to Ni_3Ti precipitates in the matrix. J. Tian, W. Wang, H. Li, K. Yang, Z. Jiang [20] demonstrated that specimens with a high titanium content are more ductile but have lower strength compared to specimens with a low Ti content. J. Tian, W. Wang, H. Li, K. Yang, Z. Jiang [20] investigated martensitic steels with different Ti content. From the analysis results, it can be noted that the martensite content is almost the same in various powder mixtures. The addition of Co in the presence of Mo in the alloying elements reduces the solubility limit in the lattice coordinate system, contributing to the formation of a uniform volume fraction of the Fe_2Mo precipitates dispersion.

S. Dehgahi, M.H. Ghoncheh, A. Hadadzadeh, M. Sanjari, B. Shalchi Amirkhiz & M. Mohammadi [21] confirmed the presence of CoNi precipitates and a high fraction of dislocations in horizontal samples with a large amount of Ti, which implies good strength of the samples. It is also worth paying attention to raising questions about the hardening of maraging alloys by copper deposition. At the initial stage of the process, Cu is deposited as a precipitate with a body-centered lattice in the α-Fe matrix, maintaining the integrity of the structure up to the peak quenching temperature. For example, G. Yang, F., Deng, S. Zhou, B. Wu & L. Qin [22] developed a new maraging steel reinforced with copper. The results show that the microstructure of such steel is mainly composed of lath martensite, δ-ferrite, as well as reduced austenite in the precipitated state. After quenching and direct aging, the microstructure consisted of martensite and reduced austenite. But it is worth noting that copper does not form compounds with iron and its solubility is about 1%. Maraging alloy steels have excellent stress resistance and corrosion resistance. However, the high cost of alloying additions such as Co or Mo prevents their widespread use [5]. In this connection, a recent promising direction is the development of maraging steels without the addition of Co, while preserving good characteristics. The addition of a large amount of Cr to improve corrosion resistance may cause the formation of precipitates, which will lead to brittleness, more precisely, the cold brittleness threshold will increase [23]. Therefore, the development of ultra-strong maraging steels with good ductility, stability and economic benefits is of great interest.

Powder metallurgy has recently gained momentum as a promising technology for the production of steels due to the production of steels with a homogeneous microstructure, which gives it the expected characteristics. The current technology used for powder steels is spark plasma sintering (SPS), which was applied to obtain these samples. This sintering technology pays attention to the rapid compaction of the powder mixture to a high density (up to 95% for the presented samples) at low temperature ranges, but at a fast time interval (in this case in 180 s) compared to traditional sintering methods. In the manufacture of steel using the SPS method, the sample is subjected to rapid sintering and then cooling, which removes nitrogen well and gives greater performance and high density. However, it must also be taken into account that the morphology and size of the powder affects the density of sintering. More precisely, the smaller the size of the powder, the denser it is sintered. During SPS sintering, plastic deformation occurs, i.e., the throughput of a pulsed direct current through the sample forms an electric field. It is also important that the powder is heated inside and outside and melted by applying pressure, which has a good effect on the sintering density and functional characteristics of the sample. The sintering temperature in this way can reach up to 2500°C, resulting in high-quality steel [24]. The preparation of maraging steels using the SPS method will not allow abrasive phases and side reactions to occur. For example, these samples were also tested for abrasion resistance, the results of which are shown in Figure 7. According to the experimental values obtained, it is noticeable that the abrasion resistance is much higher than that of other steels. This technology also has low cost (saving up to 80%), which is an important criterion.

