HIP CLADDING OF TOOLS

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Abstract
HIP cladding is a coating method to be used in the production of efficient tools. Aside from the traditional PM steel grades MMC hard phase/metal powder compounds are recommendable coating materials. When it comes to resist abrasive wear the latter are successfully employed if they contain up to 30 vol% of hard phases sized 100 µm. Pin-on-disk tests show an increased wear resistance of up to two orders of magnitude if the powder particle size is adjusted such that a hard phase dispersion is obtained. A favorable cost-benefit ratio can be achieved using titanium carbides that form during the compacting process due to the purposeful utilization of diffusion phenomena arising between the hard particle and metal matrix.

The composite layers require a heat treatment that is matched to the substrate and coating material. The dissimilar transformation behavior that might lead to cracking hazards can be appropriately counteracted by vacuum furnace treatment and possibly applying hot bath techniques.

Keywords: HIP cladding, Metal Matrix Composites (MMC), powder metallurgy, hot isostatic pressing, wear resistant material, hard phase, metal matrix, heat treatment, thick coatings, abrasive wear

INTRODUCTION

Tools that have to be wear resistant may either be fabricated of high-alloyed materials as solid bodies or if emphasis is on cost efficiency as a coated component. If the focus is on abrasion as primary wear mechanism hard alloys with hard phases (carbides, borides, nitrides) embedded in a metal matrix on Fe, Ni or Co basis have proven their worth [1, 2]. The
properties depend in the first place on the volume fraction, the size, shape and distribution as well as mechanical properties of the hard phases and metal matrix. Hard alloys contain 20 to 60 vol% of hard phases, which is in the range between tool steels and cutting materials (e.g. hard metals, Cermets). Whereas highly stressed tool edges are partially protected by build-up welding or laser surface treatments powder metallurgical manufacturing processes allow large areas of components and tools to be coated by means of hot isostatic pressing (HIP cladding). Applying current HIP parameters (1150°C, 100 MPa) the particles of an atomized steel powder if necessary with the addition of hard phases are compacted into a solid material and at the same time bonded to a suitable substrate. Powder metallurgy vs. melting metallurgy offers some decisive advantages. While the microstructure of melted hard alloys is formed based on the chemical composition and solidification sequence the PM technology allows hard phase type and size to be almost freely selected. Moreover, PM coatings enable the crackfree formation of thick coatings containing more hard phases with the homogeneity of the microstructure and bond to the substrate being much better than in build-up welding or thermal spraying techniques.

**COATING MATERIALS**

HIP cladding counts among the diffusion welding processes. Starting point is usually a solid substrate that is coated with a layer of compacted powder. As coating material high-alloy gas-atomized steel powders are available (Table 1) as used for the manufacture of rods and bars out of which cold, hot and high-speed steel tools are made, see Fig. 1a. They contain fine hard phases precipitating from the melt when the powder particles cool down in the atomizing tower. In the event of highly abrasive wear hard phase/metal powder mixtures are needed, see Fig. 1b. They should be counted to the group of metal matrix composites (MMC). As metal matrix component the steel powders listed in Table 2 are suitable due to their broad range of desirable material properties. As hard particles in MMC the metallic hard phases of significance have been listed in Table 3 with a number of properties important for the bond [3].

The microstructure of the MMC is depending on the interdiffusion of elements arising during hot compaction as well as by the particle size ratio of both powder components. For manufacturing reasons the powder components are not in thermodynamic equilibrium but they are approaching this
Table 1. Selected gas atomized powders for PM-coatings

