

Carbide Type Influence on Tribological Properties of Hard Faced Steel Layer – Part I – Theoretical Considerations

Abstract: This paper gives a theoretical review of influence of the most important alloying elements on steel, and review of the most important carbide-forming elements and states the conditions which elements should fulfill in order to be considered as carbide-forming. It primarily involves alloying elements which in the iron-carbon system can form simple, complex or special carbides, i.e. phases of interstitial and substitutive type. It also gives a review of carbide types that are formed during either production or reparatory hard facing of steel parts with different types of filler materials.

Keywords: carbides, alloying elements, metal matrix composites, steel, hard facing, wear, microstructure, filler material.

1. INTRODUCTION

This paper first of all investigates the influence of alloying elements on the steel structure, and then it gives a brief account of carbide forming elements. A special attention is paid to carbides that are formed during hard facing of steel parts with different types of filler material. It gives tribological characteristics of certain types of carbides, as well as the effect of metal matrix in which carbides are embedded. Contradictory opinions on the most suitable matrix in relation to tribological aspects can be found in the literature. Therefore, numerous experimental hard facing procedures with different filler materials and properties relevant to resistance to wear have been studied. They include: hardness and its distribution in the cross-section, basic weld zone microstructures, friction coefficient and wear zone width [1, 2, 3].

Dr Vukić Lazić¹⁾, Dr Dragan Milosavljević¹⁾,
Dr Srbislav Aleksandrović¹⁾, Petar Marinković²⁾,
Mr Gordana Bogdanović¹⁾, Dr Branislav
Nedeljković²⁾

¹⁾ Faculty of Mechanical Engineering,
University of Kragujevac,
Sestre Janjić 6, 34000 Kragujevac, Serbia,
e-mail: vlazic@kg.ac.rs

²⁾ Zastava cars, Trg topolivaca 4,
34000 Kragujevac, Serbia

2. THE INFLUENCE OF ALLOYING ELEMENTS IN STEELS

Carbon steels cannot fulfill all construction requirements which often include not only high yield strength, but good toughness, dynamic endurance, crack limit or certain properties at either low or high temperatures. Besides these basic mechanical properties, certain parts are sometimes required to have special properties, like corrosion resistance, thermal stability, etc. These can only be obtained if other elements are added, that is by alloying. Structure alloy steels are always more expensive than carbon steels, therefore quenched and tempered steels should be used when demanded yield to tensile ratio is high, and when the toughness should be high. However, high mechanical properties are not always needed. Sometimes, for example, only corrosion resistance is required. In that case it would be highly uneconomical to produce thick sheet metal from expensive high alloy steels. It would be much better to use the so-called plated sheet metal obtained by welding thin stainless steel. For reparation or production of new parts, processes of metal spraying and hard facing are applied. The contact surfaces of both sheet metals are welded by pressure or explosion methods, which results in a compact joint. Some bimetal joints on cylindrical parts, such as two-layer pipes and bearing box, are made by centrifugal casting.

2.1 The influence of alloying metal on the base metal matrix

All alloying metals influence the steel re-crystallization temperature and hence the size of either alpha or gamma phase field. For thermal treatment, their influence on the gamma field is of a primary concern. In that sense, alloying elements can be classified as:

- elements that completely open the gamma field,
- elements that expand the gamma field,
- elements that completely close the gamma field,
- elements that contract the gamma field.

2.1a Elements that completely open the gamma field

Some elements extend Fe-M¹ field of the phase γ in the binary equilibrium diagram, therefore for certain M concentrations, this phase ends in the range from solidus to room temperature. Such a binary diagram (Fe-Mn) is given in Figure 1. It also may be found in the references [4, 5, 6].

Until the concentration of the element M, given by the point C_1 , is reached, a complete pre-crystallization $\gamma \rightarrow \alpha$ will be possible. For the concentration between C_1 and C_2 only a partial pre-crystallization will take place. If the content of the alloying element is increased above C_2 , the Fe-M alloy will have only a gamma phase at room temperature. During heating (i.e. cooling), phase changes do not take place in these alloys in solid state. Iron and the elements of the γ crystal lattice form a diagram of completely open γ field. Here, the atom radius is similar to the iron atom radius and electrochemical properties and valence are also similar. Nickel and manganese belong to this group [4, 5, 6].

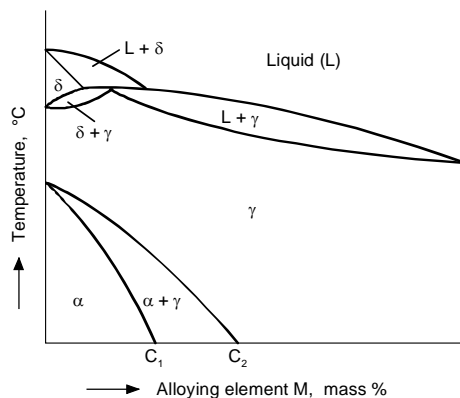


Figure 1. Equilibrium binary diagram with open gamma field

¹ M- generally stands for an alloying element.

