Cast Steel-SiC Composites as Wear Resistant Materials

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In the present paper the possibilities of making and applying of cast-in-carbide composites based on carbon steel and SiC, for the production of wear resistance machine parts such as mill hammers, escavator teets, etc. are studied. Materials usually used for the making of these wear resistant parts, the high-alloyed Cr-Mo steels, have shown very good results in practice, and considerably better safety of work of different devices in which these materials have been built in.

However, wear resistant parts used in mining, industry, civil engineering and traffics are in the exploitation exposed to the strong abrasive acting of the silica, corundum, feldspath and other minerals, and by this, strikes often occur in present stones and rocks. These strikes are especially dangerous because they can lead to breakdown of the construction part or complete device, since mentioned materials have relatively small impact toughness. The best variant of the construction is to make the wear resistant parts of the material which, besides hardness, possess high impact toughness, dynamic strength and fracture toughness. So far, used materials, mostly high-alloyed Cr-Mo steels, do not have this combination of the properties, and the aim of this research was to check the possibility of production and application of the new MMC materials based on steel matrix and SiC as reinforcement particles, which have just such characteristics. The optimized content and disposition of SiC particles in the steel combine extreme hardness and wear resistance of casting surface rich in SiC, with high strength and toughness of metal base.

Keywords: *metal matrix composites (MMC), cast-in-carbide composite, SiC reinforcement.*

1. INTRODUCTION

Rapid development and application of new wear resistance materials has started by the end of the sixties and in the beginning of the seventies of the past century, as a result of studying of friction and wearing process, systems of strain, material destructions mechanism and, generally, development of material sciences.

Materials which are today usually used for making of the parts exposed to abrasion and corrosion-abrasion wear are high alloyed Cr-Mo white iron and martensitic steels alloyed by chromium and molybdenum. High alloyed Cr-Mo steels which sometimes add small quantities of vanadium or the wolfram in practice have shown very good wear resistance and considerably larger safety of work of different machines, so that today they are widely use for making of mill balls, excavators and roto-excavators teeth, lining and partition plates in mills and similar parts.

However, wear resistance elements in mining, process industry, civil engineering and traffic are, besides abrasive action of silica, corundum, feldspath, basalts and other mineral particles, very often exposed in the exploitation to the mechanical blows and impulse loads. These blows are very dangerous because they can lead to breakdown of the construction elements or damage of a complete device, since these materials have relatively small impact toughness. The best variant of constructions is to make them using the material which, besides hardness, possesses significant impact toughness, fracture toughness and dynamic strength. Commonly used wear resistance materials, mostly alloyed steels and irons, have not this combination of properties, so the aim of this work was to investigate the possibilities of production and application of new, steel matrix composite materials which have just such characteristics. Besides this final aim, the task of this work was also to establish the most appropriate way of adding a carbide component in the steel, as well as to study phenomena which simultaneously take place.

2. EXPERIMENTAL DETAILS

Steel-SiC *cast-in-carbide* (CIC) composites present the metal matrix composites (MMC) which consist of the carbon or the low alloyed steel as the metal matrix, in which carbide grains of different dimensions, from 0.2 to 5 mm, was poured as the reinforcement. For the purpose of our research two types of steels S355JR (Č0561) and 50Mn7 (Č3134) have been used as the metal matrix and silicon carbide has been the reinforcement. Steel S355J0 was chosen because of its

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low price and relatively good impact toughness in respect to high alloyed Cr-Mo iron alloys, and 50Mn7 is usual steel grades used for making wear resistant elements. Chemical compositions of used types of steels are given in the Table 1.

Table 1. Chemical composition of steels

Type of steel	Content of alloy elements [%]					
	C	Mn	Si	P	S	N
S355JR	0.25	≤ 1.60	≤ 0.55	≤ 0.045	≤ 0.045	≤ 0.009
50Mn7	0.45 – 0.55	1.6 – 2.0	≤ 0.4	≤ 0.040	≤ 0.040	≤ 0.007

Physical and mechanical properties of used silicon carbide have the following values:

- density: 3200 kg/m^3,
- filling mass: 1250 – 1400 kg/m^3,
- thermal dissociation point: 2300 °C,
- Mohs hardness: 9.3,
- crystallographic lattice: hexagonal α and β phase and
- grain size composition: 0.6 and 1.6 mm.

