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Sinterhardening Process of Lean Cr-Mo Prealloyed Steel for Moderately Loaded Applications

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Sinterhardening is a highly important process in powder metallurgy due to its cost and time effectiveness. However, since the cooling rates are significantly lower than quenching in oil or water, it is necessary to use alloy systems that ensure the formation of martensite already at moderate cooling rates. At the same time, it is necessary to control the amount of alloying elements in order not to lose the cost efficiency of the process. Therefore, new low alloying materials such as Astaloy CrS should be considered as a solution. The article deals with sinterhardening process of Astaloy CrS + 0.85%C with different additions of Ni and various densities. The influence of additional high-temperature sintering on mechanical properties was assessed. The microstructure of the sinterhardening (SH) and high-temperature sintering + sinterhardening (HTS+SH) samples was studied quantitative analysis of the phase was given.

Keywords: Sintering, High-temperature sintering, Astaloy CrS, Density, Microstructure

1 Introduction

Modern and innovative technologies bring with them lower production costs, variability of shapes and dimensions, large-scale production and have a reduced impact on the environment, compared to traditional technologies [1].

Powder metallurgy (PM) is a promising technology for the cost-effective production of near-net shape components across several engineering industries [2,3]. PM steels find extensive applications in the automotive field, meeting the demand for complex and multifunctional parts, e.g. engine, transmission, brake, chassis and electromagnetic components [4,5,6,7]. To continue to expand PM into new industrial areas and applications, materials with enhanced properties produced in cost-effective way are needed. One of such methods is sinterhardening (SH) process, which includes classic sintering followed by fast cooling [8]. It allows to achieve high mechanical properties in comparison with standard sintering due to formation of a martensitic structure. One of the important advantages of sinterhardening is the relatively low distortions of the part, which allows achieving high class of dimensional precision without additional machining. This is especially important from the point of view of production costs, since machining introduces significant costs, as well as material losses, which significantly increases the price of the manufactured part [9]. Also with increasing demands on light-weight constructions, PM parts also have to be reduced in dimensions and mass which, in combination with increasing mechanical loads, leads to higher demands on the strength of the material [10]. Therefore, new cheap alloying systems are necessary, which offer excellent heat treatment response [11].

Compared with the traditional die casting process, it shows the advantages of less manufacturing processes, higher material utilization rate and higher dimensional accuracy [12,13]. In addition, PM technology can increase the supersaturation of alloying elements, refine the microstructure, and eliminate segregation of the alloys.

When evaluating materials for any application, understanding their mechanical properties is crucial, as these characteristics dictate how the material will perform under different types of loads and conditions. Whenever we select a material, it is tailored to the application. For powder metal components, several key mechanical properties should be considered, including hardness, tensile strength, yield strength and elongation [14].

Standard production furnaces allow for a cooling rate of 2÷3 $°C \cdot s^{-1}$, which requires high hardenability of the material. The simplest and cheapest way to increase hardenability is to add carbon. But large amount of C significantly reduces the toughness when chromium is used as an alloying element [15]. This means that adding higher amounts of carbon results more likely in the formation of proeutectoid cementite which embrittles the material drastically, even if present as very thin films. If this way actually the case, it should be possible to find intergranular failure on the fracture surface.

Other way to increase formation of a martensitic structure at reduced cooling rates is alloying with metals such as molybdenum, nickel, copper, and chromium [16]. These metals often tend to increase in price, especially molybdenum, nickel, which makes the price of powder material extremely unstable [17]. Therefore, the development of new materials with low alloying and sufficiently high mechanical properties is an important task in the growth of powder metallurgy [18,19].

In this article a solution and application of the sinterhardening process was developed based on a new material Astaloy CrS, produced by the Swedish company Hoganas AB. To increase hardenability and strength, additional alloying with low Ni content was used. Tensile strength greater than 900 MPa and hardness greater than 33 HRC allows the material to be successfully used in moderately loaded applications and assemblies and is also comparable to such frequently used and more expensive materials as Distaloy DH and Astaloy CrM [20].