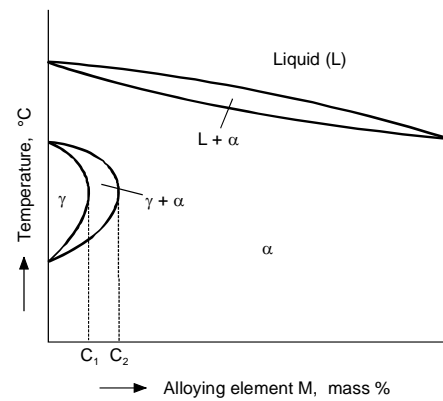


Figure 2. Equilibrium binary diagram with closed gamma field

When alloys, with concentrations of the alloying element M lower than given by the point C_1 , are heated, a complete pre-crystallization of $\alpha \rightarrow \gamma$ occurs, which means that these alloys are thermally treatable. Alloys of concentration between C_1 i C_2 will pre-crystallize when heated only partially. When they are heated till the field $\alpha + \gamma$ and then quickly cooled to room temperature, only the gamma phase is transformed. When the content of the alloying element is increased above the C_2 concentration, the α phase will be kept in the whole temperature range between solidus and room temperature. Alloys are not liable to pre-crystallization neither when cooled nor when heated, hence the structure will be ferrite at all temperatures.

2.1b Elements that expand the gamma field

Some elements (e.g. Cu, N) expand the gamma field but not enough to open that field so the pre-crystallization $\gamma \leftrightarrow \alpha$ can be completely suppressed. These elements, therefore, increase the stability of the gamma phase, but they do not increase it to the extend necessary for it to be retained at room temperature.

2.1c Elements that completely close the gamma field

If the content of alloying elements that increase pre-crystallization temperature is increased, the gamma field is closed, as shown in Figure 2. When alloys with concentrations of the alloying element M lower than given by the point C_1 , are heated, a complete pre-crystallization of $\alpha \rightarrow \gamma$ occurs, which means that these alloys are thermally treatable. Alloys of concentration between C_1 i C_2 will pre-crystallize only partially when heated. When they are heated till the field $\alpha + \gamma$ and then quickly cooled to room temperature, only the gamma phase is

transformed. When the content of the alloying element is increased above the C_2 concentration, the α phase will be kept in the whole temperature range between solidus and room temperature. Alloys are not liable to pre-crystallization neither when cooled nor when heated, hence the structure will be ferrite at all temperatures.

2.2d Elements that contract the gamma field

These elements include niobium, tantalum, zirconium and cerium. They are, however, used for alloying steel only in rare cases (e.g. Nb as a stabilizer of a stainless steel, or as filler – addition to electrodes for hard facing steel).

3. A REVIEW OF ALLOYING CARBIDE FORMING ELEMENTS AND SOME CARBIDES IN STEELS

Alloying elements have similar influence in binary alloys Fe-M and in steels. When the content of austenite forming elements in steel is increased, the pre-crystallization temperature falls. The decrease does not influence only the gamma field, but also the properties of the steel since the transformation temperature determines roughness of pearlite lamella, and hence the mechanical properties. If the pre-crystallization temperature is decreased enough, diffuser change can be completely suppressed and the austenite will pre-crystallize into martensite even when slowly cooled by mechanism of sliding (non-diffusion process). When the content of austenite forming elements increases enough, austenite structure is retained at room temperature as well. This means that the right combination of alloying elements gives steels that have austenite structures even at room temperatures. These are called *austenite steels*. They are not magnetic and they have a low yield strength and low hardness but high extension and toughness.

However, with the increase in the content of ferrite-forming elements (Cr, Mo, Si, etc.), the gamma field contracts and δ - ferrite is retained at room temperature. Some classes of steel contain both γ -elements (Ni, Mn, Cu) and α - elements (Cr, Mo, Si, Nb, etc.), so metallographic and other examinations are needed for the assessment of their structure at room temperature. Therefore, according to their influence on the steel structure, alloying elements are divided into two main categories: *austenite-stabilizers* (Ni, Mn, Cu, C and N) and *ferrite-stabilizers* (Cr, Mo, W, Si, V, Ta, Al, Ti and Nb). For hard facing is very important to analyze the

influence of carbide forming elements (Cr, Mo, W, Si, etc.) on steel properties [1-11, 16-21].

Chromium is usually present in low carbide steels up to 0.3%, in alloy steels from 0.7 to 3.5%, in chrome steels from 12-18%, while in chromium nickel steels it is contained in range of 9-35%. An increased content of chromium in carbon and low alloy steels improves their hardness at the expense of their weldability. It increases fire resistance of austenite steels in oxidation conditions but it is less effective than molybdenum or vanadium. When the content of chromium is higher than 12% steel is very resistant to corrosion. Further increase of the chromium content brings about an increase in tensile strength and corrosion resistance of the steels, but when $Cr > 20\%$ ductility is significantly decreased. Chromium forms very stable carbides - $Cr_{23}C_6$, Cr_7C_3 and Cr_3C_2 , which, in steel, can be found in free state or bound to Fe_3C (Fig. 3). If steel contains more carbon than needed for formation of pearlite, free chromium carbides are formed and precipitated at grain boundaries which in turn cause intergranular corrosion. The critical temperature of carbide precipitation is 500-800°C. Chromium increases the critical temperature A_{C1} , which makes the rate of forming of carbides in austenite significantly lower than the rate of forming of Fe_3C in carbon steels. Therefore, a higher temperature and a longer preheating time are needed for hardening of Cr-steel compared to non-alloyed steel. When hardened, Fe-Cr-C alloys can have the following structures: *hypoeutectoid*, *hypereutectoid*, *ledeburite* and *ferrite-carbide*. Alloys of all these structures have a practical application. With an increase in chromium content thermal conductivity decreases and thermal stresses increase ($gradT$ increases). This demands precaution when steel is heat treated or hard faced. Chromium dissolves in cementite, substituting iron atoms and vice versa – iron dissolves in chromium carbide substituting chromium atoms. In this way alloy cementite $(Fe,Cr)_3C$, i.e. alloy carbide $(Cr,Fe)_7C_3$ is obtained.

