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POLSKA AKADEMIA NAUK

A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S

Volume 60 2015 Issue 4

DOI: 10.1515/amm-2015-0411

P. KULECKI*, E. LICHAŃSKA*, M. SUŁOWSKI*,#

THE EFFECT OF PROCESSING PARAMETERS ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF SINTERED STRUCTURAL STEELS BASED ON PREALLOYED POWDERS

WPŁYW PARAMETRÓW WYTWARZANIA NA STRUKTURĘ I WŁASNOŚCI MECHANICZNE SPIEKANYCH STALI WYKONANYCH NA BAZIE PROSZKÓW STOPOWYCH

The object of the study was to evaluate the effect of production parameters on the structure and mechanical properties of Cr and Cr-Mo PM steels. The measurements were performed on sintered steels made from commercial Höganäs pre-alloyed powders: Astaloy CrA, Astaloy CrL and Astaloy CrM mixed with carbon, added in the form of graphite powder grade C-UF.

Following mixing in a Turbula mixer for 30 minutes, green compacts were single pressed at 660 MPa according to PN-EN ISO 2740 standard. Sintering was carried out in a laboratory horizontal furnace at 1120°C and 1250°C for 60 minutes, in 5%H_2-95%N_2 atmosphere. After sintering, the samples were tempered at 200°C for 60 minutes in air. The steels are characterized by ferritic – pearlitic, bainitic – ferritic and bainitic structures.

Following mechanical testing, it can be assumed that steel based on Astaloy CrA pre-alloyed powder could be an alternative material for steels based on Astaloy CrL powder. These steels sintered at 1250°C with 0.6% C had tensile strengths about 650 MPa, offset yield strengths about 300 MPa, elongations about 8.50 %, TRSs about 1100 MPa, hardnesses 220 HV.

Keywords: sintered steels, alloying elements, mechanical properties, microstructure, density

W artykule przedstawiono analizę wpływu parametrów wytwarzania na strukturę oraz własności spiekanych stali wykonanych na bazie komercyjnych proszków: Astaloy CrA, Astaloy CrL i Astaloy CrM produkowanych przez firmę Höganäs. Zawartość węgla w stalach wynosiła 0,2 % oraz 0,6 %. Prasowanie wykonywano w sztywnej matrycy po ciśnieniem 660 MPa, otrzymując kształtki zgodne z normą PN-EN ISO 2740. Spiekanie wyprasek prowadzono w temperaturach 1120°C i 1250°C w czasie 60 minut.Atmosferę spiekania stanowiła mieszanka wodoru i azotu w proporcjach 5%H_2 – 95%N_2. Po spiekaniu, próbki dodatkowo odpuszczano w temperaturze 200°C przez 60 minut w powietrzu. Przeprowadzone badania wykazały, że stale wykonane na bazie proszku Astaloy CrA stanowią alternatywę dla stali wykonanych z wykorzystaniem proszku Astaloy CrL. Ponad to wyższa temperatura spiekania pozwoliła na uzyskanie lepszych własności mechanicznych. Spiekane stale charakteryzowały się strukturą ferrytyczno – perlityczną, bainityczno – ferrytyczną oraz bainityczną.

1. Introduction

Technology of powder metallurgy allows manufacturing of very accurate parts, also with complex shapes. Steels made by PM technique require the same heat treatments as conventional steels. Powder metallurgy has wide application and is not limited to steel products. Examples of PM products include dental amalgams, electrical contacts, high temperature filters, friction materials, even explosives. The characteristic feature of sintered products is porosity which affects properties of these materials. Technology of powder metallurgy allows the control of porosity during manufacturing and to customize for indicated properties. Porosity can be a desirable feature for specific products, such as filters or oil-less bearings. The main customer of PM products is automotive industry. The example of products is automotive transmission gears [1-5].

Chemical composition powders mixture has the main influence on properties of PM steel. Carbon next to iron, is primary necessary component to produce steel and its content strongly changes microstructure and properties of steel. Carbon can occur in ferrite, austenite and in carbides and affects the forming of pearlite, bainite and martensite structures. With increasing carbon content, strength and hardness of steel increase but plastic properties (ductility, fracture toughness, machinability) deteriorate [6-13].

