# Aptitude of different types of carbides for production of durable rough surfaces by laser dispersing

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Different types of tungsten carbide materials (fused tungsten carbide, nickel clad fused tungsten carbide, macrocrystalline WC and sintered and crushed WC/Co) are used for laser dispersing of construction steel surfaces. Surface roughness analyses and metallographic evaluation of cross sections concerning efficiency of carbide embedding as well as crack formation tendency are carried out. Generally, all types of tested carbides permit production of rough surfaces with metallurgical bonding to the metallic matrix, but only use of nickel clad fused tungsten carbide permits to prevent crack formation. The effectiveness of silicon and silicon carbide for production of durable rough surfaces on aluminium alloys is investigated. Both silicon and silicon carbide qualify for production of rough surfaces by laser dispersing. While silicon carbide particles show higher hardness, use of silicon does not include danger of embrittlement due to formation of aluminium carbide.

## 1 Introduction

Surfaces with defined, long-term stable roughness are needed in various applications e.g. for traction control in logistic centres or on moving walkways, pulp production in paper industries, paper conveyors in paper or printing machines, rolls that transport or deflect sheet metal in steel or aluminium mills, fixation of semi-finished parts in moulds or massive forming tools, etc.. In some applications like rolls for transportation of sheet steel [1] and jaws for clamping of cylinders in massive forming processes [2] only relatively small roughness of about $R_a$ 5 µm is needed, which can be covered by HVOF spraying. Other thermal spray processes permit production of rougher coatings, but limited bond strength and / or coating cohesion restrict their use.
Laser based processes are particularly suitable for high precision of surface layer modification or cladding both concerning geometry and microstructure [3]. Among these processes laser cladding and laser dispersing are best suited to achieve surface layers that contain embedded hard materials as a prerequisite for high durability rough surfaces. Thereby laser dispersing results in only small change of the respective components surface contour and is therefore particularly suitable for treatment of already completely machined components. That makes the process especially interesting for job shops that cover various applications with relatively small amount of components.
Potential of hard materials to be used as reinforcing phase depends on the type of base material. Generally, irregular shaped powders show better aptitude to form surfaces with durable roughness peaks. Ideally, reinforcing phases should be wetted easily by the base material´s melt, but only dissolve slowly, and exhibit high fracture toughness rather than high hardness in the first place.
Generally, tungsten carbide tends to dissolve in iron based alloys quickly forming brittle mixed carbides. However, there is a large variety of tungsten carbide based materials with different chemical composition and microstructure as well as particle size distribution commercially available. In contrast vanadium carbide does not tend to dissolve in iron based alloys, especially in vanadium rich alloys, that fast and does not form brittle mixed carbides. But, it is not easily available in a particle size range suitable for laser dispersing processes. This study aims for evaluation of different tungsten carbide based materials concerning their aptitude for laser dispersing with the aim to produce durable rough surfaces.
Additionally, for manufacturing of durable rough surfaces on aluminium alloys the capabilities of silicon carbide and silicon are studied and evaluated.

## 2 Experimental

Steel dispersing experiments are carried out with high power diode laser type LDF 6000-100 (Laserline GmbH, Mühlheim-Kärlich, Germany) with wavelength between 900 nm and 1,070 nm, 1,500 µm diameter fibre, 80 mm collimation and 250 mm focal length, which results in 4.7 mm focal spot diameter. Feedstock is fed coaxially using powder nozzle PN6625 (GTV Verschleiss-Schutz GmbH, Luckenbach, Germany) with 1.5 mm ID injectors. Argon is used both as laser process gas and carrier gas. S355J2G3 substrates are treated with meander movement of the laser processing head. Properties of four different kinds of tungsten carbide based reinforcing materials are listed in **table 1**. Besides macrocrystalline WC (GTV 10.80.11), fused tungsten carbide (GTV 10.80.4) and sintered and crushed WC/Co compounds (GTV 10.80.60) a chemically nickel clad fused tungsten carbide powder (GTV 80.70.1) is applied. All powders show irregular shape.