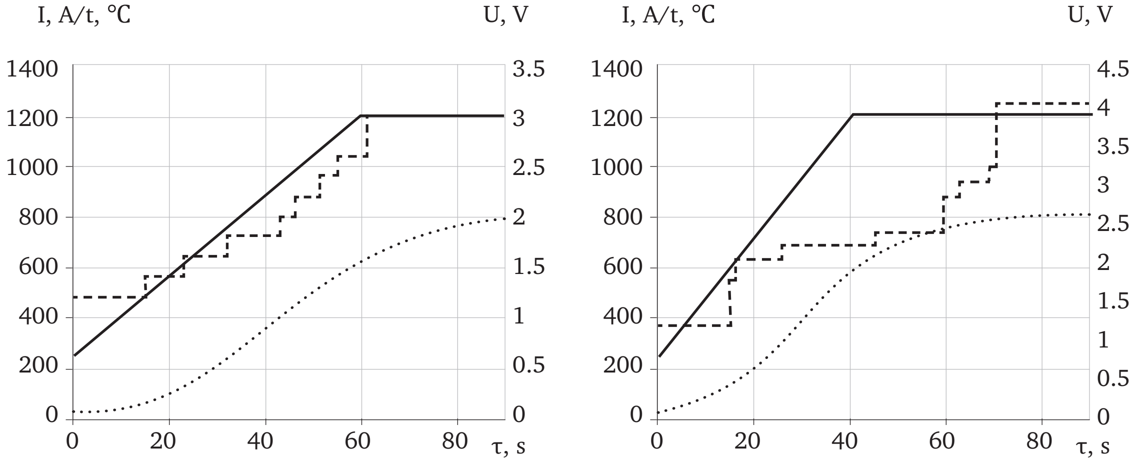

Figure 7. Experimental data results

Note: *1 – current strength; 2 – voltage; 3 – temperature in time during spark plasma sintering of the mixture 18%Ni+9%Co+5%Mo+1%Ti+1%Re+66%Fe at different heating rates*
Source: [25]

Recently, the method of additive manufacturing has gaining popularity, namely, the production of powder steel using laser deposition. Materials made using this technology demonstrate really good results, namely the unique microstructure and defects that can be controlled to obtain effective mechanical characteristics. For example, M.J. Paul, Y. Muniandy, J.J. Kruzica, U. Ramamurty & B. Gludovatz [26], Zh. Zhao, L. Wang, D. Konga, P. Liu, X. He, X. Ni, L. Zhang, Ch. Dong [27] and D. de Baere, M. Moshiri, L. Smolej & J.H. Hattel [28] obtained a maraging powder steel, the samples of which had high hardness, which allows increasing the development and use period. Maraging steels harden according to the general law of metals with a body-centered lattice, which favorably affects such characteristics as hardness, yield stress and strength. At that, to obtain the expected values, it is necessary should monitor the substance’s structure. As mentioned above, powder mixture laser deposition technology is widely used, in which a metal powder mixture is developed by laser beam assimilation one layer after another upon solidification. Obtaining optimal hardness with the help of LB-PBF (laser beam-powder bed fusion) technology requires improvements, i.e., carrying out hardening or aging. Thus, carrying out heat treatment during the laser processing will give the expected results, thus neglecting post-thermal processing.

N. Nouri, Q. Li, J. Damon, F. Mühl, G. Graf, S. Dietrich & V. Schulze [29] developed a new maraging steel by the LB-PBF method. The results show a reduction in time and cost for optimizing steel characteristics. It should be noted that the crystallographic texture also depends on the strain rate and other laser processing parameters. For example, S. Dehghahi, H. Pirgazi, M. Sanjari, R. Alaghmandfard, J. Tallon, A. Odeshi, L. Kestens, M. Mohammadi, M.H. Ghoncheh & B. Shalchi Amirkhiz [18; 19] addressed this issue, showing that the strain rate does not have a significant effect on the texture in samples that have undergone heat treatment. The results of the paper by M.A. Cerra Flore, Ú.C. Pereira, J.L. Cardoso, F.J. Santos Oliveira, W.S. Araújo, G.F. Ribas, H.F. Gomesde Abreu & M.J. Gomes da Silva [12] show that quenching has a significant effect in terms of transformation and variability in the microstructure of the sample. At that, proper selection of heat treatment parameters can eliminate microstructure defects. The microstructure of steels produced by laser processing consists of martensite with precipitates and preserved austenite. However, L. Guo, L. Zhang, J. Andersson & O. Ojo [30] report that the content of precipitates can reduce ductility and fracture toughness. Thus, the production of powder steel using the LB-PBF technology results in samples with favorable characteristics. The microstructures of such steels can reach high hardness values compared to conventional samples produced by traditional methods. Research shows that this technology also allows achieving an age hardening effect. Heat treatment during the production process can potentially lead to sufficient age hardening to allow post-heat treatment to be neglected. In the manufacture of steels by this technology, each layer of material is subjected to a repeated heating cycle, which leads to repeated austenization and the nucleation of martensite. It is also worth noting that the microstructure of steels produced by laser processing consists of martensite with precipitates and preserved austenite. A typical structure of steel produced by laser processing can be described as follows:

– the formation of multilevel hierarchical solidification systems such as molten precipitate boundaries, columnar or equiaxed grain boundaries, as well as ultrathin subgrain boundaries (i.e., columnar, dendritic and cellular subgrains);

– the distribution of segregation of elements and retained austenite along the subgrain boundaries.

Plasma nitriding has also proven itself as an effective and innovative method for improving the surface quality of maraging steel. The thermal effect of the nitriding reaction, in which energy is released or absorbed, leads to hardening of the maraging steel. Theoretically, the mechanical properties of laser-produced steel can be improved through the effect of simultaneously undergoing the aging and nitriding process. Y Hong, D.D. Dong, S.S. Lin, W. Wang, C.M. Tang, T.C. Kuang, M.J. Dai [31] report an improvement in the hardness and wear resistance of maraging steel by performing plasma nitriding, during which a nitrided layer is formed.