Molybdenum is found in structure steels in the amount of 0.2-0.5%. Due to molybdenum, grains become smaller and toughness and hardenability increase (at high temperatures). With an increase in the Mo content, tensile and yield strength increase, while extension and contraction significantly decrease at $Mo > 2.3\%$. Molybdenum increases the hardenability of steel and is particularly useful in maintaining the hardenability between specified limits. This element, especially in amounts between 0.15 and 0.30%, minimizes the susceptibility of a steel to temper embrittlement. Hardened steels

containing molybdenum must be tempered at a higher temperature to achieve the same amount of softening. Molybdenum is unique in the extent to which it increases the high-temperature tensile and creep strengths of steel. It retards the transformation of austenite to pearlite far more than it does the transformation of austenite to bainite; thus, bainite can be produced by continuous cooling of molybdenum-containing steels.

Wolfram causes small-sized grains at the expense of formation of difficult soluble carbides. Hardenability is slightly increased, and weldability is decreased due to brittleness of the weld, especially in steels with high carbon contents. Wolfram increases general resistance to corrosion and resistance to intergranular corrosion of austenite steels. It contributes to formation of unfavorable σ -phase in chromium-nickel steels. In austenite steels with the carbon content below 0.15%, addition of wolfram up to 3% does not decrease weldability. Fe-W-C alloys when hardened and cooled have the following structures: *hypoeutectoid*, *hypereutectoid*, *ledeburite* and *ferrite*. Alloys of all these structures have a practical application and they are all classified as steels. When the content of wolfram is increased, thermal conductivity decreases and weight and electric resistance increase.

Silicon, which is substitutionally dissolved in ferrite increases its, tensile strength and elastic limit and from this aspect, it is a desirable alloying element for spring steels. The amount of this element in a steel, which is not always noted in the chemical composition specifications, depends on the deoxidation practice specified for the product. Rimmed and capped steels contain minimal silicon, usually less than 0.05%. Fully killed steels usually contain 0.15 to 0.30% silicon for deoxidation; if other deoxidants are used, the amount of silicon in the steel may be reduced. Silicon has only a slight tendency to segregate. In low-carbon steels, silicon is usually detrimental to surface quality, and this condition is more pronounced in low-carbon resulfurized grades. In high alloy steels it prevents chromium oxidation. Most austenite steels contains up to 1% Si only. In steels of 18Cr8Ni type, silicon contributes to ferrite formation and increases tensile strength and resistance to intergranular corrosion. Silicon is not prone to segregation; moreover it makes segregation of some elements difficult, for example segregation of sulfur and phosphorus.

Vanadium is found in special steels in the range of 0.2-0.85%, and in steels for work in the range of 1-

1.5%. It makes steel welding difficult due to increased hardenability. Vanadium decreases steel sensitivity to overheating at hard facing and thermal treatment in general, since vanadium carbides slow down grain growth.

Tantalum is an element with high tendency towards carbide formation and it has an application in austenite chromium-nickel steels as a stabilizer that suppresses intergranular corrosion. It has to be added in right quantity in order to bind all carbon and thus prevent formation of chromium carbide, i.e. intergranular corrosion which is of great importance in welding of stainless steels [1-10].

Aluminum displays a great tendency towards nitride formation – thus decreasing sensitivity of steel to aging. When aluminum is added in the amount of 0.02-0.2%, it makes the grain size of the original austenite smaller, which is due to the effect of aluminum nitride and Al_2O_3 . In small amounts aluminum not only slows down grain growth, but it also decreases the tendency towards hardenability of the transit zone. When aluminum is added to stainless steels, it increases resistance to oxidation [1-10], but in the amount above 1% steels become difficult to weld.

Titanium is an alloy element of the greatest affinity towards carbon and it is, therefore, often used as a stabilizer in steels resistant to electrochemical corrosion because it binds carbon and prevents formation of chromium carbides. If the ratio of the titanium to carbon in steel fulfills standard requirements, the steel will be resistant to intergranular corrosion. Titanium nitride, which is also formed, is insoluble in its solid state and it becomes the center of crystallization in phase changes in the solid state. Titanium increases the resistance of welded metal to heat [1-10].

Niobium displays a great tendency towards iron therefore it forms stable carbide NbC. It is often used in micro-alloyed steels in the amount up to 0.05%. Its influence on the properties of steel primarily lies in the fact that it slows down the segregation process. Chromium ferrite steels that contain niobium are less sensitive to cracking at elevated temperatures. It contracts the austenite field, decreases hardening and improves weldability [1-11]. A small amount of Nb is added to electrodes used in hard facing, which is especially important because small carbides NbC resistant to wear are formed in the welded metal.

Boron is a carbide forming element that increases steel hardenability if added in small amounts. If

boron is added in higher amounts steel hardenability decreases and a brittle rough-grained structure is formed. It is usually added to steels in small amounts - about 0.003%. According to the references [1-11], boron expands the iron γ field. In austenite chromium-nickel steels boron added in micro amounts increases thermal stability which is related to strengthening of grain boundaries.

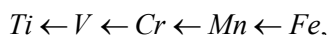
4. CARBIDES IN METAL BASE AND THEIR IMPORTANCE

The greatest number of alloying elements in steel and cast iron chemically react with carbon forming

Table 1. Carbide forming elements, atomic numbers, energy state, atomic radius in nm and ratio of carbon atomic radius (0.077 nm) to those radii [2, 3].