Chromium is a very important alloying element in PM steels. It increases strength, hardness and hardenability and

* AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY. FACULTY OF METALS ENGINEERING AND INDRUSTIAL COMPUTER SCIENCE, AL. A. MICKIEWICZA 30, 30-059 KRAKOW, POLAND

Corresponding author: sulek@agh.edu.pl

forms hard carbides. Chromium, which has a somewhat stronger carbide-forming tendency than iron, partitions between the ferrite and carbide phases ((Fe, Cr)$_3$C, Cr_7C_3 and $Cr_{23}C_6$). It can also increase the toughness of steel and the wear resistance. However, the advantages of using chromium-containing PM steels have been hindered by the necessity to reduce oxides at high sintering temperatures. This element can also retard transformation during tempering of steel.

Molybdenum is added to steels for nitriding and also to increase creep resistance. During nitriding of steel, molybdenum forms strengthening nitrides. This element has a high affinity for carbon and forms carbides for example Mo_6C which improves the hardenability of steel [14-28].

2. Material and preparation of test samples

The powders used were alloyed iron powders: Astaloy CrL, Astaloy CrM and Astaloy CrA. Carbon, in the form of graphite C-UF (ultra fine), in amount of 0.2% and 0.6%, was introduced into the mix. Physical and technological properties of based powders were described in Ref. [26].

The powder mixture, listed in Table 1, were prepared in a Turbula mixer for 30 min.

The mixed powders were single-action pressed at 660 MPa in accordance to the PN-EN ISO 2740 standard. Mean values of density are presented in Table 2. Sintering was conducted in a semi-closed container at 1120°C and 1250°C for 60 minutes. The heating and cooling rates were 75°C/min and 60°C/min, respectively. Sintering atmosphere consisted of 5%H_2-95%N_2 mixture with a dew point of -60°C. After sintering, the samples were tempered at 200°C for 60 minutes in air. As sintered densities are presented in Table 2

3. Scope of the research

To evaluate the effect of processing parameters, the physical and mechanical properties of sintered steels were evaluated, including:

- density by the Archimedes method,
- tensile strength (UTS), transverse rupture strength (TRS), elongation (A), an offset yield point set at 0.2% strain ($R_{0.2}$) and hardness,
- microstructure of metallographic polished sections.

Tensile strength test was carried out on the MTS 810 testing machine. The parameters of tensile test were defined in accordance with PN-EN 10002-1 standard. Crosshead speed was 1 mm/min.

TRS tests were made on ZD10 testing machine. During bending test, the sample was on cylindrical supports at a distance of 28.6 mm.

Hardness was determined using Innovatest hardness tester with a load of 100 g for 10 seconds, every 0,5 mm. The scheme of hardness measurement is shown in Figure 1.

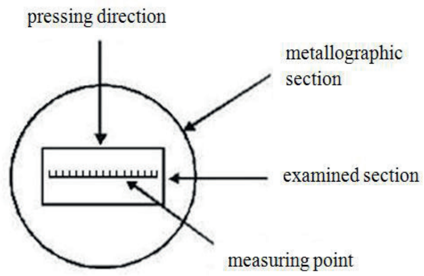

Fig. 1. The scheme of microhardness tests; the distance between test points - 0.5 mm

The samples used for microhardness measurements had tensile strengths close to mean for the whole series.

Metallographic procedure was described in Ref. [30]. After polishing the surfaces of metallographic section were etched 3% Nital. Observations were made on a Leica DM4000M optical microscope using bright field (BF) technique. The total magnification of microscope was 500x.

4. Results of research

Table 2 reports values of green and as-sintered densities measured by Archimedes method in accordance with ASTM B962 – 15 standard.

In Table 3 results of mechanical properties are reported. Figures 2-3 show the characteristic microstructures of the examined steels.

TABLE 2

Density of sintered steels calculated by Archimedes method

Mark	Mean density, g/cm^3			Density changes after sintering, %	
	Archimedes			1120°C	1250°C
	Green	1120°C	1250°C		
CrA+0.2%C	6.81	6.83	6.82	0.29	0.15
CrA+0.6%C	6.85	6.91	6.94	0.87	1.30
CrL+0.2%C	6.85	6.92	6.97	1.01	1.72
CrL+0.6%C	6.86	6.97	7.00	1.15	1.57
CrM+0.2%C	6.87	6.85	7.03	0.15	2.70
CrM+0.6%C	6.91	6.95	6.95	0.58	0.58

