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Effect of alloying elements on the mechanical behavior and wear of austempered ductile iron

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Abstract – This paper treats the effect of alloying elements on the modification of the microstructure and properties of austempered ductile iron. The basic cast iron was elaborated in an induction furnace, its solidification shows a ferrite-pearlitic structure. This cast iron was alloyed with Mn, Ni, Mo and V. The samples were cast in the form of cylindrical bars of 22 mm in diameter and 300 mm in length. They have undergone a bainitic heat treatment type. Microstructures were characterized by optical microscopy, "SEM" and "XRD". Tensile strength, hardness, microhardness, resilience and wear were determined and correlated with the microstructure. In the treated condition, metallographic study shows that the structures were formed of bainitic ferrite and feathery upper ausferrite. The results of mechanical tests and wear show that the cast irons studied achieve superior properties.

Key words: Austempered ductile iron / ausferrite / bainite / bainitic ferrite / bainitic heat treatment

Nomenclature

ACI	Alloyed cast iron
ADI	Austempered ductile iron
BCI	Basic cast iron
HRB	Rockwell-B Hardness
HV	Vickers Hardness
SEM	Scanning Electron Microscope
XRD	X-Ray Diffraction
Materials symbols	
C	Carbon
Cu	Copper
Fe	Iron
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
Ni	Nickel
P	Phosphorus
S	Sulfur
Si	Silicon
V	Vanadium

1 Introduction

Austempered ductile iron is obtained by heat treatment of the bainitic type. The principle is to give it a bainitic treatment with austenitizing between 810–982 °C, followed by a staged quenching. This treatment has an effect on obtaining a bainitic matrix type to ensure a stable microstructure and permits to achieve mechanical properties comparable to those of some high strength steels. These properties are related to its bainitic microstructure [1–6]. This new family of engineering materials also offers great potential for cast parts in many applications. "ADI" is actually represented as an attractive alternative to steel. It shows high toughness, excellent wear resistance, and cost less than that of steel casting. Because of their superior properties and low production cost, "ADI" has been increasingly used for industrial parts such as gears, crankshafts and cylinder heads [7]. From previous research [8–12], it was concluded that the microstructure and properties of ADI are associated with the chemical composition and the parameters of the production process stages such as melting method and the technology of heat treatment. Thus the principal factors affecting the mechanical properties of "ADI" are the matrix structure, such as the presence of ferrite and austenite, existence and distribution of carbides and martensite in the microstructure and graphite morphology, such as the size and circularity of graphite nodules.

In this paper, the main objective of the present research is to investigate the correlation between microstructure, from one side, mechanical properties, and wear resistance of low alloyed "ADI" from the other side. The effect of alloying elements on the formation of the microstructure and mechanical properties of "ADI" has been

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Table 1. Chemical composition of experimented cast irons (wt, %).

Irons	C	Si	Mn	P	S	Ni	Mo	V
BCI	3.50	2.175	0.430	0.034	0.0073	0.099	0.011	0.008
ACI	3.50	2.175	0.930	0.034	0.0073	1.599	0.511	0.108

studied in order to improve these properties for the manufacture of agricultural tractor parts in particular front and rear axles, ploughshares, gearbox, pinions, transmission shafts and crankshafts. The best mechanical properties such as microhardness, hardness, yield strength, tensile strength, elongation, resilience and wear resistance were found based upon various structural and mechanical characterizations based upon alloying elements such as Mn, Ni, Mo and V added in the basic cast iron. "ADI" constitutes ferrite and austenite as a matrix often referred to as an ausferritic microstructure. Such a dual phase microstructure confers a high strength with favourable hardness. Ductile cast iron can possess ausferritic structure by alloying addition together with austempering treatment. A two-stage heat treatment is employed for "ADI", austenitizing and austempering [10]. Microstructure has to do with the alloying elements, many of these elements define the matrix microstructure and mechanical properties [11]. These alloying elements added to nodular irons are of particular interest for the manufacturing of mechanical parts, because of benefits to the resulting mechanical properties [12].