**Table 1.** Properties of applied tungsten carbide based powders

| powder | 10.80.11 | 10.80.4 | 10.80.60 | 80.70.1 |
|---|---|---|---|---|
| material | WC | $WC/W_2C$ | WC/Co 88/12 | $WC/W_2C$ Ni clad |
| particle size [µm] | +75 -180 | +30 -75 | +75 -150 | +10 -53 |
| W [wt.-%] | base | base | base | base |
| C [wt.-%] | 6.21 | 3.97 | 5.48 | 3.72 |
| Co [wt.-%] | - | - | 11.85 | - |
| Ni [wt.-%] | - | - | - | 8.87 |

Ranges of investigated process parameters for dispersing of S355J2G3 steel are listed in **table 2**.

**Table 2.** Process parameters for laser dispersing of S355J2G3 with tungsten carbide based powders

| | |
|---|---|
| Laser power [W] | 900 - 1,500 |
| Laser process gas flow rate [l/min] | 20 |
| Carrier gas flow rate [l/min] | 4 - 12 |
| Powder feed rate [g/min] | 10 - 20 |
| Surface speed | 1.0 m/min |
| Offset between paths | 2.0 mm |

Laser alloying / dispersing of AlSi10Mg substrates with silicon and silicon carbide is carried out with high power diode laser type LDF 6000-60 (Laserline GmbH, Mühlheim-Kärlich, Germany) with wavelength between 980 nm and 1,060 nm, 1,000 µm diameter fibre, 80 mm collimation and 250 mm focal length, which results in 3.1 mm focal spot diameter. Feedstock is fed coaxially using powder nozzle PN6625 (GTV Verschleiss-Schutz GmbH, Luckenbach, Germany) with 1.0 mm ID injectors. Argon is used both as laser process gas and carrier gas. GTV 70.11.6 and GTV 70.85.2 are used as silicon and silicon carbide feedstock respectively. The silicon powder shows 99.9% purity and a particle size distribution +45 -125 µm, while silicon carbide feedstock shows 99.5% purity and particle size distribution +45 -90 µm. The ranges of investigated process parameters are listed in **table 3**.

**Table 3.** Process parameters for laser alloying / dispersing of aluminium substrates

| | |
|---|---|
| Laser power [W] | 600 - 1,400 |
| Laser process gas flow rate [l/min] | 15 - 25 |
| Carrier gas flow rate [l/min] | 3 - 5 |
| Powder feed rate [g/min] | 2 - 3 |
| Surface speed | 1.0 - 4.0 m/min |
| Offset between paths | 1.5 - 2.0 mm |

Cross sections of laser dispersed specimens are prepared and analysed by optical microscopy. Surface roughness is determined by stylus instrument Mitutoyo SJ 201P.

## 3 Results

### 3.1 Laser dispersing of S355J2G3 with tungsten carbide based powders

When dispersing S355J2G3 surfaces carrier gas flow rate takes strong influence on topography. **Figures 1** and **2** show the effect at the example of dispersing with nickel clad fused tungsten carbide. Despite large optimal working distance of PN6625 nozzle, i.e. 25 mm, even relatively small carrier gas flow rates of 6 l/min cause displacement of carbide reinforced melt from the centre to the sides and according wavy surface appearance. In contrast 4 l/min carrier gas flow rate permits avoiding melt displacement to the sides with all other parameters kept constant. However, this carrier gas flow rate also represents the lower limit in order to ascertain continuous transportation of relatively heavy tungsten carbide based powders through the feed hoses.


**Fig. 1.** Surfaces of S355J2G3 dispersed with nickel clad fused tungsten carbide using carrier gas flow rate of 6 l/min (top) and 4 l/min (bottom)

Ratio of powder feed rate and laser power determines content of reinforcing particles as well as microscopic surface roughness of dispersed layers, **figure 3**. Melt pool size increases with laser power and thereby provides an according volume that can take up hard phases. With increasing content of hard phases injected into the molten volume melt flow is hindered, which results in formation of an increasing density of microscopic peaks at the surface of dispersed layers.
Both investigated pure carbides, i.e. macrocrystalline WC and fused tungsten carbide, tend to dissolve relatively fast inside the steel melt. Upon cooling high contents of carbon and tungsten cannot remain dissolved inside the metallic matrix and form precipitates, **figure 4**.