TABLE 1

Chemical compositions and description of powders mixtures

Chemical composition	Mark	Alloyed iron powder	Cr, % mas.	Mo,% mas.	C, % mas.	Fe
Fe+1.8%Cr+0.2%C	**CrA+0.2%C**	Astaloy CrA	1.8	-	0.2	Bal.
Fe+1.8%Cr+0.6%C	**CrA+0.6%C**		1.8	-	0.6	Bal.
Fe+1.5%Cr+0.2%Mo+0.2%C	**CrL+0.2%C**	Astaloy CrL	1.5	0.2	0.2	Bal.
Fe+1.5%Cr+0.2%Mo +0.6%C	**CrL+0.6%C**		1.5	0.2	0.6	Bal.
Fe+3%Cr+0.5%Mo+0.2%C	**CrM+0.2%C**	Astaloy CrM	3	0.5	0.2	Bal.
Fe+3%Cr+0.5%Mo+0.6%C	**CrM+0.6%C**		3	0.5	0.6	Bal.

TABLE 3

Mechanical properties of investigated PM steels – mean values (10 samples)

Mark	1120°C					1250°C				
	UTS, MPa	$R_{0.2}$, MPa	A, %	TRS, MPa	HV 0.1	UTS, MPa	$R_{0.2}$, MPa	A, %	TRS, MPa	HV 0.1
CrA+0.2%C	336±19	198±17	5.41±0.83	506±55	125±22	319±45	221±33	8.22±0.53	547±24	117±17
CrA+0.6%C	525±21	257±8	3.12±0.28	838±54	201±62	717±39	308±21	2.83±2.72	1134±73	223±62
CrL+0.2%C	355±6	202±7	4.40±0.47	485±36	133±32	372±5	258±7	5.31±0.89	517±27	126±24
CrL+0.6%C	565±20	285±13	1.31±0.27	981±24	182±47	629±20	291±29	2.66±0.96	1082±36	221±44
CrM+0.2%C	700±23	253±72	2.41±0.77	959±31	210±42	679±46	281±37	4.03±0.72	998±65	227±65
CrM+0.6%C	818±88	294±20	1.35±0.87	1206±83	379±89	870±33	312±14	2.70±0.94	1392±144	320±78