2 Materials and experimental methods

2.1 Elaboration of the alloyed ductile iron and samples casting

The ductile iron destined to "ADI" was elaborated in an induction furnace. The spheroidal form of carbon graphite and refining of the structure were produced by a mixed treatment of spheroidization by the Mg and inoculation by the Si with 0.6% of Fe-Si-Mg containing 45% Si and 10% Mg using the sandwich technique. The melt of iron was then alloyed with 0.5% Mn, 1.5% Ni, 0.50% Mo and 0.10% V and cast at 1450 °C into self-hardening sand moulds. The samples were cast in the form of round cylindrical bars of 22 mm in diameter and 300 mm in length. In order to elaborate "ADI" with required mechanical properties, those alloying elements must play roles to increase the temperability and avoid pearlite formation as well as stabilize austenite during austempering heat treatment. In that way, ductile cast irons can produce an austenite and therefore ausferrite phase can be easily obtained. Mn, Mo and V play a significant role in increasing hardenability of ductile irons, Mo with V were alloyed expecting suppression of pearlite formation. A concentration of Ni and Mn in cast iron may affect tensile strength and quenchability of "ADI" as well as decreasing of elongation [10, 13]. The chemical composition of experimented cast irons elaborated is reported in Table 1.

2.2 Heat treatment

The samples were austenitized at 830 °C in a gas furnace for 60 min, then soaked in a salt bath at 550 °C for 60 min. At the end, the samples were cooled at room temperature. This optimised treatment was chosen so that it is considered as a dual matrix heat treatment, which had an advantage of controlling the ausferrite and ferrite volume fractions. It is preferable to austenitize at a lower temperature such as 830 °C. This will also give a refined microstructure. Increasing austenitizing temperature is known to increase the carbon content of the austenite and coarsen the microstructure. In other hand, the driving force for the first stage process of austempering decreases with increasing austenitizing temperature. Due to this, at higher austenitizing temperatures, there will be a considerable amount of martensite containing segregated regions at the prior austenite grain boundaries. Such a microstructure results in poor mechanical properties, and is not desired [10, 14]. At 550 °C, the hardness is not too elevated and ADI keeps its ductility.

2.3 Metallographic study

The metallographic study was performed on an optical microscope equipped with a camera type "LEICA" and a scanning electron microscope type "JEOL.JSM.6390LV". Metallographic examinations was carried out on the samples taken from bars, these samples were attacked at 4% nital.

2.4 X-ray diffraction

Phases analysis was carried out using the X-ray diffraction method and a "Bruker D8 ADVANCE" X-Ray diffractometer using Cu anode with a wavelength of 0.15406 nm. The ferrite and austenite were determined by the direct comparison method using the integrated intensities of the {110}, {200} and {211} planes of ferrite and the {111}, {200} and {220} planes of austenite [15,16] and using High Score software.

2.5 Mechanical tests

A Vickers microhardness tester type "Zwick/ROELL ZHV10" was used to determine the microhardness. The tests were carried out using 0.1 kg load for 15 s loading period. Six tests were performed for each phase of the specimen and the average was taken. The used method of measuring hardness was "HRB". Tensile tests were performed at a strain rate of 8×10^{-3} s^{-1} on a "Zwick/ROELL Z100" testing machine, three samples were tested for each cast iron and the average was taken, the tests were carried at 20 °C. Resilience tests were performed using "SINTCO" type machine.

2.6 Wear test

In this study, the quantity of lost material was determined after a passage of the specimen on a disk, on

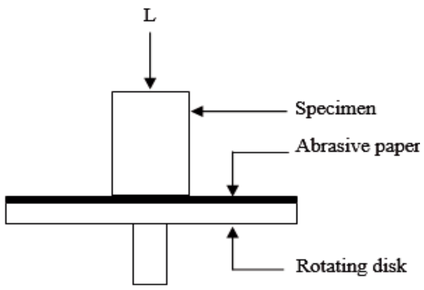


Fig. 1. Principle of wear test.

which a silicon carbide abrasive paper (800 grit) was fixed. It travels a total distance of 420 m at 80 rotations per minute. The applied load "L" was 12.4 N. Figure 1 shows the principle of the wear test. 6 mm diameter and 10 mm long specimens were used for the test. After an initial run of 6 min for each specimen, the weight of each specimen was measured using a 0.1 mg precision scale. After wear test, each specimen was weighed to determine the weight loss. Three tests were effected for each specimen, the weight loss was represented by the calculated average of these three tests.