All experimental pouring has been performed on castings which have been exposed to wear in the exploitation, and which are in the production program of *Livnica Ljig* foundry. We chose shovel for asphalt mixer and tooth for the excavator SRS 1700, (*REIK Kolubara*). Patterns for moulds making for these castings production are presented in Figure 1.

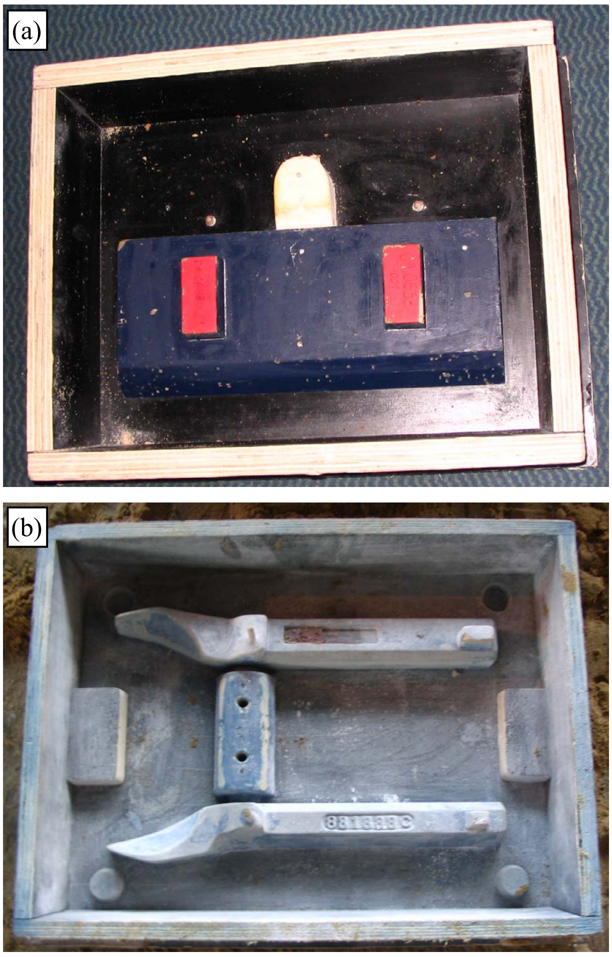

Figure 1. Patterns for moulds making: (a) shovel for asphalt mixer and (b) excavator tooth SRS 1700

2.1 Forming of composites

Optimizations of procedure for imputting of carbide in molten steel and forming composites have presented most important and most sensitive phase of this research. Technological parameters we varied were:

- Grain size composition of silicon carbide (0.6 and 1.6 mm);
- Content of carbide (3.0, 5.0 and 7.0 wt. %) and
- Mode of silicon carbide inputting in molten steel (the inputting in the pouring ladle and mixing by whirling, and inputting in the cavity of the mould in the combination with whirling).

In metal matrix composites, connections between the reinforcement and matrix are realized across the contact surface, named interface, and due to its physical nature may be very different. One type of joining is forming of single interatomic connections, and other, which frequently appears in the composites, is forming of new phases which emerge by the chemical reaction and which settle between the matrix and reinforcement. But, disregarding the mechanism of forming the interface, its basic quantitative characteristic is the change of chemical free energy which accompanies its forming.

For example, in processes such as infiltrations and dispersions, where the reinforcement is surrounded by the mass of metal, change of free energy, ΔG, presents the energy spent for the substitution of square meter of reinforcement surface with the surface energy σ_r with the square meter of interface surface which has the energy G_i per square meter:

$$\Delta G = G_i - \sigma_r .$$

If the forming of interface happens without chemical reactions, the energy of interface zone, G_i becomes equal to surface energy of the metal matrix σ_m, and the total change of free energy is equal to the work of reinforcement immersion, W_i:

$$W_i = \sigma_m - \sigma_r .$$

According to Jang-Dipere equation:

$$-W_i = \sigma_r - \sigma_m = \sigma_i \cos\theta$$

where: σ_i is the surface energy of interface zone, and θ is the wetability contact angle, according to Figure 2.