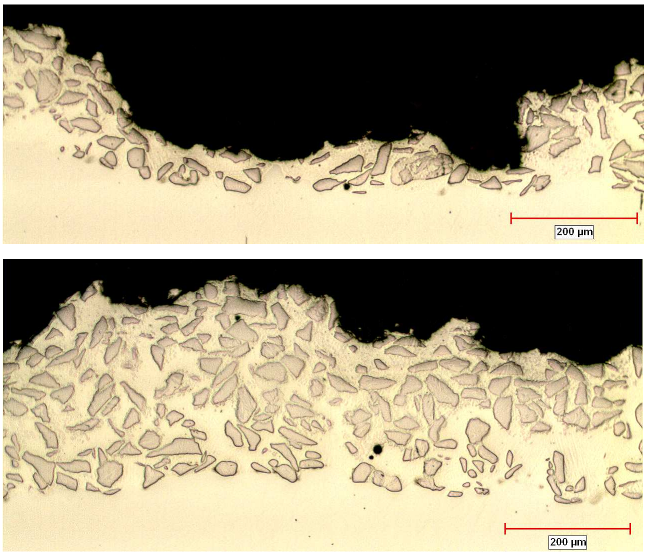


**Fig. 2.** Cross section of S355J2G3 dispersed with nickel clad fused tungsten carbide using carrier gas flow rate of 6 l/min (top) and 4 l/min (bottom)

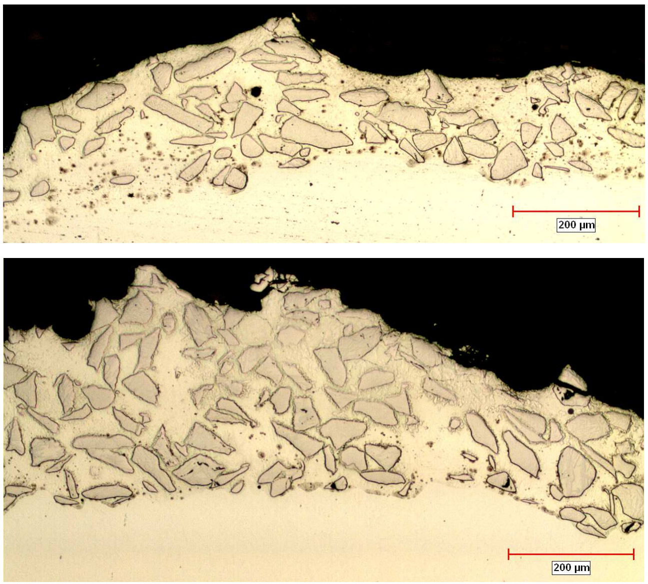


**Fig. 3.** Cross section of S355J2G3 dispersed with fused tungsten carbide using 10 g/min powder feed rate at 1,000 W laser power (top) and 20 g/min powder feed rate at 1,200 W laser power (bottom)

Observed dissolution inside the steel melt is higher for GTV 10.80.11 compared to GTV 10.80.4, which can be attributed to smaller particle size and accordingly larger specific surface area of the latter. Macrocrystalline WC might also tend to dissolve less in the steel melt, which is reported at least for nickel based matrix alloys [4-5].

Despite their nickel cladding fused tungsten carbides in particularly fine sized GTV 80.70.1 also undergo some dissolution in the steel melt. However, dissolution is less than for GTV 10.80.4.

Also, sintered and crushed WC/Co 88/12 compounds partially dissolve in the steel melt, **figure 5**. Thereby cobalt phase is dissolved in the first place and WC particles with average size of about 2 µm remain mostly intact and become distributed in the cobalt enriched steel matrix. Some WC/Co particles form core-shell structures, which might be due to partial impregnation by steel melt. However, high resolution SEM and EDS were needed to verify that explanation approach.