Shell – Principal quantum number	N (4)		O (5)		P (6)	
		Ti 22	V 23	Cr 24	Mn 25	Fe 26
	$3d^24s^2$		$3d^34s^2$		$3d^54s^1$	
	0.147/0.524		0.132/0.583		0.125/0.616	
	Zr 40	Nb 41	Mo 42			
	$4d^25s^2$		$4d^45s^1$		$4d^55s^1$	
	0.158/0.487		0.143/0.539		0.136/0.566	
	Hf 72	Ta 73	W 74			
	$5d^26s^2$		$5d^36s^2$		$5d^46s^2$	
	0.157/0.490		0.143/0.538		0.137/0.562	

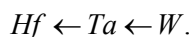
In accordance with the given rule, carbide forming order goes in the direction from iron towards manganese, chromium, vanadium to titanium:



from molybdenum, through niobium to zirconium:



from wolfram through tantalum to hafnium:



Alloying elements whose sub layer d is more occupied by electrons than iron do not form carbides in alloy steels, this is especially the case with elements with completely occupied sub layer d , like copper or zinc. In the case when there are several carbide forming elements in an alloy steel, carbon will always bind to an element of greater carbide forming tendency. This means that in steel alloyed with Cr and V, more V and less Cr-based carbides should be expected, while for higher contents of V and Cr there are no iron-based carbides. The carbon atomic radius is 0.071 nm, while atomic radii of all carbide forming elements are higher than 0.1 nm. When the ratio of the

interstitial phases or complex structures usually called *carbides*. Experiments have shown that the tendency towards carbide forming in steels is related to electron configuration of alloying elements. Those elements whose sub layer d is less occupied by electrons than in iron form special carbides. The smaller the electron number in the sub layer d , the higher is the tendency towards forming special carbides and, hence, the more stable carbide. Table 1 gives atomic numbers, energy state, atomic radii of important carbide forming elements, as well as ratios of carbon atomic radius and the atom radius of the corresponding element [1-9].

carbon atomic radius and the atomic radius of a carbide forming element is less than 0.59 (Zr, Hf, Ti etc.) *intermetallic phases* with the following characteristics are formed:

- they have (or have retained) stoichiometric ratio MC or M_2C (where M- metal, and C- carbon),
- they have a simple crystal lattice formed by metal atoms as well as mixed lattice, usually face-centered cubic (carbides of MC type) or close-packed hexagonal crystal lattice (carbides of MC or M_2C type),
- they can form a crystal lattice with no carbon atoms, i.e. they can crystallize with incomplete occupancy of sites,
- they are very stable compounds with extremely high melting temperatures (2000-3500°C) and almost insoluble in austenite,
- they possess high hardness.

When the ratio of the carbon atomic radius and the atomic radius of carbide forming element is higher

than 0.59 (e.g. Mn), carbides have a *complex structure*. Most of known carbides crystallize into three crystallographic systems: *cubic*, *hexagonal* and *rhombic*. Some elements can form two types of carbides, whereas manganese and chromium can form even three types of carbides with different crystal lattices [8, 11, 19].

The simplest carbides crystallize in a cubic system of a primitive lattice of MC type. These carbides are formed by V, Ti, Nb, Ta and Hf. More complex carbides crystallize in a hexagonal system with lattices of MC and M₂C type. Only molybdenum and wolfram have hexagonal lattices of MC type, while V, Nb and Ta have M₂C type lattice. The ε carbide found in hardened and low tempered steels also has a hexagonal lattice of MC type. Rhombic lattices are formed by Cr, Mn, Fe, Co, Ni carbides. From the aspect of resistance to wear and high temperatures, it should be pointed out that chromium and manganese carbides crystallize in a regular², hexagonal (Cr₇C₃ and Mn₇C₃), as well as in rhombic (Cr₃C₂ and Mn₃C) system. Except for chromium carbide Cr₃C₂, all others are found in iron alloys, where a certain number of iron atoms can be replaced with another metal (alloyed cementite).

Figure 3 illustrates areas of existence of different phases in alloys of Fe-C-Cr type depending on the content of Cr and C. When the content of chromium is low special carbides are not formed because chromium dissolves in ferrite and cementite, giving the mixture (α + (Fe,Cr)₃C) in the field I. There is alloyed carbide (Cr,Fe)₇C₃ in the field II. No alloyed cementite (besides ferrite) can be found in the field III except chromium carbide with dissolved iron (Cr,Fe)₇C₃. Ferrite and two types of chromium carbide with dissolved iron (the first carbide (Cr,Fe)₇C₃ and the second carbide (Cr,Fe)₂₃C₆) may be seen in the field IV. There is only ferrite and the second chromium carbide with dissolved iron (Cr,Fe)₂₃C₆ in the field V, whereas in the field VI besides ferrite and the second chromium carbide with dissolved iron (Cr,Fe)₂₃C₆, an intermetallic phase of iron with chromium Fe-Cr can also be found [8, 11, 19].

In the field VII, only ferrite and intermetallic phase of iron with chromium Fe-Cr are found, and finally, in the field VIII only ferrite can be found. Other systems of the Fe-M-C type are similar to the system Fe-Cr-C, but due to a smaller number of phases, they are simpler.