3 Results and discussion

3.1 Metallography

From the microstructures shown in Figures 2 and 3 it can observe the microstructure of the basic cast iron "BCI" before bainitic heat treatment (Fig. 2a) formed by ferrite and pearlite where the ferrite surrounds graphite nodules. This structure shows that a ferrite rate more prominent than the perlite one. The morphology of graphite nodules is wholly spherical. After bainitic heat treatment, the structure of the basic cast iron is formed of the bainitic ferrite and upper ausferrite in the form of condensed feathers with a predominance of bainitic ferrite (Fig. 2). The structure in the treated condition is finer than that one obtained in the cast condition.

The alloyed cast iron "ACI" before bainitic treatment (Fig. 3a) has a ferrite-pearlitic structure. Compared to the basic cast iron, the alloyed cast iron structure exhibits an increase of pearlite amount. This is due to high rates of Ni (1.5%) and Mn (0.5%). The morphology of graphite nodules in the microstructure of the cast iron is entirely spherical. In the treated condition, the microstructure of this cast iron (Fig. 3b) is formed of bainitic ferrite in large amount and of feathery upper ausferrite. The refining effect of alloying elements (Mn and Ni) is not observed in the alloyed cast iron. The morphology of graphite nodules in the microstructure of the cast iron remains entirely spherical.

The observation with a scanning electron microscope of the "BCI" and "ACI" shows that their structures (Figs. 4a and 4b) present a matrix formed of bainitic ferrite and feathery upper ausferrite. This observation shows in a remarkable manner the appearance of white bright zones caused by the maintaining time not prolonged to the

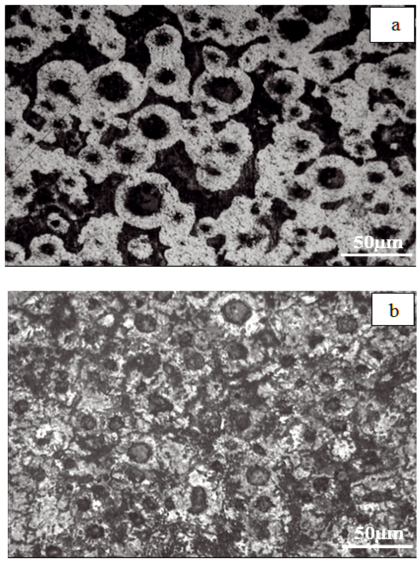


Fig. 2. Microstructures of basic cast iron. (a) In the cast condition. (b) In the treated condition.

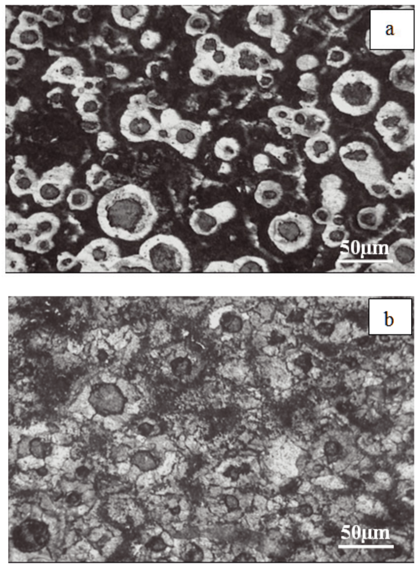


Fig. 3. Microstructures of alloyed cast iron. (a) In the cast condition. (b) In the treated condition.

austempering temperature, or can be caused by the segregation of manganese (0.5%). These white bright zones probably consist of martensite, retained austenite and carbides [17–19].

3.2 X-ray diffraction

The X-ray diffraction profile of austempered samples of the basic and alloyed cast irons is shown in Figure 5. The specters represent the diffracted intensity depending of diffraction angle 2θ. From these spectres, it can see ferrite peaks representative (110), (200), (211) and (220) crystallographic planes. In addition to the ferrite, the X-ray data showed the existence of graphite, retained