2 Materials and Methods

The powder metallurgy process consists of mixing elemental or alloy powder, compacting the mixture in a die and then sintering or heating the resultant shape in a controlled atmosphere. Powder metallurgy is a highly developed method of manufacturing ferrous and nonferrous materials. It is a chip less working process. This process is cost effective in producing simple or complex part in manufacturing rates which can range from a few hundreds to several thousands parts per hour. Due to high cost of die and equipment this process is suitable for mass production only. The basic steps involved in the production process are:

- Preparation of powder or powders of desired composition.
- Mixing and blending – Powder are mixed thoroughly and blended to ensure desired property.
- Compacting the powders into desired shape and size.
- Sintering – Green compacts are heated at elevated temperature to create bonds between particles and-providing strength to the parts.

Samples for testing tensile strength and elongation are shown in Fig. 1. They were produced according to ISO 2740:2023 [21] and were pressed on a hydraulic press Dorst (Technologies GmbH, Germany) at densities of 7.0 and 7.2 g·cm^{-3}.

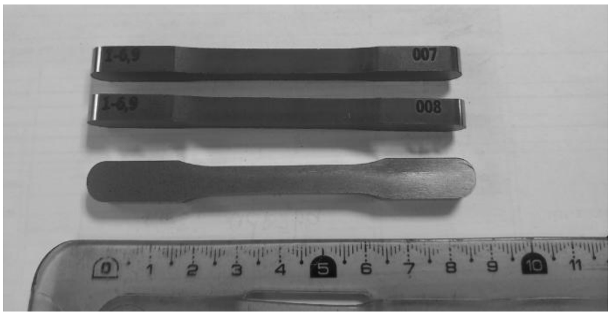


***Fig. 1** Pressed samples for testing mechanical properties*

The sinterhardening process was carried out in a Mahler conveyor belt furnace with a cooling zone (Mahler GmbH, Germany). Sintering temperature was 1 120 °C, sintering time was 20 minutes, protective sintering atmosphere was 90 %/10 % nitrogen/hydrogen mix. The frequency of the cooling fans was set to 40 Hz. High-temperature sintering (HTS) was carried out in a Cremer walking beam furnace (Cremer Thermoprozessanlagen GmBh, Germany), sintering temperature was 1 200 °C, sintering time eas 30 minutes, protective sintering atmosphere was 90 %/ 10 % nitrogen/hydrogen mix.

After sinterhardening the samples were tempered at a temperature of 200 °C for 1 hour in air. Tensile strength and elongation were measured by Hoganas on tensile machine Olssen (Tinius Olssen testing machine company, USA) according to ISO 6892:2019 [22]. Hardness was measured on universal hardness tester InnovaTest (InnovaTest Europe BV, The Netherlands) according to ISO 6507-1:2023 [23] and ISO 6508-1:2023 [24].

The samples for metallographic investigation were cut in cross sections and molded in bakelite. The microstructure of the samples was investigated in light optical microscopy. Picral ($(O_2N)_3C_6H_2OH$) was used as an etchant. The amount of phase was measured for each sample by determining the phase at 100 points from a 10x10 grid. This was repeated at 10 different locations for each sample.

The composition and densities are shown in Tab. 1. Elements Cr and Mo are added to the base material Astaloy CrS by pre-alloyed method, Ni and C are admixed.

***Tab. 1** Composition and densities of the used powder mixes*

Material	Cr [%]	Mo [%]	Ni [%]	C [%]	Compacting density [g.cm^{-3}]
Astaloy CrS-1Ni-7.0	0.85	0.15	1.00	0.85	7.0
Astaloy CrS-1Ni-7.2	0.85	0.15	1.00	0.85	7.2
Astaloy CrS-2Ni-7.0	0.85	0.15	2.00	0.85	7.0
Astaloy CrS-2Ni-7.2	0.85	0.15	2.00	0.85	7.2

3 Results

The following text summarizes the results of the experiments and measurements carried out.