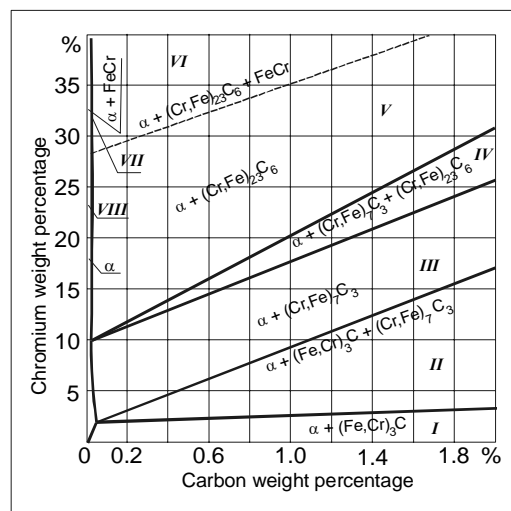


Figure 3. Areas of different phases of Fe-C-Cr alloys at the temperature of 20°C [8]

When there several carbide forming elements are present in steel-filler material, carbides of elements with greatest affinity towards carbon will be first formed. For example, in steel with a certain content of carbon W and Mo carbides and Fe₃(W,Mo)₃C are formed first, then chromium carbide Cr₂₃C₆, and finally the second chromium carbide Cr₇C₃ is formed. If there is enough carbon left cementite can be formed too.

Therefore, if the chemical composition of the filler and the main material (steel) is known, it is possible to predict approximately what kind of carbide will be formed. Furthermore, based on the stability of certain carbides, their solubility in austenite, i.e. thermal stability can also be predicted.

Since special carbides are less soluble in austenite than in cementite (lower diffusion rate), alloy steels should be kept longer at austenitization temperature. It is sometimes desirable to keep some undissolved carbides in the structure because they prevent growth of austenite grain (e.g. in fast-cut steels). Special carbides have higher hardness than cementite and martensite. When they are formed in a hard martensitic matrix, steel resistance to wear is increased; i.e. harder carbides provide greater resistance to wear. Resistance to wear is not only determined by carbide hardness, but also by its size, distribution and shape. Large and irregularly-shaped carbides may be easily pulled out of the metal matrix, especially if they are located on the cutting edge of the tool. Carbides precipitated at the grain boundaries and arranged in a line significantly decrease resistance to wear.

² Regular lattice refers to a cubic lattice.

In some steels, time of holding at tempering temperatures influences the type of precipitated carbides. At tempering, stable equilibrium carbide is not directly precipitated; transitional carbide is initially precipitated and then it slowly transforms into an equilibrium carbide.

Some elements (except for Ni, Co, Fe, Mn and Cr, and in certain cases W and Mo) form interstitial phases. A representative of this phase is vanadium carbide. Elementary lattice of vanadium carbide VC does not have to be fully occupied by carbon atoms; there can be vacancies in some vanadium lattices.

From the aspect of great resistance to wear, *wolfram carbide* is of an enormous importance. For hard facing, it is delivered in the form of full cross-section wires or steel pipes filled with carbides. Hardness of this carbide ranges from 2400-2700 HV (95 HRA), while hardness of the metal base of the hard faced metal is 45-65 HRC, suggesting an extremely high resistance to pressure, but low ductility. WC oxidizes at the temperature above 538°C [1-3] (so-called yellow oxide), therefore these hard faced layers are not recommended for work in corrosive environments. Hard faced metal is very sensitive to transversal cracks.

Manganese is a weak carbide forming element. It does not react with iron in steel to form separate carbide, it partially dissolves in cementite, where it replaces a part of iron atom $(Fe,Mn)_3C$.

Filler material for hard facing is mostly chosen on the base of both required properties of hard facing layer and available equipments. Wear mechanism and analysis of wear process of each particular element lead to conclusion that damages are mostly caused by friction, although sometimes it may be caused by corrosion, thermal and thermo mechanical fatigue etc. [1, 9].

If material is subjected to increased corrosion, filler material should be chosen exclusively on the base of chemical structure which may provide corrosion resistance, whereas for parts exposed to friction force choice of filler material become more complex. Nevertheless hardness and chemical structure should not be only criteria for estimation of suitability of facing material.

Papers [6, 14] display short list of the most often applied filler materials specially those resistant to wear, electrochemical corrosion and oxidation. Wear and corrosion resistant filler materials for hard facing may be classified in six groups: steel,

cast iron (white), wolfram carbides, cobalt alloys, nickel alloys and cooper alloys. Since the greatest number of industrial parts is withdrawn from exploitation due to wear (53% abrasive, 24% adhesive, 10% impact and other kinds of wear) and corrosion (13%) (Fig. 4), filler materials are classified on the base of these criteria [1-3]. For that reason, diagrams showing contents of carbon and alloying elements in alloys for hard facing for most common types of wear are given in Figure 5 [12].

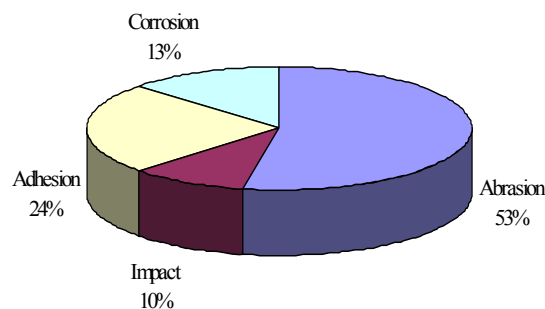


Figure 4. Different kinds of wear [12]