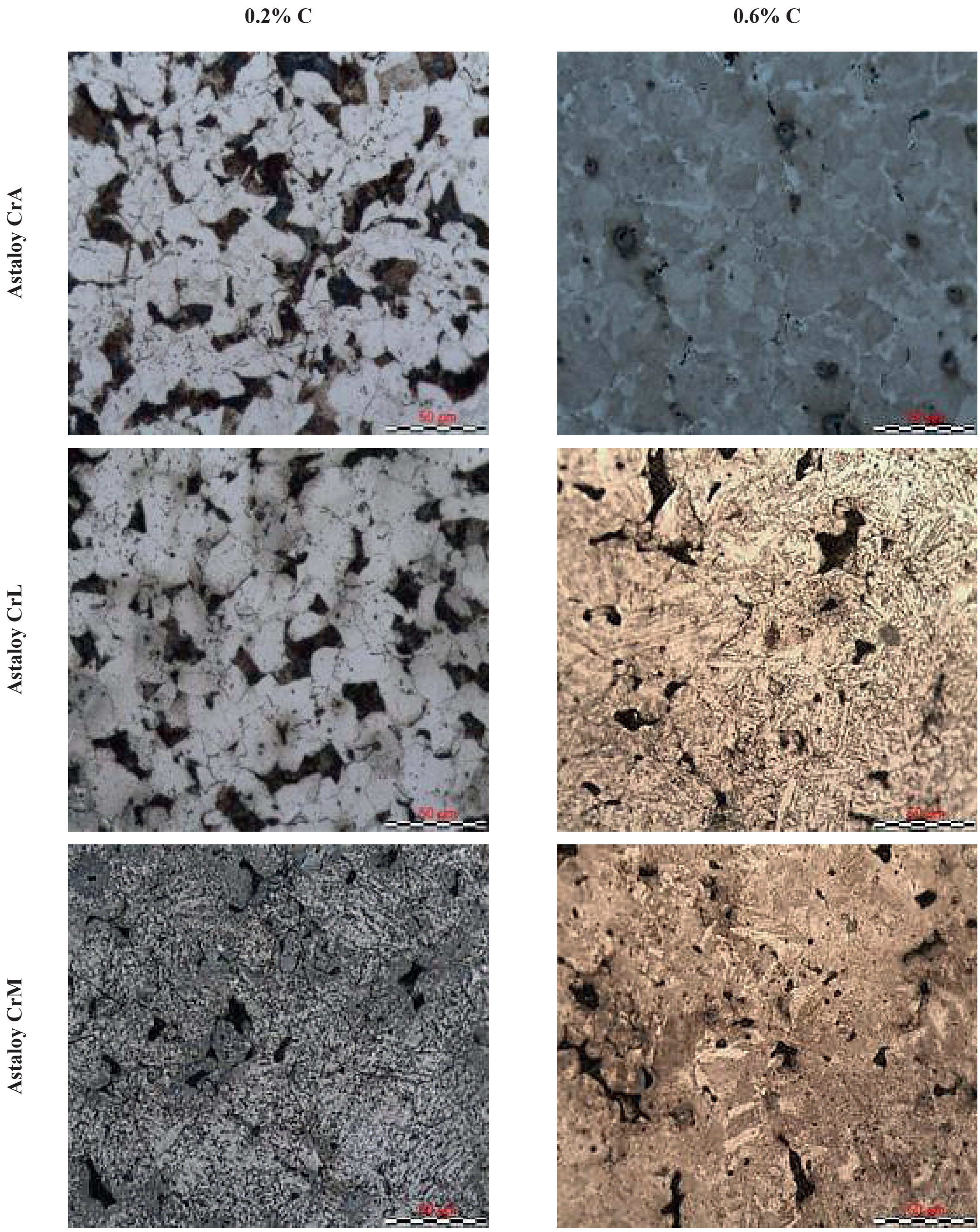

Fig 2. The characteristic microstructures of steels sintered at 1120°C (marker 50 µm)