3.1 Density and mechanical properties

The results of measuring the final density and dimensional change are in Tab. 2 and 3.

***Tab. 2** Dimensional change samples processed by sinterhardening*

Material	Dimensional change, tool – green part [%]	Dimensional change, green part – sinterhardening [%]	Dimensional change, tool – sinterhardening [%]	Final density [g.cm^{-3}]
Astaloy CrS-1Ni-7.0	0.128	-0.064	0.064	6.99
Astaloy CrS-1Ni-7.2	0.176	-0.078	0.098	7.20
Astaloy CrS-2Ni-7.0	0.181	-0.203	-0.022	7.00
Astaloy CrS-2Ni-7.2	0.128	-0.100	0.028	7.23

***Tab. 3** Dimensional change samples processed by high-temperature sintering + sinterhardening (HTS+SH)*

Material	Dimensional change, tool – green part [%]	Dimensional change, green part – sinterhardening [%]	Dimensional change, tool – sinterhardening [%]	Final density [g.cm^{-3}]
Astaloy CrS-1Ni-7.0	0.127	-0.463	-0.336	7.06
Astaloy CrS-1Ni-7.2	0.176	-0,435	-0.259	7.25
Astaloy CrS-2Ni-7.0	0.178	-0.627	-0.450	7.07
Astaloy CrS-2Ni-7.2	0.127	-0.431	-0.304	7.28

The final density of samples processed by high-temperature sintering and sinterhardening is higher than that of samples after sinterhardening. This is due to additional sintering at a high temperature, which activates the diffusion process more quickly and thereby increases the density to 0.05-0.07 g·cm^{-3}. The results of measuring the mechanical properties are in Tab. 4 and 5. The material Astaloy CrS-2Ni-7.2 has the greatest hardness after high-temperature sintering + sinterhardening. The hardness of samples with Ni 2 % composition is significantly higher compared to materials with Ni 1 %. The increase in hardness due to the increase in compacting density is smaller than when the Ni content is increased. The hardness of the samples after sinterhardening and high-temperature sintering + sinterhardening has a small difference, 6.1 % when measured by the Vickers method, 5.7 % when measured by the Rockwell method (HRC, HRB), which shows that additional sintering does not have a great effect on the hardness of the samples. Also, the reason for the slight difference in hardness may be carbothermal reduction of chromium oxides at higher temperatures which uses the combined carbon as reducing agent. The carbon forms CO (and some CO_2) being transferred into the gaseous phase [25].

***Tab. 4** Mechanical properties of samples processed by sinterhardening*

Material	HV10	HRB	HRC	Tensile strength Rm [MPa]	Yield strength Re [MPa]	Alongation A [%]
Astaloy CrS-1Ni-7.0	228	96	-	688	568	0.65
Astaloy CrS-1Ni-7.2	264	-	23	825	638	1.09
Astaloy CrS-2Ni-7.0	315	-	32	794	709	0.35
Astaloy CrS-2Ni-7.2	386	-	35	944	785	0.49

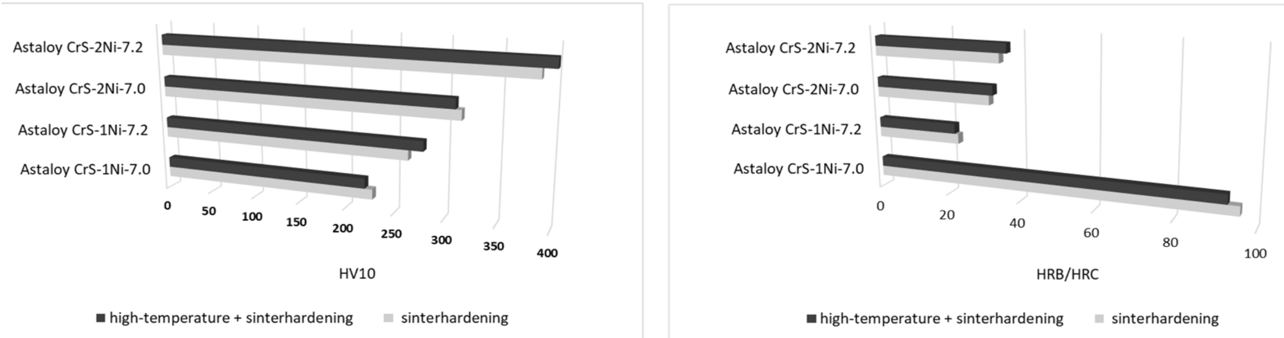
***Tab. 5** Mechanical properties of samples processed by high-temperature + sinterhardening*

