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# Utilisation of sinter-hardening treatment for various sintered steels

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## ABSTRACT

**Purpose:** Purpose of this paper was to present the benefits of powder metallurgy technology and development of sinter-hardening process applied to different steels including pre-alloyed Ni-Mo steels with W addition, Astaloy CrM and experimental sintered duplex stainless steels. The mechanical properties, focusing in particular on hardness and wear resistance, of two different sinter-hardened steels were described. Microstructure characteristic of produced sinter-hardened steels was taken under consideration.
**Design/methodology/approach:** Different compositions have been tested in order to investigate the influence of sinter-hardening of steels under different cooling rates on microstructure and properties. As a first group of materials Ni-Mo pre-alloyed steel powders were used, differing with the addition of tungsten and amount of carbon. Green compacts were sintered at the temperature 1120ºC for 1 hour. The next set of investigated materials was produced by mixing the Astaloy CrM powder with carbon amount of 0.6% and then compacted and sintered in the same conditions. Under sinter-hardened conditions, experimental sintered duplex stainless steels were also evaluated. After sintering, different cooling rates were applied.
**Findings:** The applied sinter-hardening process resulted with achievement of material characterized by proper microstructure. The investigation of sinter-hardened steels proved that applied process of sintering under vacuum and rapid cooling brought expected outcome.
**Research limitations/implications:** Considering the achieved outcome, it was revealed that chemical composition and applied process of steels preparation, sinter-hardening with rapid cooling, results in achievement of materials with relatively high apparent hardness and significant resistance to abrasion. Anyhow, further researches should be performed.
**Originality/value:** The paper contributes to better understanding advantages of sinter-hardening process applicable to different sintered steels.

**Keywords:** Powder metallurgy; Sintering; Low alloyed steels; Sinter-hardening

## 1. Introduction

Sinter-hardening is a good known treatment technique in field of powder metallurgy, applicable to ferrous materials with sufficient hardenability and prone to develop microstructure containing significant percentage of martensite in the as-sintered condition. The key to obtain a desired microstructure is significant cooling rate directly form sintering temperature and obviously proper alloying elements balance. The application of sinter-hardening process allows avoiding secondary heat treatment, contamination of pores in the sintered steels with quench oil and helps in subsequent surface treatment, improving the environment of working place. Ultimate tensile strength and hardness of sinter-hardened parts are equivalent and even superior to those conventionally heat treated powder metallurgy steels obtained by double pressing and sintering. Cost reducing, technical and manufacturing economy, improved efficiency of process, densities and mechanical properties, make PM products more appealing, especially in case of applications where high wear resistance is required. Sinter-hardening permits the production of powder metallurgy components having high apparent hardness and high strength and is applied for components difficult to be quenched because of their shape or dimensions [1-3]. Sinter-hardening treatment may be applied to other than martensitic microstructure materials for example sintered stainless steels what permits to obtain biphasic microstructure, composed of ferrite and austenite in duplex stainless steels, reducing in this manner cost of subsequent heat solution treatment [6-15].

Utilization of powder metallurgy technology strictly defines possible applications of manufactured parts and creates new possibilities of produced alloys. Today the technology trends for sintered parts have been made in two fronts, where one is the improvement of mechanical properties by optimizing alloy design and second front is development of manufacturing technologies leading to higher liberty in alloying methods and thus creating new applications of developed technologies for vide variety of sintered materials.

Introduction of PM steels with a success into new applications requires meeting the needs and expectations of end users for improved performance and superior efficiency than current systems. Even though every application has individual necessities, several common features and market requirements for PM steels can be listed: lower cost, closer tolerances, higher tensile and fatigue strength, higher yield strength and improved ductility [2].