<table>
<thead>
<tr>
<th>Designation</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>W</th>
<th>Si</th>
<th>C</th>
<th>B</th>
<th>Co</th>
<th>Ni</th>
<th>Fe</th>
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<tbody>
<tr>
<td>Ni-4</td>
<td>7.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.5</td>
<td>0.3</td>
<td>-</td>
<td>-</td>
<td>bal.</td>
<td>2</td>
</tr>
<tr>
<td>Ni-6</td>
<td>15</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.3</td>
<td>0.8</td>
<td>1.8</td>
<td>-</td>
<td>bal.</td>
<td>4</td>
</tr>
<tr>
<td>Co-12</td>
<td>29</td>
<td>-</td>
<td>8</td>
<td>1.4</td>
<td>1.9</td>
<td>3.1</td>
<td>bal.</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Co-6</td>
<td>28</td>
<td>-</td>
<td>4</td>
<td>1.1</td>
<td>-</td>
<td>bal.</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1.2380</td>
<td>13</td>
<td>1.1</td>
<td>4</td>
<td>-</td>
<td>0.4</td>
<td>2.3</td>
<td>-</td>
<td>-</td>
<td>bal.</td>
<td>-</td>
</tr>
<tr>
<td>1.3344</td>
<td>4.2</td>
<td>5</td>
<td>3.1</td>
<td>6.4</td>
<td>-</td>
<td>1.3</td>
<td>-</td>
<td>-</td>
<td>bal.</td>
<td>-</td>
</tr>
<tr>
<td>ASP 60</td>
<td>4</td>
<td>7</td>
<td>6.5</td>
<td>6.5</td>
<td>0.4</td>
<td>2.3</td>
<td>10.5</td>
<td>-</td>
<td>bal.</td>
<td>-</td>
</tr>
<tr>
<td>CPM10V</td>
<td>5.2</td>
<td>1.3</td>
<td>10</td>
<td>-</td>
<td>0.9</td>
<td>2.4</td>
<td>-</td>
<td>-</td>
<td>bal.</td>
<td>-</td>
</tr>
<tr>
<td>R124</td>
<td>20</td>
<td>1.3</td>
<td>10</td>
<td>0.8</td>
<td>-</td>
<td>3.6</td>
<td>-</td>
<td>-</td>
<td>bal.</td>
<td>-</td>
</tr>
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</table>

Table 2. Gas atomized matrix powders for MMC

<table>
<thead>
<tr>
<th>Designation</th>
<th>TA [°C]</th>
<th>α [10⁻⁶ K⁻¹]</th>
<th>Hardness [HRC]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2714</td>
<td>6NiCrMoV7</td>
<td>830 - 870</td>
<td>12.2 14.3</td>
</tr>
<tr>
<td>1.2344</td>
<td>X40CrMoV5-1</td>
<td>1020 - 1060</td>
<td>11.5 13.0</td>
</tr>
<tr>
<td>1.2380</td>
<td>X230CrVMo13-4</td>
<td>1050 - 1150</td>
<td>12.2 13.9</td>
</tr>
<tr>
<td>1.3344</td>
<td>HS6-5-3</td>
<td>1150 - 1200</td>
<td>11.5 12.9</td>
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</table>

Table 3. Physical properties of metallic hard phases in MMC

<table>
<thead>
<tr>
<th>Hardness [HV0.05]</th>
<th>Density [g/cm³]</th>
<th>α [10⁻⁶ K⁻¹]</th>
<th>TS [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(FeCr)₇C₃</td>
<td>1400</td>
<td>6.92</td>
<td>10.3</td>
</tr>
<tr>
<td>Cr₇C₃</td>
<td>2300</td>
<td>6.68</td>
<td>10.6</td>
</tr>
<tr>
<td>CrB₂</td>
<td>2250</td>
<td>5.58</td>
<td>10.5</td>
</tr>
<tr>
<td>WC/W₂C</td>
<td>2560</td>
<td>16.53</td>
<td>5.9</td>
</tr>
<tr>
<td>VC</td>
<td>2900</td>
<td>5.41</td>
<td>7.3</td>
</tr>
<tr>
<td>TiC</td>
<td>2950</td>
<td>4.93</td>
<td>8.3</td>
</tr>
</tbody>
</table>

state as hot compaction takes place. Therefore, diffusion zones of varying size were found to have formed in all examined materials around the hard particles added. In Fig. 2 this is shown for CrB₂ in 56NiCrMoV7. As a
result of an outward boron diffusion and a weak inward iron diffusion CrB further outward M₃B and M₂₃(B,C)₅, have formed around the CrB₂ core. Although the resulting phases are softer than the CrB₂ core due to the decreasing boron content in outward direction, a hard particle proportion of 15 vol% added turns into a hard phase content of 30 vol% [4]. Similar effects are noticeable when WC/W₂C is used in steel matrices. The diffusion zone is of WC/W₂C-type and further outward M₆C, see Fig. 1b. The diffusion rims as a rule have a positive influence on the adherence to the steel matrix because the change in properties (E, H, α) at the interface between hard phase and matrix is found to be moderate.