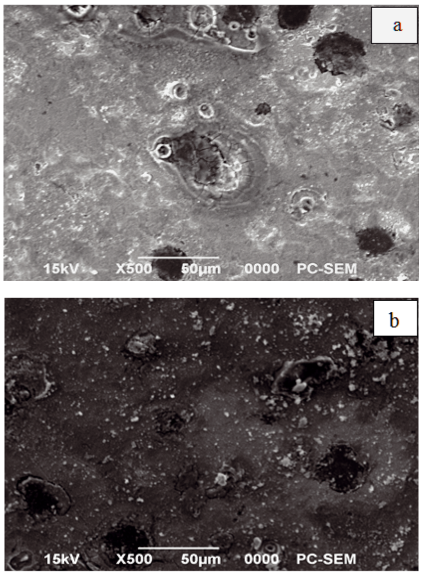


Fig. 4. Microstructures by SEM in the treated condition. (a) Basic cast iron. (b) Alloyed cast iron.

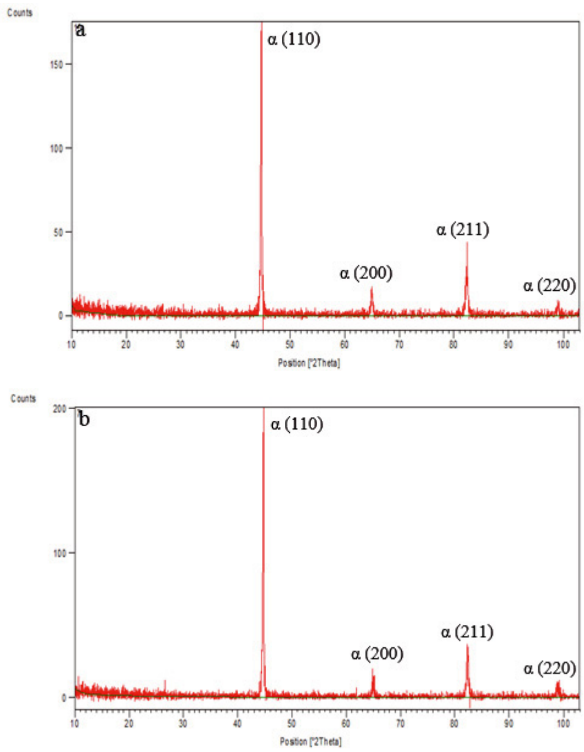


Fig. 5. X-ray diffraction specters: basic cast iron (a); alloyed cast iron (b).

austenite and carbides in these samples. Austenite associate with the ferrite can give a harder phase called ausferrite and carbides precipitation can cause an increase in hardness and reduction in ductility.

3.3 Microhardness

Microhardness measurements (Fig. 6) of microstructural constituents of the basic cast iron have given a ferrite of 132 HV and pearlite of 214 HV in the cast condition. In the treated condition, other microstructural constituents were formed with 205 HV for bainitic ferrite and 306 HV for feathery upper ausferrite. For alloyed cast iron "ACI", in the cast condition the microhardness of the ferrite is 151 HV and that of pearlite is 273 HV. After austempering treatment, it is 229 HV for bainitic ferrite and 353 HV for feathery upper ausferrite. Compared to the basic cast iron, an increase of microhardness of various microstructural constituents is observed before and after treatment. This can be explained by the effect of Mn and Ni on cast irons elaborated in a positive manner because of the change of the structure and formation of carbides that cause structural hardening.