Conclusions

The studied powder steel grade PS-H18K9M5TR, pressed by spark plasma sintering, is a heavy-duty maraging steel, the hardness value of which amounts to 60 HRC according to the Rockwell method. The presence of a number of alloying elements such as cobalt, molybdenum, titanium and rhenium gives this steel an advantage over other structural materials. After quenching, a uniform distribution of finely dispersed particles of secondary phases takes place in the martensitic matrix. In the course of the research, elemental and phase analyzes were carried out, microphotographs of the structure were obtained and described. In the course of elemental analysis, regions enriched in iron were identified; the basis of the compressed powder mixture is an iron frame. Elemental analysis also shows that there is a large amount of iron on the surface with added alloying elements within the range above 26 microns.

The high content of Ni promoted martensitic transformation, increased the strength of the steel without reducing toughness, as well as reduced the cold brittleness threshold, thereby reducing the likelihood of brittle fracture. During phase analysis, it was noticed that diffusion reactions slowdown, which in turn affects the formation of phase inhomogeneity throughout the volume of the material obtained, or rather, the presence of precipitates. The high Ti content resulted in improved strength due to martensitic phase transformation and precipitation hardening. The presence of Re in the studied grade gives the steel a special advantage – a low diffusion rate, which fundamentally affects the thermal stability. This, in turn, increases the operating range of the final material, which helped to form a further study of the effect of the content of Ti, Re and precipitates on the structure, as well as physical and mechanical functional characteristics of steel.

New technologies for the manufacture of powder steels lead to improved optimization of maraging steels, i.e., there is an improvement in the chemical composition with properties superior to those of traditional steels. There is a spread of maraging steel powder in the laser additive production, because its low carbon content helps prevent thermal cracking on cooling. In addition, the parts produced in this way have high strength and hardness. Powder mixture laser sintering (LB-PBF) is a method, by which a sample of the same mixture is to be examined and compared with the spark plasma sintering method. The sintering parameters of the powder mixture in both methods significant affect the microstructure, morphological features and functional qualities of maraging steels, from which the next task is set for further research.

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Дослідження зміцнення та структури мартенситно-порошкової сталі марки PS-H18K9M5TR (18%Ni+9%Co+5%Mo+1%Ti+1%Re+66%Fe)

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Анотація

Актуальність. Високоміцні сталі користуються все більшим попитом у сучасній промисловості для різних застосувань. Мартензитно-старінні сталі є основним матеріалом для виготовлення більшості деталей літаків, а також компонентів машинобудування. Цей тип є низьковуглецевим і багатий нікелем, який утворює мартенсит при охолодженні, а також демонструє такі властивості, як висока твердість, зносостійкість тощо. Процес гартування є основним фактором, що впливає на функціональні властивості мартенситно-старої сталі. При певних температурах аустеніт має здатність переходити в різного роду фази. Однак недолік, який полягає в наявності деяких домішок, обмежує встановлені типи технологій поліпшення, що призводить до пошуку інноваційних методів поліпшення характеристик сталі без втрати будь-яких бажаних властивостей. Хороші якості з'являються в мартенситно-стартових сталях в основному після обробки розчином при температурі близько 1000°C і під час старіння при температурі близько 490°C.

Мета. Отже, метою цієї наукової роботи є аналіз структури порошків мартенситно-стартової сталі та вивчення термічного впливу на її властивості.

Методологія. У цій роботі порошкову сталь пресували за технологією іскрового плазмового спікання під тиском 60 МПа до порошкової компактної форми та нагрівали при температурі 1100°C протягом 180 с зі швидкістю 20°C/с, після чого зразки піддавалися фазі та елементного аналізу було виміряно їх твердість, значення якої склало близько 60 HRC.

Результати. Результати цього наукового дослідження демонструють наявність різноманітних опадів. Наявність таких домішок, як Co, Ti, Re призводила до підвищення міцності за рахунок мартенситного фазового перетворення та дисперсійного зміцнення, а також уповільнювала процес дифузії.

Висновки. Крім того, визначено завдання для подальших досліджень з проблеми виготовлення мартенситностартових сталей адитивним методом виробництва. Ця технологія дозволяє отримувати міцні мартенситно-стареючі сталі на основі порошкової суміші з необхідними характеристиками

Ключові слова: іскрове плазмове спікання, лазерна обробка, адитивне виробництво, надміцна сталь, термічна обробка