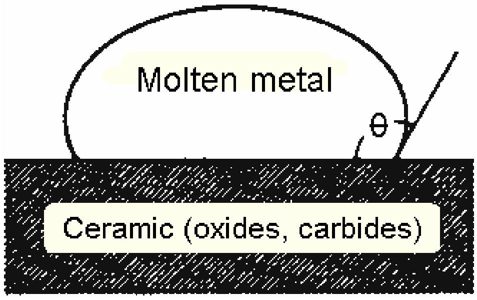

Figure 2. Contact angle of metals on flat ceramic substrate

It is clear that the metal matrix will wet the reinforcement better, when the θ angle is smaller, but the value of this angle under 90º is desirable, and sufficient condition for forming of MMC by casting methods. Chemical reaction between the metal and reinforcement as well as the dissolving of reinforcement in the metal matrix does have the influence on θ angle value, and usually makes easier the process of composites forming [1,2].

When we use ceramic reinforcement, especially carbides, the presence of the dissolved oxygen increases the θ angle, so that the wetability can be achieved only if the complete deoxidization of metal matrix is done. In the case of steel-SiC composites, before adding of reinforcement, it is necessary to make total deoxidization of steel, and after that, to refine the molten steel by blowing, with argon. The presence of magnesium and cerium has positive effect, because these metals reduce θ angle and enable wetting, more exactly, forming a single interatomic bond between the steel and silicon carbide [3].

2.2 Moulds making and composites pouring

The moulds were made of CO_2 sand mixture, manually, using the flaskless "box in basket" technology. Risering of the castings was done by appropriate risers. Having in mind the configuration of castings, it is clear that the "effect of heat pin" had the influence on the solidification process. The net castings mass was 60 – 70 % of poured molten steel. It has been already said that carbide aggregate of different grain size was placed into the bottom half of some moulds.

Pouring was performed in a usual way. We placed the carbide aggregate on the bottom of hot pouring ladle and, after that, we poured molten steel in it. Then, we mixed two phases by whirling and poured molten mixture into the mould. When excavator's tooth was poured, the mould was inclined at 10 – 15º angle, so the top of the tooth was settled in the highest position. The aim of such method of pouring was to concentrate the carbide component in the part of casting, which is directly exposed to abrasive wear. This excavator's tooth casting is presented in the Figure 3.

Figure 3. Casting of excavators tooth, immediately after shakeout from the mould

3. RESULTS AND DISCUSSION

Samples of steel-SiC composite castings were tested for:

- hardness,
- macrostructures along the cross section and
- microstructures.

Hardness test points to the very high concentration of carbide in the surface layer of some numbers of samples, which reached 800 HV. This high hardness has been noticed only in samples by which carbide phase has been placed into the mould, because the stream of metals carried the largest grains which, due to their small density, concentrated on the upper surface layer of castings. Grains of SiC were practically drowned in the metal matrix, and the depth of hardened layer was 2.5 to 3.0 mm. The distinction is that there is no continuous reduction of SiC concentration along the casting wall, so that high hardness can be noticed only beside the surface of samples. The desirable structure has to contain hardened layer in which decrease of hardness is gradual, so that on the exposed surface of castings appeared "cortex" of approximately 10 mm thickness, with the hardness of 800 to 550 HV. This indicates that further investigations must be directed to the problem of better wetting and more uniform disposition of carbide phase along the cross-section. The scheme of desirable SiC distribution is shown in Figure 4.

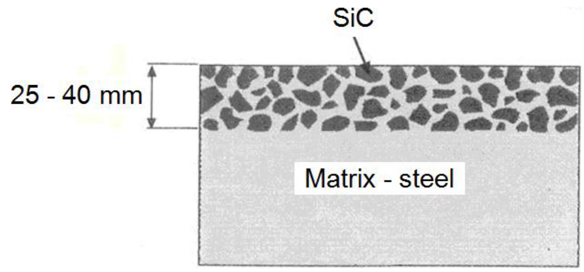

Figure 4. Desirable SiC distribution in composites

Characteristic structures of the examined cast steel-SiC composites are shown in Figure 5. The figure presents microstructures of the carbide phase distribution on the nonetched sample, at the distance of 5 mm below the upper surface of the sample. The figure shows noticeable dissolving of the carbide phase, so that the size of particles reduces to approximately 200 μm. During testing of the samples, we have established one interesting phenomena. The structure of steel metal matrix, regardless of the chemical composition, became more fine-grained, and the hardness significantly increased. Hardness increasing was greater than expected only because of the presence of hard carbide phase in the structure. The value of the hardness of different samples is presented in the Table 2.