In a new manufacturing process the diffusion of carbon with phase transformation in the solid state is purposefully used for the in-situ formation of TiC [5]. During this process a crushed ferro-titanium powder of 100 µm average grain size and in a proportion ranging between 10 and 30 vol% is admixed to a steel powder of type 56NiCrMoV7. In addition, carbon in the form of graphite powder is added to such an extent as is required to enable the stoichiometric formation of TiC. During the HIP treatment TiC is formed from outside-to-inside as a result of a carbon diffusion into the FeTi powder with iron at the same time diffusing towards the outer case Fig. 3. The transformation to TiC is not always complete since diffusion is prevented due to growing TiC rims. For this reason, in-situ TiC is often dish-shaped with small residual areas of Fe-Ti inside. Whereas due to the high cost of the hard material the MMC powder is much more expensive than the pure
matrix powder the price of MMC with in-situ TiC ranges below that of the matrix powder since the ferro-titanium is inexpensive.
Nevertheless, phase transformation may also entail negative effects. For example, Cr$_3$C$_2$ in steel matrices is rather unstable and under standard HIP conditions it is completely transformed to (FeCr)$_7$C$_3$. With a hardness of 1400 HV$_{0.05}$ M$_7$C$_3$ is significantly softer than Cr$_3$C$_2$ (2300 HV$_{0.05}$) and does not have the anticipated high wear resistance to minerals having a high quartz content. The distribution of hard phases can be influenced via the grain size ration and the proportion of the hard phase and matrix powder volume. For example, if an MMC is produced from grade 1.2380 plus 30 vol% of VC using commercially available grain sizes a network-like arrangement of the VC carbides around the grains of the matrix powder will be attained, Fig. 4. The fracture toughness of such a microstructure is extremely low because of cracks propagating along the hard phase network without the tough metal matrix being involved. This may lead to high wear rates due to microfractures. Furthermore, as a result of the low ductility there is a more pronounced crack hazard when quenching the material during hardening. The use of hard material and matrix powders of comparable grain size will result in a more favorable dispersed hard phase distribution as shown in Fig. 1b for a MMC with pelletized fused tungsten carbide.

![Microstructure of a MMC (1.2380 < 200 µm + 30 vol% VC < 40 µm.)](image)

**Figure 4.** Microstructure of a MMC (1.2380 < 200 µm + 30 vol% VC < 40 µm.)
WEAR RESISTANCE

Since the wear resistance of a material is system dependent it cannot be viewed as a universally applicable property. If PM coatings are used to withstand abrasion it is recommendable to thoroughly analyze the wear system as well as the mechanisms and sub-mechanisms involved to enable an optimized composite material to be developed on this basis. The role that the hard phases play in this context is generally known. They can only be effective if their hardness is higher than that of the groove-generating mineral and if they are of sufficient volume and extend beyond the characteristic groove width actually caused in a wear system [1, 2]. If this is not the case they are practically of no use and are scored off together with the metal matrix.

To classify wear resistant materials often a pin-on-disk test is employed in which cylindrical pin samples are moved over various types of emery paper (flint, garnet, Al₂O₃, SiC) without overlapping. Taking the weight losses detected and based on length of the wear path, density and contact area a dimensionless wear rate can be determined that has been shown as a function of the abrasive hardness in Fig. 5 for some PM coatings.