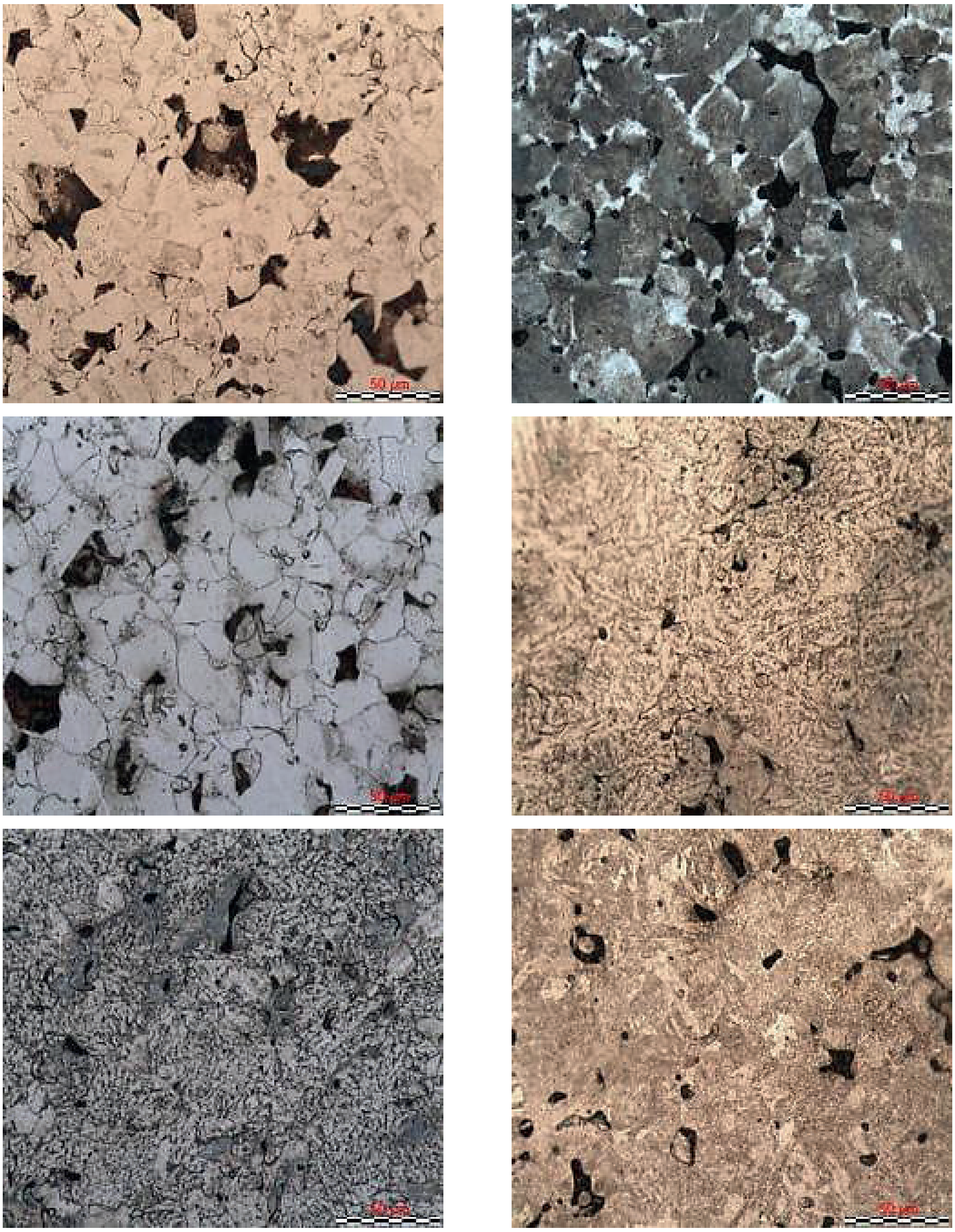

Fig 3 The characteristic microstructures of steel sintered at 1250°C (marker 50 µm)

5. Discussion of results

After sintering at 1250°C, densities of steels based on Astaloy CrA+0.2% C powder decreased in comparison with stees 1120°C. For steels based on Astaloy CrA+0.6% C, Astaloy CrL and Astaloy CrM powders densities were similar or higher. Changes in densities were caused by differences in chemical composition of sintered at pre-alloyed iron powders and by used sintering atmosphere. Higher amount of alloying additions based powders Astaloy CrL and Astaloy CrM caused formed higher amount of carbides which stopped austenite grain growths.

The results of mechanical properties, Table 3, show that increasing of carbon content caused improvement of mechanical properties (UTS, $R_{0,2}$ and TRS). For both sintering temperatures, specimens based on all alloy powders with 0.2% C and 0.6% C reached the highest values of UTS and $R_{0,2}$, caused by the influence of alloying additions, as Astaloy CrM powder containing the most [29].

For steels based on Astaloy CrA powder decreasing in elongation for variants with 0.2% C and 0.6% C were observed. Part of carbon form carbides (steel with 0.6% C) with the whole amount of chromium and rest of carbon dissolved in groundwork – that caused strengthening effect of steel based on Astaloy CrA.

For steels based on Astaloy CrL powder sintered at 1120°C the decrease of elongation from 4.40% to 1.31% were noted with increasing the carbon content from 0.2% C to 0.6% C, elongation of this steels sintered at 1250°C the decrease from 5.31% to 2.66% were noted with increasing the carbon content from 0.2% C to 0.6% C.

After increasing carbon content from 0.2% to 0.6%, steels based on Astaloy CrM powder noted the decrease of elongation from 2.41% to 1.35% and from 4.03% to 2.70% for sinters processed at 1120°C and 1250°C, respectively.

Steels sintered at the higher temperature based on Astaloy CrA and Astaloy CrL powders noted increasing TRS; for steels with 0.2% C it was about 50 MPa and for steels with 0.6% C it was about 200 MPa. In all cases the increase of carbon content caused improvement in TRS because of increasing amount of pearlite or bainite in structure.

With increasing of carbon content, hardness of steels increased. After sintering at 1120°C and 1250°C, the highest values of hardnesses were obtained for steel based on alloy powder Astaloy CrM+0.6%C. After sintering at 1250°C the hardness of steels with 0.2% C was similar compared with steels sintered at 1120°C and hardness of steels with 0.6% C slightly decreased compared with steels sintered at 1120°C.

Steels based on Astaloy CrA and Astaloy CrL alloy powders after sintering at the higher temperature possessed better mechanical and plastic properties, but hardness of these steels was similar or lower. The exception was steels based on alloy powder Astaloy CrM+0.2% C, which after sintering at the higher temperature, had lower UTS, better plastic properties (A), hardness (HV 0.1) and TRS caused by insufficiency total amount of carbon.