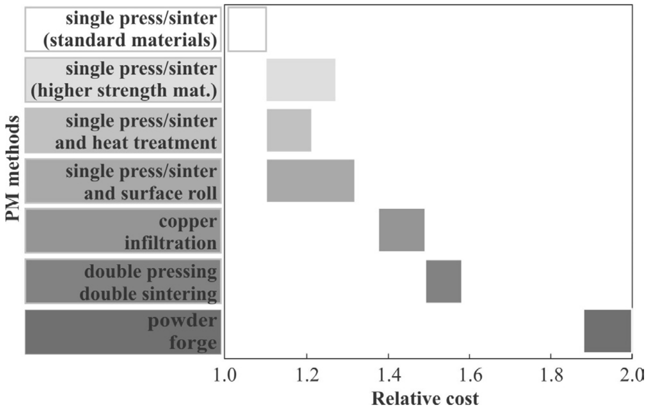

Fig. 1. Relative cost of various comparisons PM methods

Application of sinter-hardening process allows avoiding secondary heat treatment, contamination of pores in the sintered steels with quench oil and helps in subsequent surface treatment improving the environment of working place. Ultimate tensile strength and hardness of sinter-hardened parts are equivalent and even superior to those conventionally heat treated powder metallurgy steels obtained by double pressing and sintering. A comparison of the relative cost of different PM methods allows to characterize the sinter-hardening process as cost reducing (fig. 1). Technical and manufacturing economy, improved efficiency of process, densities and mechanical properties, make PM products more appealing, especially in case of applications where high wear resistance is required. Sinter-hardening permits the production of powder metallurgy components having high apparent hardness and high strength and is applied for components difficult to be quenched because of their shape or dimensions [4-15].

## 2. Experimental procedure

In present study different steels were sinter-hardened. As a first group of materials pre-alloyed steel powders were used, differing with the addition of tungsten and amount of carbon. The compositions were tested in order to investigate the influence of various tungsten additions into low 0.4% and high 0.6% carbon content of pre-alloyed ferrous steel powders. In prepared powder composition the amount of alloying elements were following: 2.00%Ni, 1.50%Mo and quantity of tungsten were different varying from 0% to 0.3% with step of 0.1%. In this manner eight different compositions were studied. Prepared Ni-Mo and Ni-Mo-W steel powders, with addition of 0.7% Acrawax C lubricant were compacted at pressure of 700MPa. Before the sintering process de-waxing was performed at 550ºC for 60 minutes in a fully nitrogen atmosphere. Sintering was carried out in vacuum furnace with argon backfilling. The temperature of sintering of green compacts was equal 1120ºC for 60min. After the sintering the samples were cooled with a rate of 2.5ºC/s directly from sintering temperature.

The next set of investigated materials was produced by mixing the Astaloy CrM powder (Fe-3% Cr-0.5% Mo, Hoganas) with carbon amount of 0.6% and then compacted and sintered in the same conditions. After the sintering, samples were cooled with different cooling rates 5.0ºC/s 3.2ºC/s and 2.2ºC/s.

Under sinter-hardened conditions experimental sintered duplex stainless steels described in detail in studies [8,15] were also evaluated. Sintered duplex stainless steels were obtained starting from austenitic X2CrNiMo17-12-2 (AISI 316L) or ferritic base powders X6Cr13 (AISI 410L) by controlled addition of alloying elements, such as Cr, Ni, Mo and Cu in the right quantity to obtain the chemical composition similar to biphasic one. Acrawax was used as lubricant in a quantity of 0.65 wt.% for all compositions produced. Samples were compacted at pressure of 800 MPa and sintered in a vacuum furnace with argon backfilling at temperature 1260°C for 60min. After sintering different cooling rates – rapid cooling 4.1ºC/s, 2.0ºC/s and slow 0.1ºC/s were applied using nitrogen under pressure.

In order to evaluate the densities of sinter-hardened steels, water displacement method was used. Microstructure was investigated using light and scanning microscopy. Hardness in the HRA and B scale of studied materials was performed. Room temperature unnotched Charpy impact test was performed on all materials.

The investigation of wear resistance was performed through pin-on-disk and then on disk-on-disk tests. In the case of pin-on-disk, the abrasive media was a 3 mm diameter pin machined from WC-Co and the discs were prepared from analyzed materials. According to the wear resistance of achieved steels, 15N and 25N loads were applied during experiment; the rotation speed of the disc was 0.26m/s. Samples were tested on both sides and weighted several times up to 1000 meters of total sliding distance. Disk-on-disk test was done on device with 500N and 1000N of load (for samples with low and high concentration of carbon, respectively). Analyzed disc ran against the abrasive disk machined from WC-Co with the 10% of difference between their rotation speeds. The speed selected for driver was 0.2m/s and 0.18m/s for driven disc. During the test, the weight change of samples was measured using weight with the sensibility of $10^{-4}$g. The measurements were done after each 100m up to 500m of the total sliding distance.