Material	HV10	HRB	HRC	Tensile strength Rm [MPa]	Yield strength Re [MPa]	Alongation A [%]
Astaloy CrS-1Ni-7.0	220	93	-	795	570	1.83
Astaloy CrS-1Ni-7.2	279	-	22	929	653	2.00
Astaloy CrS-2Ni-7.0	309	-	33	1028	791	0.81
Astaloy CrS-2Ni-7.2	400	-	37	1152	832	1.08

Material Astaloy CrS-2Ni-7.2 has the highest tensile strength after high-temperature sintering + sinterhardening. Tensile strength certainly increases with increasing compaction density, Ni content and addition of high-temperature sintering. The material Astaloy CrS-1Ni-7.2 has the greatest elongation after high-temperature sintering + sinterhardening. Elongation is increased by increasing the compacting density, adding high-temperature sintering, and decreasing the Ni content. The reason for the difference in tensile strength and elongation is the difference in microstructure, which will be described below.

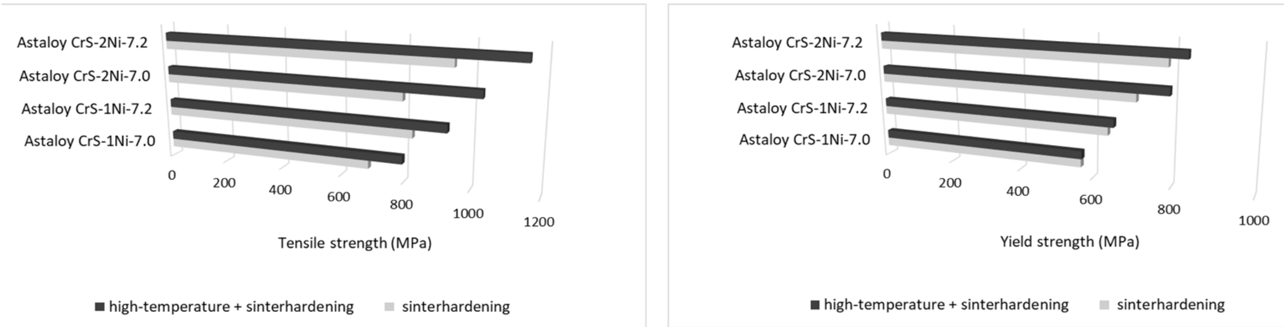
The Fig. 2a, shows a graph comparing the measured hardness values using the HV10 method for high-temperature sintering + sinterhardening. The Fig. 2b, shows a graph comparing the measured hardness values using the HRC and HRB methods for high-temperature sintering + sinterhardening. For the Astaloy CrS-1Ni-7.0 material, the HRC method cannot be used due to its very low hardness, so it was measured using the HRB method.