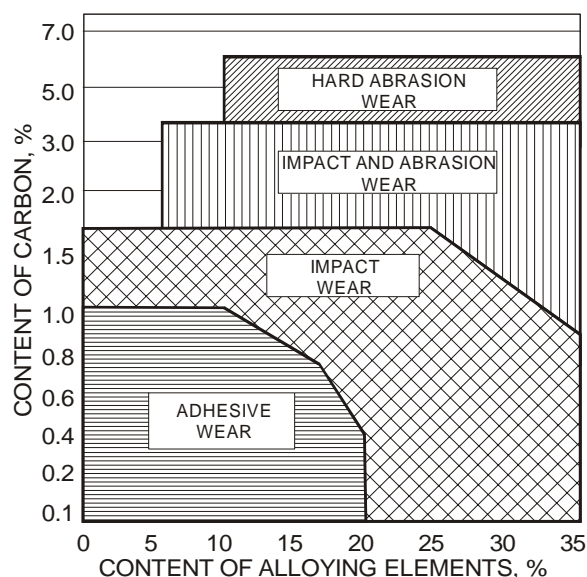


Figure 5. Alloys for hard facing [12]

5. ILLUSTRATION OF FORMED TYPICAL CARBIDES

In figures 6 to 9 characteristic microstructures of chromium thermostable steels are displayed, with typical pulled up carbides of carbide-forming elements. Steels are firstly quenched, and then tempered by variation of both temperature and tempering time.

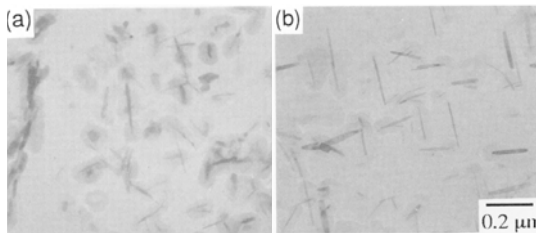


Figure 6. Extraction replica transmission electron micrographs of M_2C in 3Cr1.5Mo steel tempered at 600°C for (a) 50 h and (b) 200 h [11]

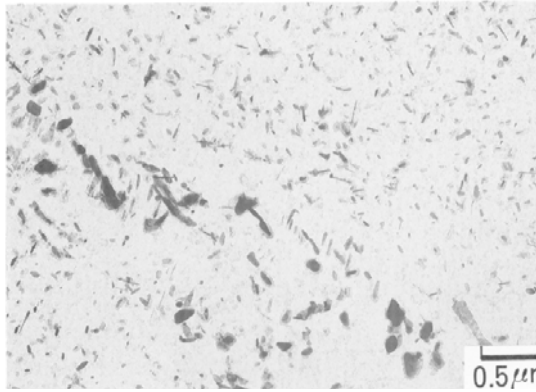


Figure 7. Transmission electron micrograph of 2.25Cr1Mo steel tempered at 600°C for 200 h, showing numerous needles of M_2C [11]

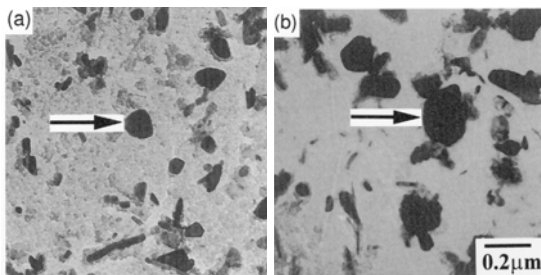


Figure 8. Extraction replica transmission electron micrographs of M_7C_3 in 2.25Cr1.5Mo steel tempered at 650°C for (a) 10 h and (b) 100 h (Arrows indicate M_7C_3 particles) [11]

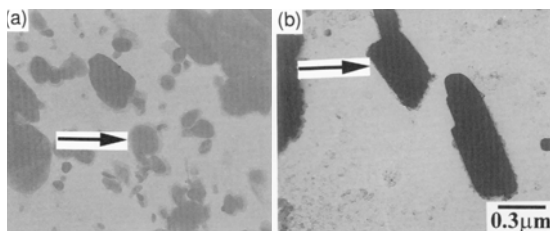


Figure 9. Extraction replica transmission electron micrographs of $M_{23}C_6$ in 3Cr1.5Mo steel tempered at 700°C for (a) 10 h and (b) 100 h (Arrows indicate $M_{23}C_6$ particles) [11]

Figures 10 to 14 represent hard facing microstructure with displayed carbides formed by application of different filler materials. Figures 10 and 11 show hard facing layers microstructures after repaired steel for work in hot environment by hard facing, while figure 13 shows hard faced

microstructure of austenite manganese steel (Hadfield's steel) for both before (13a) and after (13b) cold forging weld. Figure 14 shows microstructure of hard faced double layered plate. These are results that contributors of present paper already have published [1, 3, 13, 14, 15].

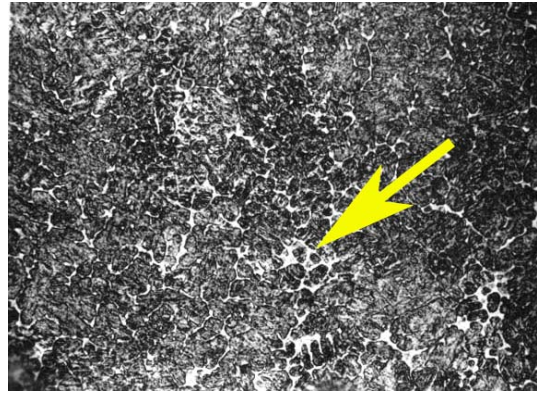


Figure 10. Microstructure of hard faced layers - martensite with precipitated carbides (200×) (FM: E3-UM-40T - DIN 8555 → 0.13C, 5Cr, 4Mo, 0.2V) [1, 2, 13]