## 3. Results and discussion

Obtained results in terms of sintering densities were included in the range from 7.16 to 7.26Mg/m$^3$ for sinter-hardened Ni-Mo-W steels. For steels without addition of tungsten, 0.6 and 0.4% C, the density was equal 7.25 and 7.26Mg/m$^3$, respectively. Amongst materials with different additions of tungsten, the highest density equal 7.23Mg/m$^3$ obtained the steel marked as 2B containing 0.2%W and low carbon content. The addition of tungsten in analyzed steels strictly influences and lowers sintered density.

The sinter-hardening process determined the formation of mainly martensitic microstructures with small amounts of lower bainite and retained austenite in hardened Ni-Mo-W steels (fig. 2). Microstructure observations revealed Ni-rich austenite regions and heterogonous distribution of W, which create agglomerates in the vicinity of pores. The dimension of tungsten agglomerates can be presented as a function of the amount of added tungsten and grows as tungsten addition increases.

For sintered Astaloy CrM density about 6.9Mg/m$^3$ and independently of applied cooling rates proper microstructure composed of martensite due to efficient carbon content was obtained.

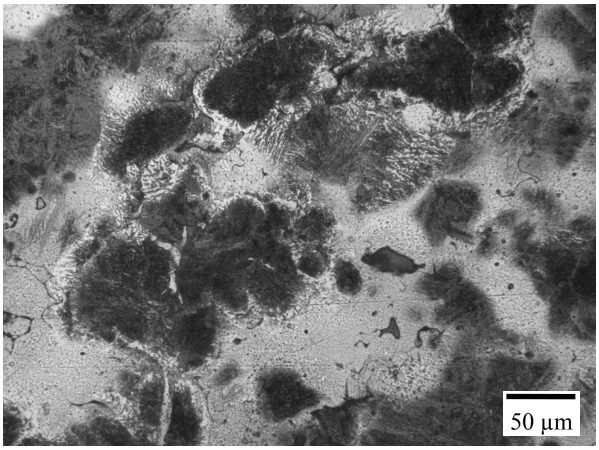

Fig. 2. Microstructure of sinter-hardened Ni-Mo steel with addition of 0.3%W

Utilization of sinter-hardening process in case of sintered duplex stainless steels results in satisfactory density in as-sintered condition included in the range of 6.95 to 7.25Mg/m$^3$ and depending on stainless steel base powder portion and addition of alloying elements. The main advantage of sintering method is obtaining proper biphasic microstructure directly after sintering and rapid cooling, which depends on modification of cooling rate. Impact energy of sintered duplex steels cooled at 4.1ºC/s reaches from 87 to 99J for compositions based on austenitic powder however for composition based on ferritic powders shows the highest values; 151J of impact energy was measured for composition with equal amounts of ferrite and austenite. Obtained results are in accordance with quantity rate of austenite and ferrite in the microstructure. Slower cooling rate causes the decrease of mechanical properties due to precipitation of intermetallic phases. Obtained mechanical properties are sufficient too ensure good tensile strength and impact properties as well as corrosion resistance ready to be introduced in industrial practice when using rapid cooling at 4.1ºC/s and 2.0ºC/s. Application of this heat treatment method, in case of stainless steels, leads to obtain precipitate free microstructure that has also influence on decrease of corrosion properties.

The hardness of as-sintered Ni-Mo and Ni-Mo-W steels differed according to the carbon level. Increase of carbon amount influences the increase of apparent hardness which for steel with 0.4%C was approximately 90HRB, while for 0.6% of carbon rose to 100HRB. The addition of tungsten lightly influences apparent hardness increase due to its agglomerations behaviour. Mechanical properties and especially wear resistance are in great interest of sinter-hardened steels. The evaluation of performed pin-on-disk results revealed that, apart from higher carbon content, addition of tungsten leads to significant improvement of wear resistance of investigated Ni-Mo-W steels. Wear resistance evaluated in pin-on-disk and disk-on-disk tests revealed increase of resistance to abrasion with increase of tungsten addition, for both cases 0.4 and 0.6%C. The highest relative mass loss in pin-on-disk test achieved the steel without addition of tungsten and low carbon content. Disk-on disk test allowed confirming that the Ni-Mo-W sinter-hardened steel with addition of 0.3%W and 0.4%C is more resistant to abrasion when comparing to the other containing lower tungsten. The composition of high addition of carbon, 0.2% and 0.3% of tungsten results with great improvement of wear resistance (relative mass loss noted was 0.25 and 0.21%, respectively).