Initially, a significant influence of the volume fraction of hard phases can be noticed. The highest wear rates are found for PM steel grade 1.2714 that does not contain hard phases. Slightly below is the curve characterizing grade 1.2380 with approximately 23 vol% of fine hard phases, see Fig. 1a. The addition of hard constituents no matter whether these are tungsten, vanadium or titanium carbide results in a significantly lower wear rate. The most pronounced effect is achieved with 30 vol% of fused tungsten carbides (WSC) that lower the wear rate against flint on a pure steel matrix by a factor of 100. An MMC based on 1.2380 with 30 vol% of VC shows results that are only insignificantly inferior. A comparison between 1.2714 and 1.2714 with 10 vol% of TiC also indicates the wear reducing effect of hard phases (here in-situ TiC). The wear rate reduction in this case however is not as pronounced since only 10 vol% of hard constituents have been admixed.

MMC were particularly effective in withstanding grooving wear caused by corundum and abrasives in the same hardness range. Obviously, the harder carbides, WC/W₂C, VC and TiC, improved the resistance to wear considerably. As in case of flint the lowest wear rates against corundum are detected on MMC consisting of 1.2380 and WC/W₂C.
high hardness fused tungsten carbide has an excellent fracture toughness that adds to the material’s efficiency [6]. The wear reducing effect of the hard phases is even apparent with SiC as wear-causing mineral since the MMC wear rates are significantly below those of commercially available alloys. Differences found between 1.2380 with tungsten carbide and with vanadium carbide are due to the distribution of the hard phases, see Fig. 1b and Fig. 4. As the abrasive hardness increases the hard-phase network of the VC has a wear-increasing effect.

The wear rates with 1.2714 to which only 10 vol% in-situ TiC has been added are found to be remarkably low.

**MANUFACTURE**

**HIP CLADDING**

Due to their steel matrices PM materials are especially suited as layers on base materials made of steel [7]. HIP-cladding of steel powders to a solid base material is performed by specialist companies. Using an appropriate
encapsulation technique layers can be clad on a substrate with low distortion and very close to the final shape. Regarding the thickness of the coating layer there is practically no limit. After the removal of the capsule by machining the coated HIP component is subjected to a heat treatment. Such treatment must be suitably performed to make sure the desired properties of the layers and base material are attained.

HEAT TREATMENT

During HIP treatment particularly the base metal will suffer overheating associated with grain growth. While in high-alloy coating materials this is counteracted by fine carbides the grains in the low-alloy base material may grow to millimeter size. Martensitic hardenable steels are normalized by the $\alpha - \gamma - \alpha$ transformation during the hardening treatment. If unalloyed steels are clad with non-heat treated Ni- and Co- base alloys the HIP treatment should be followed by normalizing since a grain coarsening will have a substantial effect on the strength and toughness of the base material.

The desired properties of layer materials on iron basis are attained by making use of a martensitic hardening process. Special emphasis in this context is on the hardening temperature. If coatings are produced with high-alloy steel powders such as 1.2380 or 1.3344 the austenitizing temperatures are significantly above 1000°C. Since toughness and ductility aside from strength is often recommended from the base material martensitic hardenable steels are a good choice of substrate material. The problem of the austenitizing temperature being approximately 200°C lower than that of the coating material may be circumvented by selecting an MMC matrix similar to the base material (e.g. base material 1.2714 with MMC of CrB$_2$ in a 1.2714 matrix).

When heating up to austenitizing temperature care must be taken that the temperature difference $\Delta T$ between case and core and thus the associated thermal stresses remain small. As is customary with tool steels the heating process must include holding stages for temperature balancing and a correspondingly slow heat-up rate [8]. In most cases the holding period at hardening temperature may be kept shorter than with materials made by fusion metallurgical processes because the fine HIP microstructure can be faster converted to a homogeneous austenite. As a result of their high content of hard phases MMCs have a lower thermal expansion coefficient than the base material which may lead to thermal stresses arising in the boundary
surface or interface. In this case a hard phase gradient in the coating has brought about positive effects.