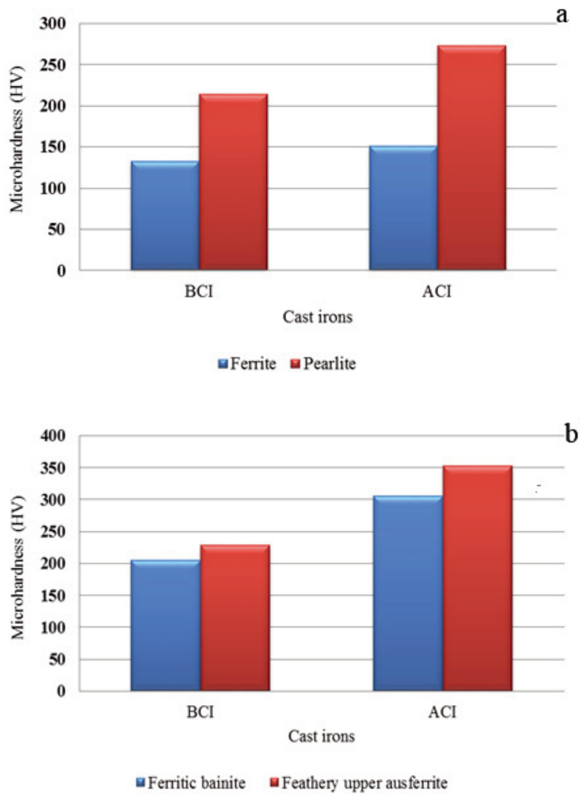
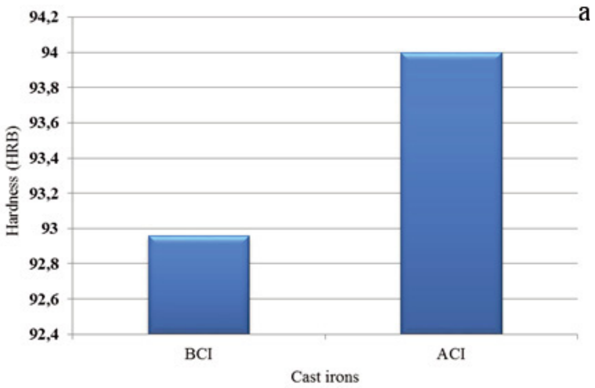


Fig. 6. Microhardness of cast irons studied. (a) In the cast condition. (b) In the treated condition.

3.4 Hardness

Figure 7 presents the hardness results before and after bainitic heat treatment. In the cast condition (Fig. 7a), the hardness of the "BCI" is 92.6 HRB and that of "ACI" is 94 HRB. In the treated condition (Fig. 7b), the hardness reached 95.5 HRB for "BCI" and 98.6 HRB for "ACI". It is noticed that there is a remarkable increase in hardness before and after heat treatment, the hardness of "ACI" is superior then that of "BCI" in both cases. This may be due to the variations in chemical composition by addition of alloying elements that favour formation of carbides causing structural hardening and the change of



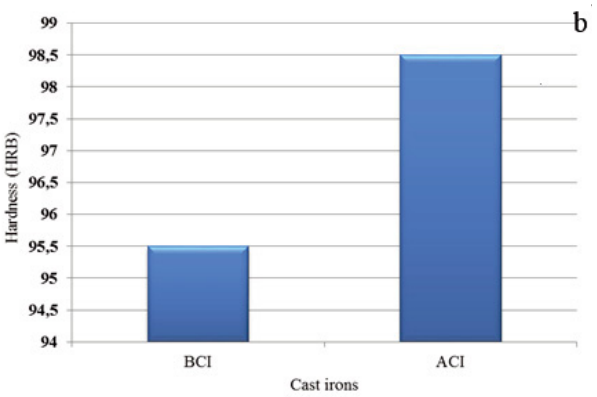


Fig. 7. Hardness of cast irons studied. (a) In the cast condition. (b) In the treated condition.

the structure by appearance of harder phase called upper ausferrite.

3.5 Yield strength, tensile strength and elongation

The results of the yield strength, tensile strength and elongation are shown in Table 2. The yield strength of the basic cast iron "BCI" is 525 MPa. An increase (601 MPa) is observed for alloyed cast iron "ACI" as a result of the addition of Mn (0.5%), Ni (1.5%), Mo (0.5%) and V (0.1%). This may refer to presence of elements that favour formation of carbides. The tensile strength of the basic cast iron is 707 MPa. The growth of the resistance of alloyed cast iron to 756 MPa is due to the increased Mn content to 0.5% and that of Ni to 1.5%. These two elements improve the quenchability of cast iron and thereby promote this increase. This growth in resistance is caused by the dissolution of these elements in the solid solutions and structural hardening resulted by formation of carbides. The elongation of the "BCI" is 4.63%. The elongation of "ACI" (2.5%) has decreased relative to the basic cast iron. The lower elongation of "ACI" is related to the fact that this material contains carbides due to alloying elements. These carbides are known to reduce the ductility.