Tungsten addition influences impact properties of Ni-Mo steels causing decrease of impact energy with increasing its content. This behaviour is more evident in case of steels with lower carbon content. Maximum impact energy value equal to 26J was obtained for steels with 0.6%C and without tungsten addition. Fractography analysis demonstrates that fracture surfaces of all steels are a mixed type of ductile and brittle fracture. In all studied steels the brittle cleavages of martensitic microstructure and tungsten agglomerates were revealed (fig. 3).

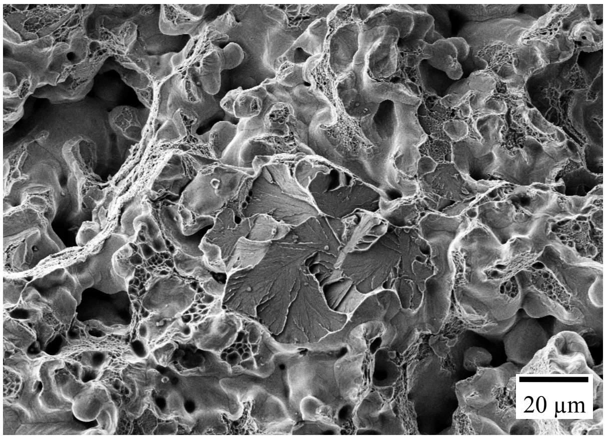

Fig. 3. SEM image of fracture surface of high carbon Ni-Mo steel with addition of 0.3%W (3A)

Sinter-hardened Astaloy CrM in terms of impact properties obtained values from 12.6 to 18.2J of impact energy due to martensitic microstructure and little underrated density. The microharness of manufactured steel reaches 585HV0.1 while for Ni-Mo sinter-hardened steel about 280HV0.1 and raises to 450HV0.1 with increase of tungsten addition.

## 4. Conclusions

Sinter-hardening is an increasingly popular technique that offers an alternative method through hardening the powder metal components without the application of traditional austenitisation, oil quench and tempering cycle. The sinter-hardening process requires the compaction of PM component, sintering and tempering cycle, that needs to cool parts from the sintering temperature at a rate sufficient to transform a significant portion of the material matrix into martensite for selected materials or to stop proper microstructure created in sintering stage and keep it until the end of sintering as in sintered stainless steels.

Basing on performed researches of utilization of sinter-hardening treatment for Ni-Mo and Ni-Mo-(W) steels, it was revealed that chemical composition and applied process of steels preparation, sinter-hardening with the cooling rate 2.5ºC/s, results in achieving materials formed of mainly martensitic microstructures with small amounts of lower bainite and retained austenite, with relatively high apparent hardness and significant resistance to abrasion. Studied materials show good resistance to abrasion which could place them among materials in the specific field of application, especially where this feature is desired and determines their use. The evaluation of obtained microstructures specifies that tungsten was distributed preferentially, observed as accumulations in the proximity of pores. In the same time, addition of tungsten influences decreasing of mechanical properties what might be a fault of poor tungsten distribution in the material matrix. Addition of tungsten into Ni-Mo steels influences the impact properties causing decrease of impact energy with increasing its content, causing heterogeneous regions in pore vicinity however, further studies should be performed.

Sinter-hardened Astaloy CrM revealed martensitic microstructure under applied cooling rate resulting in high apparent hardness and wear resistance. The microharness of manufactured steel reached 585HV0.1 while for Ni-Mo sinter-hardened steel about 280HV0.1 and rose to 450HV0.1 with increase of tungsten addition.

The application of sinter-hardening process thus achieving fast cooling rate directly from sintering temperature has enabled precipitates free microstructure of sintered duplex steels in one sintering cycle. According to the achieved results, it was affirmed that the applied sintering method as well as powder mixtures preparation allows for manufacturing the sintered duplex steels with proper biphasic microstructure and desired balance between phases. The applied producing method of sintered duplex stainless steels and used sintering cycle prove their advantage in case of mechanical properties, and what is more important, it seems to be very promising for obtaining a balanced duplex microstructure, working also with cycles easy to be introduced in the industries.

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