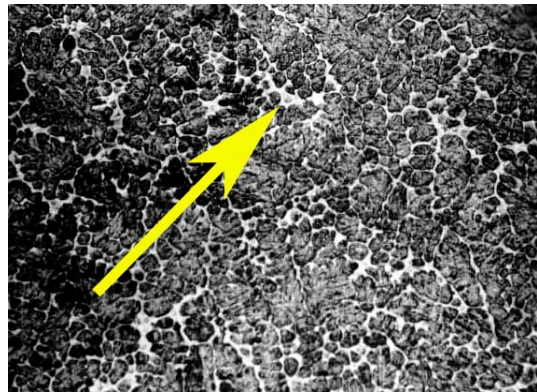


Figure 11. Microstructure of hard faced layers - martensite with precipitated carbides (200×) (FM: E6-UM-60T - DIN 8555 → 0.5C, 5Cr, 5Mo, 0.6V) [1, 3, 13, 14, 15]

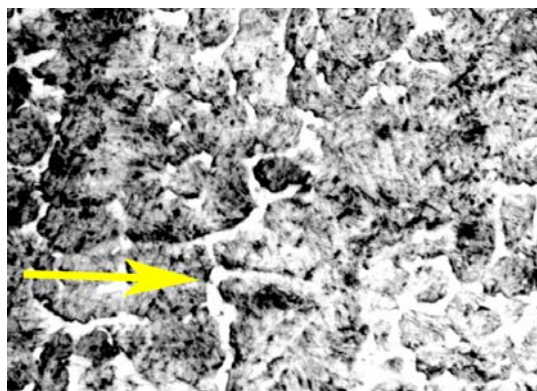
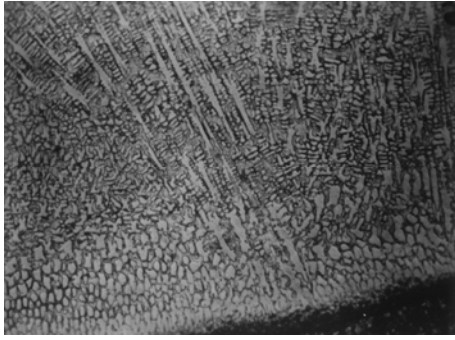


Figure 12. Microstructure of hard faced layers - martensite with precipitated carbides (shown by arrows) at grain boundaries (500×) (FM: E300 k umhilit – DIN 8555 → 0.7C, 1.5Mn, 1.39Si, 6Cr, 2Mo and the rest is Fe) [1, 3, 14, 15]



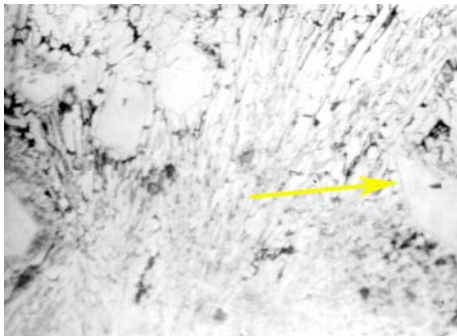
a) Austenite base with excreted carbides (200×)

Figure 13.a Microstructure of some hard faced zones (a) Hadfield's steel (FM: E300 k umhilit – DIN 8555 → 1.2C, 17.5Mn, 9.5Cr, 2.8Nb), microstructure of skin deep hard faced zones layers after forging (b) [1, 2, 3, 13, 14, 15]

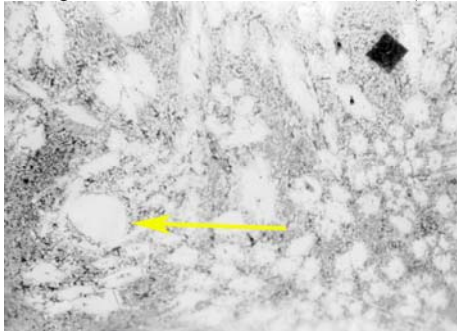


b) Carbides in martensitic base (500×)

Figure 13.b Microstructure of some hard faced zones (a) Hadfield's steel (FM: E300 k umhilit – DIN 8555 → 1.2C, 17.5Mn, 9.5Cr, 2.8Nb), microstructure of skin deep hard faced zones layers after forging (b) [1, 2, 3, 13, 14, 15]



a) Complex carbides in martensite base (800×)



b) Complex carbides in martensite base (200×)

Figure 14. Microstructure of hard faced surface double layer hard faced Cera metal sheet [3]

Beside emphasized significance of carbides in metal systems, primarily Fe-C systems, it should be noticed big importance of carbides in nanotechnologies. In shallow applied facing layers very hard inter-metal structures are set leading to increased resistance of all wear, corrosion and higher temperatures [16-20]. Figures 15 and 16 display examples of described structures, with pull up carbides of both silicon and titanium [20].