The Fig. 3 shows graphs comparing the mechanical properties of individual materials, Fig. 3a Tensile strength and Fig. 3b Yield strength.



a, b,

Fig. 2 *Graphs comparing the hardness of HV 10 (a,) and HRB/HRC (b,) of individual materials*



a, b,

Fig. 3 *Comparison of mechanical properties of individual materials, (a,) Tensile strength and (b,) Yield strength*

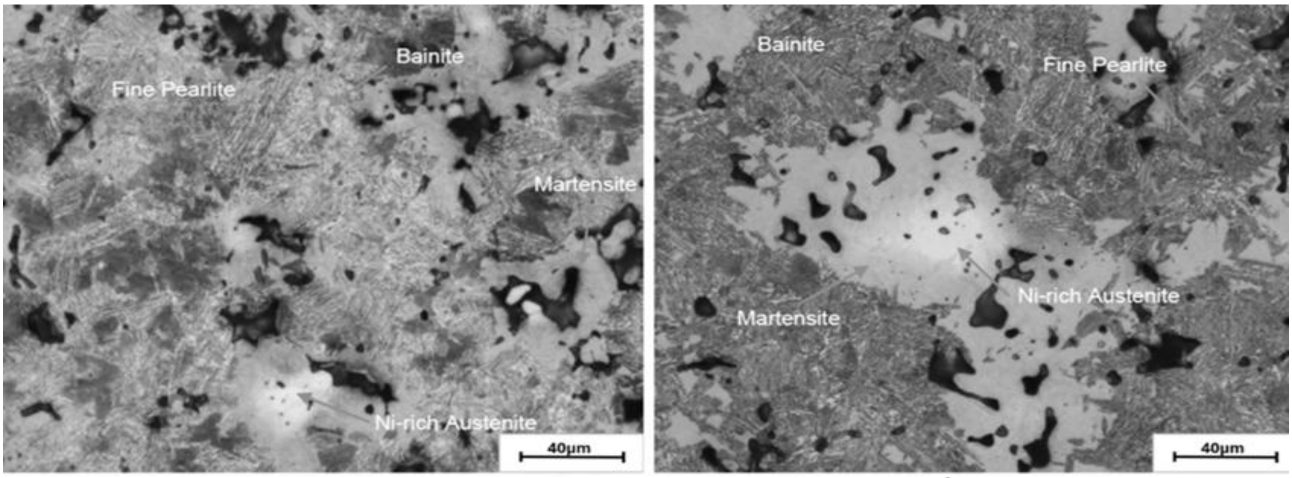
3.2 Microstructure

The microstructure of the samples is a mixture of martensite, bainite, fine pearlite and Ni-rich austenite. The phase content of the composition is in Tab. 6. There is no difference between the microstructure of the center and the surface of the part, sinterhardening proceeds without significant decarburization and oxidation of the surface. Samples with a composition of Ni 2 % certainly have a higher content of martensite, which is the main reason for the difference in hardness and elongation. Samples with a composition of Ni 1 % have low hardenability, the cooling rate during sinterhardening (≈2,5°C.sec^{-1}) is not sufficient for the formation of a large content of martensite, the structure contains a large ratio of fine pearlite/bainite, which causes less hardness, strength and greater toughness.