Table 2. Hardness of composites steel-SiC (5 mm under the surface)

Type of steel and SiC content	Hardness [HB]
S355JR (without carbides)	148
S355JR (SiC 3 wt. %)	170
S355JR (SiC 5 wt. %)	185
S355JR (SiC 7 wt. %)	187
50Mn7 (without carbides)	230
50Mn7 (SiC 3 wt. %)	280
50Mn7 (SiC 5 wt. %)	290
50Mn7 (SiC 7 wt. %)	290

Possible explanation of this phenomenon lies in the fact that the presence of fine-dispersed carbide phase in the molten steel makes possible the heterogeneous crystallization of steel. This phenomenon – modification of structure, usually improves the mechanical properties of alloy and can have significant influence on the forming of very fine grains, and due to that, on hardness increasing. The noted effect may be of importance in expansions of the application of this research result. Fine-grained structures grow of tensile strength and hardness of MMC castings may be helpful on a wide range of castings, not only wear resistant parts. Dependence between hardness of composites steel-SiC (5 mm under the surface) and contents of SiC is shown in Table 2.

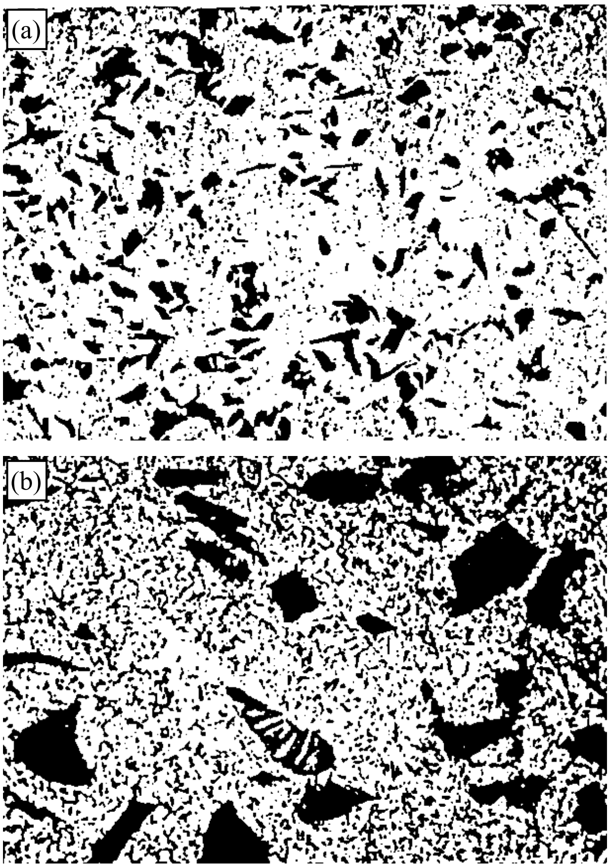

Figure 5. Carbide phase in the steel S355JR with 5 % SiC, grain size 0.6 mm (nonetched): (a) 20X and (b) 100X

Further increasing of SiC content in the composites, over 7 wt. %, provokes the formation of carbide foam on the casting surface, because in that case it is impossible by standard way of pouring to mix matrix and reinforcement. Probably, the application of *rheo-casting* treatment will enable the forming of composites with high contents SiC, but in consideration of the steel matrix, the operational technique is very complex. Namely, compulsion mixing of components, which is present in *rheo-casting* technique needs high heat resistant equipment, since pouring temperatures are around 1560 – 1580 ºC.

We will now discuss some aspects of composites forming. The phenomena occurring on the contact surface between steel as the metal matrix and SiC as the reinforcement are essential questions in the development of technological process of MMC castings manufacturing. For good, high quality MMC castings, it is necessary to provide contact surface which will maximize all good characteristics of composites since the enlargement of adhesion of these two phases improves only some characteristics of composites on account of the others. Mechanical characteristics and corrosion resistance of composites are in close ties with diffusion, or with products of chemical reactions which take place during the production or application of composite material. The frequent reason for chemical reaction between reinforcement and matrix is the insufficient purity of SiC, which has to be min. 99.0 wt. % of carbide. Then, the type of bond on the contact area, stability of contact area, reactions on the contact area and possibility of modeling these three characteristics, present basic and, at the same time, most significant parameters of MMC castings quality. Knowledge of the reactions on the matrix-reinforcement contact area, such as: reaction of dissolving of carbide phase, forming of intermediate phases and recrystallizations of metallic grains in the process of heat treatments is very important for the MMC castings quality.