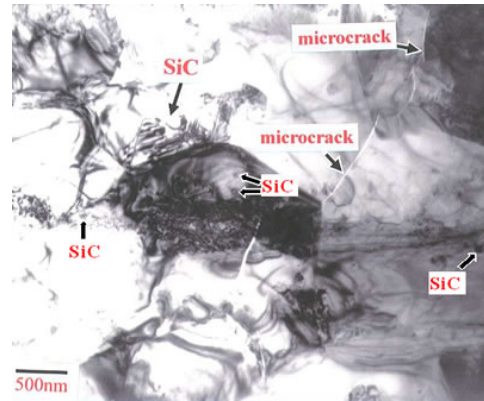


Figure 15. TEM micrographs of the worn surface of (a) monolithic alumina and (b) alumina - 5 vol% silicon carbide nanocomposite [20]

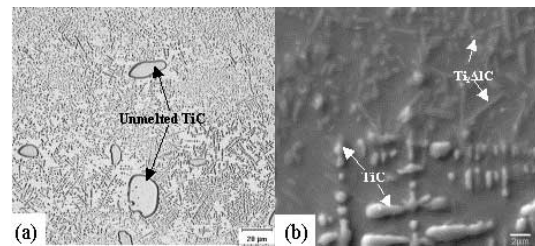


Figure 16. Microstructure of LENS deposited Ti-48Al-2Cr-2Nb + 20 volume% TiC composite as shown in (a) LOM (b) SEM micrographs [21]

6. CONCLUSION

In this paper, we have shown that the successful hard facing of forging dies is possible only after detailed investigations on models. The presented investigations, as well as those that were not presented in this paper, point to the fact that here presented reparation procedure, verified on models, can give satisfactory results also in real conditions. Besides requirements for good mechanical properties of the hard faced layers, wear resistance, and thermal fatigue, it is also necessary that they have good toughness, convenient microstructure, as well as the good machinability. These contradictory requirements can be satisfied by proper selection of the reparation procedure and corresponding filler materials, then by selection of optimal technology of hard facing, including into that the cheapest possible final machining of the repaired part.

REFERENCES

- [1.] Lazić, V.: *Optimization of hard facing process from the aspect of tribological properties of hard-faced metal and remaining stresses*, PhD thesis (in Serbian), Faculty of Mechanical Engineering in Kragujevac, 2001.
- [2.] Lazić, V., et al.: *Influence of the carbide type on tribological properties of the hard-faced layers*, Eight's International Conference on Tribology, October 8-10, 2003, pp 111-121.
- [3.] Nedeljković, B., et al.: *Influence of the carbide type on tribological properties of the hard-faced layers*, Metallurgy – Journal of Metallurgy, Association of metallurgical engineers of Serbia, Vol 16, No 2, 2010, pp. 77-90.
- [4.] Flinn, K., R., Trojan, K., P.: *Engineering Materials and Their Applications*, 4-th edition, John Wiley & Sons, New York, 1995.
- [5.] Smith, W., F.: *Principles of Materials Science and Engineering*, 3-th edition, McGraw-Hill, International edition, 1996.
- [6.] Askeland, D., R., Phulé, P., P.: *The science and engineering of materials*, Forth Edition, COPYRIGHT © 2006 by Nelson, a division of Thomson Canada Limited.
- [7.] Wesolowski, K.: *Metaloznawstwo i obróbka cieplna z ćwiczeniami* (in Polish), Wroclawskie Zakłady Graficzne, Wroclaw, 1977.
- [8.] Prowans, S.: *Materialoznawstwo* (in Polish), Wydanie drugie, Warszawa-Poznan 1980.
- [9.] Hetmanczyk, M., Woznica, H.: *Metaloznawstwo* (in Polish), © Copyright by Wydawnictwa Szkolne i Pedagogiczne, Warszawa, 1979.
- [10.] Schumann, H.: *Metallographie*, (Serbian translation): N. Vidojević et al., Zavod za izdavanje udžbenika SRS, Belgrade, 1965.
- [11.] Fujita, N.: *Modelling carbide precipitation in alloy steels*, Ph. D. thesis, University of Cambridge, February 2000.
- [12.] Dumović, M.: *Choice and Application of Alloys for Hard facing, Welding and welded structures*, (in Serbian), Belgrade, Vol. 42, No. 3, 1997., 233-236.
- [13.] Jovanović, M., et al.: *Optimization of the hard facing process of forging dies from the aspect of tribological characteristics*, AMTECH 99, Proceedings Vol. II, pp. 474-479, Plovdiv, Bulgaria, 1999.
- [14.] Lazić, V., et al.: *Choosing of the most suitable technology of hard facing of mixer blades used in asphalt bases*, Tribology in Industry, Vol. 30, No. 1-2, 2008., pp. 3-10.
- [15.] Mutavdžić, M., et al.: *Model investigations of the filler materials for regeneration of the damaged parts of the construction mechanization*, Tribology in Industry, Vol. 30, No. 3-4, 2008., pp. 3-9.
- [16.] Lira-Olivares J., et al.: *Microstructure development and mechanical properties of Ni matrix/carbide composites*, Advanced Performance Materials, Volume 4, No. 1, 1997., pp. 95-103.
- [17.] Scandella F.; Scandella R.: *Development of hard facing material in Fe-Cr-Nb-C system for use under highly abrasive conditions*, Materials science and technology, Volume 20, Number 1, January 2004., pp. 93-105.
- [18.] Oscar, O., et al.: *Transverse rupture strength of a PM tool steel*, Materials Research, Vol. 8, No. 2, 2005., pp. 173-176.
- [19.] Atamert, S Stability: *Wear resistance, and microstructure of iron, cobalt and nickel-based hard facing alloys*, Ph. D. thesis, University of Cambridge, 1988.
- [20.] Seung-Ho KIM, et al.: *Tribological properties of hot pressed alumina-silicon carbide nano-composite*, Azojomo Journal, Vol. 6, No.1 2004., pp. 1-6.
- [21.] Liu, W., DuPont, J N.: *Fabrication of carbide reinforced titanium aluminide matrix composites by laser engineered net shaping*, Metallurgical and Materials Transactions, Vol. 35A, March, 2004, pp. 1133-1140.