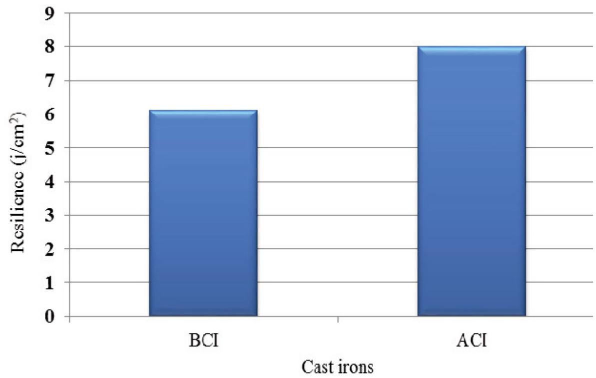


Fig. 8. Resilience of cast irons in the treated condition.

Table 2. Yield strength, tensile strength and elongation of cast irons in the treated condition.

Cast irons	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
BCI	525	707	4.63
ACI	601	756	2.50

3.6 Resilience

The study of the impact resistance of "ADI" elaborated was carried after bainitic heat treatment. The results of these tests are illustrated in Figure 8. The basic cast iron has a resilience of 6.12 $J.cm^{-2}$. This characteristic achieved 8 $J.cm^{-2}$ for alloyed cast iron due to the addition of 0.5% Mo and 0.1% V. These elements create carbides that cause structural hardening.

3.7 Wear

The wear resistance of "ADI" was determined after austempering treatment. The test results are shown in Figure 9. These results show that the weight loss of the basic cast iron "BCI" under the used conditions is 0.043 g. The weight loss of the alloyed cast iron "ACI" is 0.019 g. A net improvement of this characteristic compared to the basic cast iron is observed. This improvement is due to the addition of alloying elements, which are dissolved in the solid solution and create carbides causing structural hardening of the cast iron. When the abrasives are forced to press into the iron surface and slide along it, wear mechanism will occur. The wear rate of the irons can be affected by three factors. The first factor is the applied load affecting the pressing in depth of abrasives that can accelerate the sliding wear of iron. As the applied load increases, the sliding wear of the iron will become more and more marked [20]. The second factor is the microstructure and properties of the cast irons. The ausferritic matrix is ductile, it gave the wear rates which can be explained by their low hardness. The last factor is the graphite. The wear of irons was caused by their graphite phases. The graphite phase caused the increased wear rates of the irons by accelerating the wear of matrices on the surface. In fact the graphite, being with low strength, cannot resist the elastic strain caused by wear stresses [20–22].

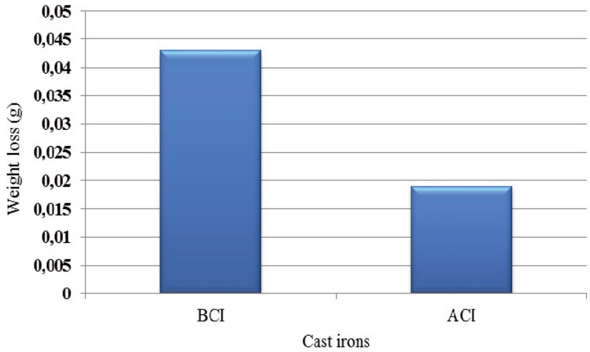


Fig. 9. Weight loss of cast irons in the treated condition.

4 Conclusion

The cycle of bainitic heat treatment is a "dual-phases" type, which contributed to the constitution of a matrix composed of two phases ferrite and ausferrite. The optical microscope observation shows that the cast irons have structures formed of bainitic ferrite and feathery upper ausferrite. The observation in scanning electron microscopy shows that there are white bright zones caused by the maintaining time not prolonged to the austempering temperature, or can be caused by the segregation of manganese, their aspects are similar to those of carbides precipitated during austempering treatment or during martensitic structures tempering. Compared to the basic cast iron, an increase of microhardness of various microstructural constituents was observed before and after treatment. This can be explained by a higher content of manganese increased to 0.5% and that of nickel to 1.5%. The hardness of alloyed cast iron is greater compared to the basic cast iron, this is due to the increase of the Mn and Ni content. The alloyed cast iron has reached a higher tensile strength than that of the basic cast iron with an important ductility, result of the addition of Mn (0.5%), Ni (1.5%), Mo (0.5%) and V (0.1%). The same ascertainment can be made for resilience. For the wear test, it is noted that the weight loss decreases with the addition of the alloying elements compared to the basic cast iron.

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