Nevertheless, most important problems which we had to solve were wetting of reinforcement and getting of homogeneous matrix-SiC mixture. On the basis of some earlier performed experiments, we know that the question of good mixing is clear immediately, just during the work. If the mixing is not good, the ceramic particles remain on the surface of molten steel as the powder or slag. In the making of composites we choose the whirling method because it creates even less operational difficulties provoked by high pouring temperature of steel. In some experiments, silicon carbide granules have been additionally placed on the special prepared hole in the mould. The aim was to improve mixing of carbide and steel, in other words, to enlarge the concentration of carbide phase in surface layers of casting. Stream of metals, during its flow through the gating system, seize the particles of carbides, carrying them into the mould cavity, so that they concentrate in the surface layer of casting and form a very hard cortex. Ladle refining by argon contributes to better mixing, because the decrease of quantity of dissolved oxides and oxygen, generally speaking, reduces the surface tension and improves wetting.

Since the work on the optimization of technological procedure is still going on, we have not our own results of wear resistance of MMC castings in real conditions of exploitations. Only for comparison, the Table 3, which was taken over from the material of Swedish company *Sandvik A.B.* [4,5] and some others [6], give the review of wear resistances of castings made from different alloys exposed to abrasive wear. The relative resistance on the abrasive wear is given in respect to the carbon steel with 0.8 % C, with martensite structures, which has the index 100. It is noticeable from the table that the best wear resistance have high alloyed Cr-Mo steels and MMC castings with the steel matrix and SiC granules as reinforcement. MMC castings (*Sandvik*) made by *cast-in-carbide* technique have shown practically two times larger resistances on the abrasive wear than eutectic carbon steel with martensite structure.

4. CONCLUSION

- The addition of SiC reinforcement into the molten steel and forming of composites with the steel as the matrix gives us new material with completely different, improved characteristics

Table 3. Relative wear resistance of excavators tooth

Type of alloy	Heat treatment	Relative wear resistance [%]
X120Mn12	quenched	130 − 140
50Mn7	quenched and tempered	120
Ni-Cr iron (*Ni hard*)	without heat treatment	105
(G-X200CrMo 15 3)	quenched and tempered on cube martensite	78 − 82
G-X180CrMoV12	quenched and tempered on cube martensite	60 − 70
Steel-SiC (*cast-in-carbide*)	normalized	50 − 60

and with the very hard surface layer. Hardened surface layer and metal base with good toughness make possible its application for castings with high resistance to abrasive wear;

- In respect to the structure, MMC steel-SiC castings do not need the complex heat treatment and it is enough to apply the normalizing annealing which improves the characteristics of matrix. It is clear that the simple heat treatment reduces the cost of the final product.

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КОМПОЗИТИ ЧЕЛИК-SiC ДОБИЈЕНИ ЛИВЕЊЕМ КАО МАТЕРИЈАЛИ ОТПОРНИ НА ХАБАЊЕ

Дејан Чикара, Марко Ракин, Александар Тодић

У раду су разматране могућности израде и примене *cast-in-carbide* композита, челик-SiC, за производњу машинских делова отпорних на хабање као што су: млински чекићи, зуби багера, итд. Материјали који се уобичајено користе за израду делова изложених хабању, високолегирани Cr-Mo челици, показали су веома добре резултате у експлоатацији и веома добру сигурност у раду различитих уређаја у које су такви делови били уграђени.

Међутим делови изложени хабању који се користе у рударству, индустрији, грађевинарству и саобраћају су у експлоатацији изложени јаком абразионом дејству кварца, корунда, фелдспата и других минерала, а често и ударима о присутне стене и камење. Ови удари су посебно опасни јер могу да доведу до лома конструкционих делова или комплетног уређаја, обзиром да наведени материјали имају релативно малу ударну жилавост. Најбоља варијанта конструкције је да делови буду направљени од материјала који, поред тврдоће поседује високу ударну жилавост, динамичку чврстоћу и жилавост лома. Обзиром да уобичајено коришћени материјали, углавном високолегирани Cr-Mo челици, не поседују овакву комбинацију особина, циљ истраживања је био да се испитају могућности производње и примене нових композитних материјала са металном основом заснованих на челику као основи и честицама SiC као ојачивачу, који поседују управо такве карактеристике. Оптимални садржај и распоред SiC честица у челику, комбинују високу тврдоћу и отпорност на хабање површинског слоја богатог са SiC са добром жилавошћу и чврстоћом челичне металне основе.