In the paper [27] the results of mechanical properties of steels based on Astaloy CrA, Astaloy CrL and Astaloy CrM powders, with 0.4% C and 0.8% C are presented. The differences between properties of steels containing 0.2% C, 0.4% C, 0.6% C and 0.8% C are significant. In steels sintered at 1120°C, based on Astaloy CrA powder, with increasing of carbon content UTS, yield strength ($R_{0,2}$), TRS and hardness (HV 0.1) were increased. Elongation of steels based on Astaloy CrA powder decreased with higher carbon content. Higher amount of carbon caused forming more strengthening phases. After sintering at 1250°C mechanical properties of steels, based on Astaloy CrA powder, were better except hardness, which was similar or less for steels with 0.8% C. Higher sintering temperature could caused decomposition of hard cementite.

In steels sintered at 1120°C, based on Astaloy CrL powder, with increasing of carbon content the increase of UTS, yield strength $R_{0,2}$ and TRS was observed. The highest hardness was noted for steels with 0.8% carbon. Elongation of steels based on Astaloy CrL decreased with higher carbon content. After sintering at 1250°C, mechanical properties of this steels were better than after sintering at 1120°C, except hardness, which was similar or less for steels based on Astaloy CrL with 0.8% C caused by lower content of cementite.

Steels sintered at 1120°C based on Astaloy CrM powder showed the increase of UTS, A, yield strength ($R_{0,2}$), and TRS with the increasing at carbon content from 0.2% to 0.6%C. Steels with carbon content higher than 0.6% had significantly lower plasticity, which can be caused by higher amount of pearlite. The highest hardness was noted for steels with 0.6% content of carbon. After sintering at 1250°C mechanical properties of steels based on Astaloy CrM were better or similar compare to this steels sintered at 1120°C.

Microstructures of materials based on Astaloy CrA powder with 0.2% C showed ferrite and pearlite. With increasing of carbon content to 0.6% C, only pearlite was observed. Low content of alloying additions caused an increase amount of pearlite in comparison with investigated variants of steels. The increased alloying elements content declining temperature of pearlitic and bainitic transformations.

Investigated steels based on Astaloy CrL powder with 0.2% C had ferritic - pearlitic structure. Steels with higher carbon concentration, 0.6%, were characterized by bainitic structure.

Increasing of alloying addition, comparison with steel based on Astaloy CrA powder, with higher carbon content – 0.6 %, caused the formation of more carbides, which slowed the diffusion transformations (pearlitic). It led to the formation of a bainitic structure [28].

Metallographic investigations of steels based on Astaloy CrM powder with 0.2%C revealed bainitic – ferritic structures. Steels with 0.6%C sintered at 1250°C produced bainitic structure. Lower sintering temperature of these steels resulted in the formation of bainitic structure. Increased content of alloying elements separated of pearlitic and bainitic transformations regions.

6. Conclusions

The studies allow the following conclusions:

1. Sintered steels based on Astaloy CrM alloy powder showed the best mechanical properties.
2. Higher sintering temperature resulted in a significant increase in mechanical and plastic properties for all alloy variants.
3. In steels based on Astaloy CrA powder with 0.2% C ferrite and pearlite was obtained. With increase of carbon content up to 0.6%C, pearlite was observed.
4. Investigated steels based on Astaloy CrL with 0.2% C had a ferritic and pearlitic structure. Steels with higher concentration carbon (0.6%) were characterized by bainitic structure.
5. Metallographic investigation of steels on the basis of Astaloy CrM powder with 0.2% C revealed ferritic - bainitic structure. Steels based on Astaloy CrM with 0.6% C steels sintered at 1120°C and 1250°C consisted of bainitic structure.
6. The appearance of the bainitic structure caused increases of hardness in the variants based on alloy powder Astaloy CrM.
7. The best properties were obtained for steels based on Astaloy CrM with 0.6% C sintered at 1250°C in the atmosphere 5%H_2-95%N_2, but good alternative for steels based on Astaloy CrM with 0.6% C can be steel based on Astaloy CrL powder with 0.6% C sintered in the same conditions.
8. Steels based on Astaloy CrA powder exhibit similar properties to steels based on Astaloy CrL.

Acknowledgments

The financial support of the Ministry of Science and Higher Education under AGH contract no 11.11.110.299 is acknowledged.

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Received: 30 November 2015.