The rapid cooling of a PM composite material required for martensitic transformation is to be viewed as particularly critical. Such a cooling process should therefore only be just as quickly as is necessary since the risk that cracks will develop in the hard layer increases with wall thickness but most of all with the amount of hard phases present in the layer. Quenching in hot bath will reduce the crack hazards. Sometimes the time-temperature-transformation (TTT) diagrams of the steel matrix are no longer applicable to the MMC. In particular if the diffusion reactions between hard phase and matrix are strong the composition of the steel matrix and thus the transformation behavior may change. This can be viewed as positive if, for example, carbon is transferred to the matrix shifting the pearlite-field towards longer times. In this case cooling down can be more slow so that the risk of crack formation is reduced.

Aside from cooling stresses also stresses caused by transformation have to be considered. There is a risk that, due to the increase in volume caused
by the martensitic transformation of the core, the already martensitic case is subjected to tensile stresses and fails. Ideally, base and layer materials should therefore be selected such that the base material’s martensitic or bainitic transformation takes place before the layer material is transformed. For example, this is the case for a coating of 1.3344 steel grade on 1.2885 as base material. Figure 6 shows the TTT-diagram for cooling down a 200 mm thick composite sheet being quenched under the N$_2$-pressure of 6 bar. Due to the very pronounced bainite zone despite a slower cool-down rate the core is transformed before the case has reached the martensitic starting temperature. In this rather favorable case the transformation of the base material has already been completed before martensite starts to form in the surface area. With a continuous cooling down process this may not be achieved with other materials. Also recommendable here is a hot bath treatment during which the base material is transformed isothermally to upper bainite while the coating layer becomes martensitic only during subsequent cooling of the layer.

Suitable heat treatment processes especially for high-alloy coating materials are the salt bath and vacuum hardening methods. More flexibility is offered by the vacuum furnace that enables all boundary conditions associated with the safe heat treatment of the composite to be satisfied.

![Figure 7](image)

Figure 7. Hardness of PM-coatings as a function of tempering temperature.
Hardening is followed by a tempering treatment by means of which the hardness of the coating and the strength of the base material are suitably adjusted. Favorable layer materials and metal matrices are those that show a secondary hardness maximum allowing high tempering temperatures at which any residual austenite is transformed to martensite leading to a high surface hardness and a tough base material. Generally the macrohardness of MMC is higher than that of the non-strengthened steel matrices, see Fig. 7. At a high austenitizing temperature residual austenite causes a decrease in quenching hardness and alleviates cracking hazards. However, it is transformed when tempering is carried out above the secondary hardness maximum so that the maximum hardness can be reached.

APPLICATIONS

Examples of successful applications have been found in the plastics processing industry in recent years [9]. Here the outside of extrusion screws and the respective extruder casing (inside) are provided with coating applied by the HIP cladding process. Figure 8 shows a composite screw segment with 1.2380 outside and mild steel inside together with the microstructure of the interface between both materials. Those composite components have become the standard solution for twin screw extruders in the chemical industry where hard additions to the polymer material caused remarkable wear. As these tools must meet constantly increasing expectations the tool steels used nowadays such as 1.2380, CPM10V or even corrosion resistant variants will be substituted by wear and corrosion resistant MMC before long.

In the past few years PM claddings and coatings of tools used in mineral and mining industry were successfully applied. Steel rings up to 1400 mm in diameter and a total weight of 3,5 tons that were provided with HIP claddings, were shrunk onto roller cores and employed as briquetting and crushing rollers in the respective devices. In this context the surface provided with hard hexagons of MMC as shown in Fig. 9 has proved its worth as roller hardfacing material in high-pressure comminution roller presses [10, 11]. Only the HIP cladding technique enables such a two-component surface to be produced that in comparison to conventional roller designs improves the service life and at the same time increases the crushing efficiency by creating better intake conditions and allowing higher admissible pressures.

It is to be assumed that the MMC’s outstanding resistance to wear as well as the safe control of the HIP cladding technology will enable powder metal-
HIP Cladding of Tools

Figure 8. Composite screw segment for a twin screw extruder (IMT-Bodycote).

Figure 9. HEXADUR-coating on cement grinding rolls.

lurgical processes to be employed in tools in numerous fields of application in the future.
REFERENCES