Tab. 6 *Phase content of samples*

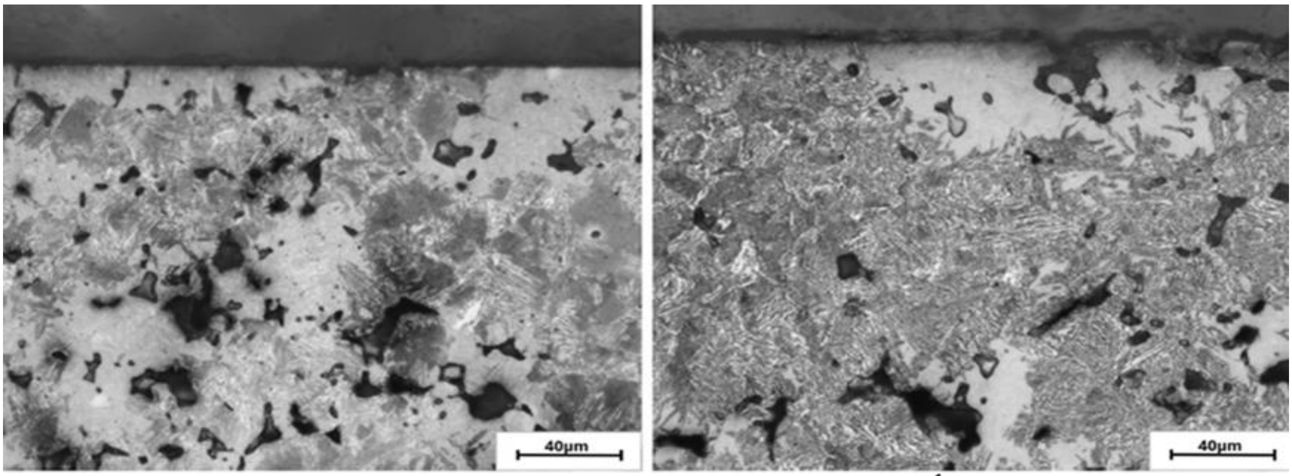
Sample	Bainite	Perlite	Martensite
Astaloy CrS-1Ni-7.2 SH	70.5%	10,9%	18,6%
Astaloy CrS-1Ni-7.2 HTS+SH	71.2%	5.0%	23.9%
	Bainit/Perlite		**Martensite**
Astaloy CrS-2Ni-7,2, SH	48.3%		51.7%
Astaloy CrS-2Ni-7,2, HTS+SH	38.3%		61.7%

The microstructure of the sinterhardening (SH) and high-temperature sintering + sinterhardening (HTS+SH) samples Astaloy CrS-1Ni-7.2 in center is shown below in Fig. 4 and in the surface is in Fig. 5.



a, b,

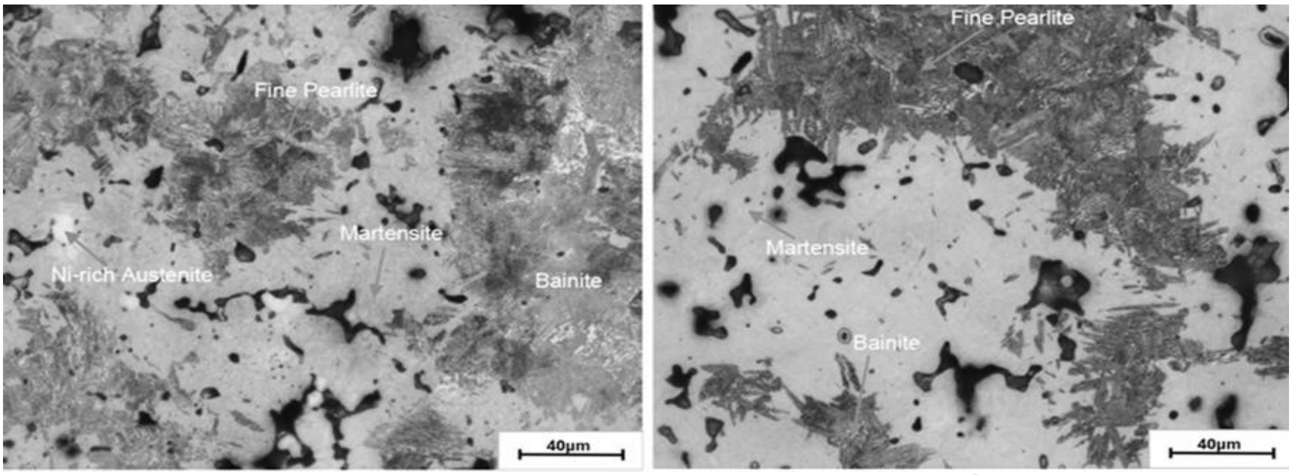
Fig. 4 *Astaloy CrS-1Ni-7.2 – (a,) SH, center, x500 magnification; (b,) HTS+SH, center, x500 magnification*



a, b,

Fig. 5 *Astaloy CrS-1Ni-7.2 – (a,) SH, suface, x500 magnification; (b,) HTS+SH, surface, x500 magnification*

The microstructure of the sinterhardening (SH) and high-temperature sintering + sinterhardening (HTS+SH) samples Astaloy CrS-2Ni-7.2 in center and on the surface is in Fig. 6 and in the surface is in Fig. 7.



a, b,

Fig. 6 *Astaloy CrS-2Ni-7.2 – (a,) SH, center, x500 magnification; (b,) HTS+SH, center, x500 magnification*

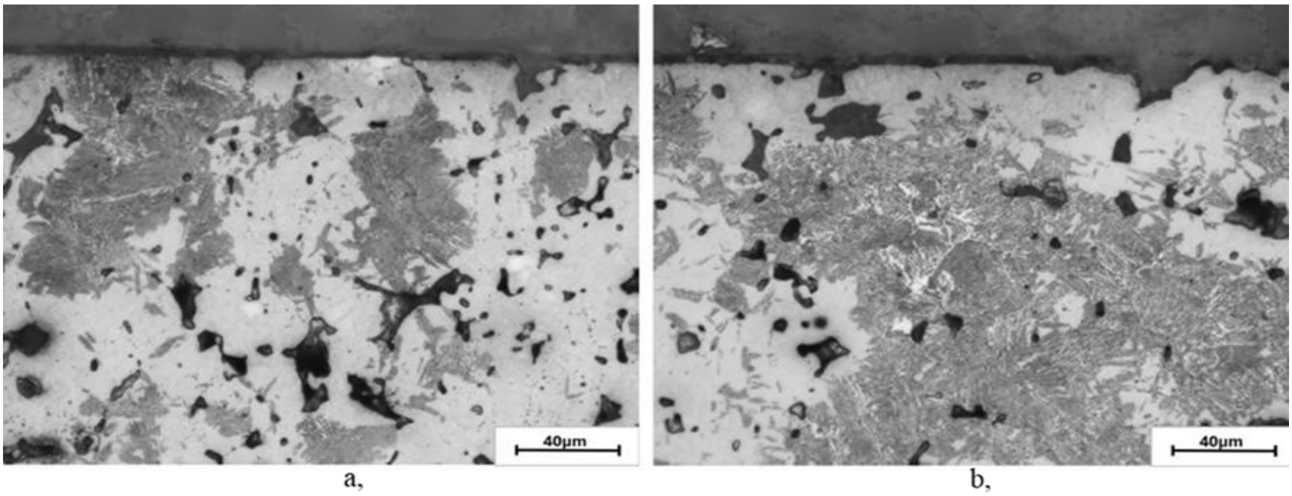


Fig. 7 *Astaloy CrS-2Ni-7.2 – (a,) SH, surface, x500 magnification; (b,) HTS+SH, surface, x500 magnification*

4 Conclusion

New sinterhadening material solution based on Astaloy CrS was studied. Lean prealloyed Cr-Mo material Astaloy CrS with addition of Ni and C can be processed by sinterhardening process with the following results:

- Martensite phase content more than 50 % can be achieved directly after sinterhardening and after combination with high-temperature sintering.
- Tensile strength greater than 900 MPa and hardness greater than 33 HRC.
- Density 7.2 g·cm^{-3} can be obtained by single compacting.

Material has great good compressibility due to low content of Cr and Mo, which provides higher mechanical properties, better tightness of materiál and possibility for stable mass production of part with complex shape. For industrial powder metallurgy production new material solution is more convenient for compacting and sinterhardening, which increases the durability of the compcting tool, facilitates quality control of the sintering atmosphere and cooling system. Astaloy CrS + 2% Ni + 0.85% C compacted to 7.2 g.cm-3 processed by high-temperature sintering + sinterhardening achieves 1 152 MPa tensile strength and 37 HRC hardness which can be compared with more expensive Distaloy and Astaloy CrM materials. Considering that the main factor in increasing the amount of martensite phase is nickel content, a further slight increase in alloying elements is planned to improve mechanical properties.

Acknowledgement

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