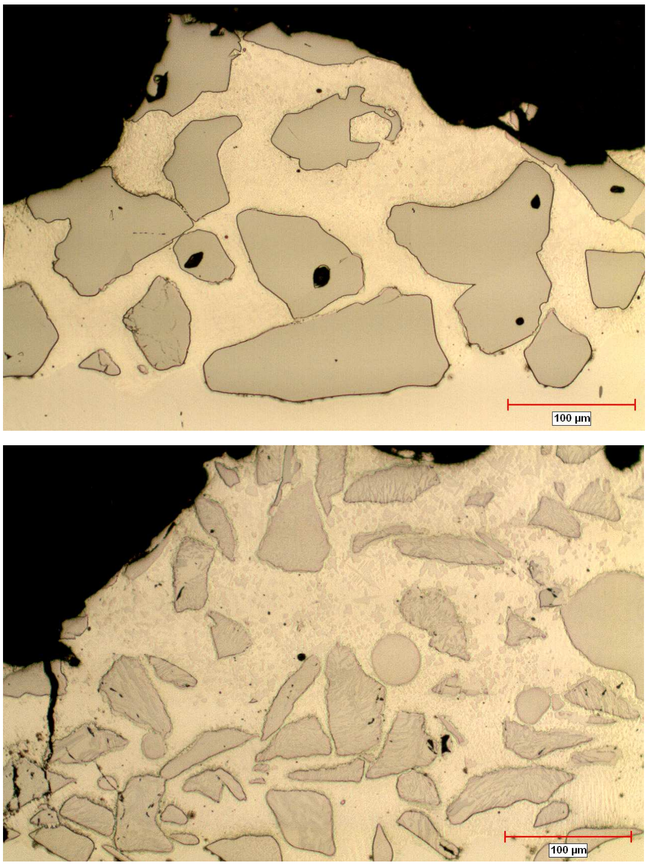


**Fig. 4.** Precipitates of macrocrystalline (top) and fused (bottom) tungsten carbides that were dissolved in S355J2G3 melt

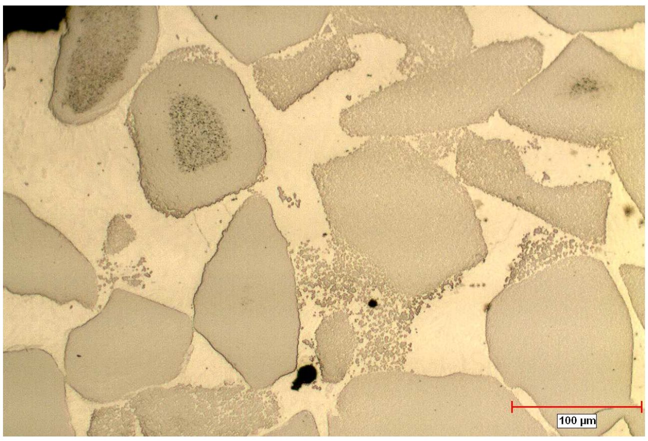


**Fig. 5.** Partial dissolution of WC/Co compound particles in S355J2G3 melt and partial formation of core-shell structure particles

There is no clear correlation between particle sizes of dispersed tungsten carbide based particles and roughness of surfaces that have been produced in the limits of this study, **table 4**. That can be attributed to the relatively deep melting of the substrate surface that results in thickness of reinforced surface layers that clearly exceeds the size of dispersed tungsten carbide based particles.

**Table 4.** Roughness of laser dispersed S355J2G3 surfaces

| **powder** | **10.80.11** | **10.80.4** | **10.80.60** | **80.70.1** |
|---|---|---|---|---|
| $R_a$ [µm] | 16 - 26 | 12 - 24 | 14 - 33 | 17 - 23 |
| $R_z$ [µm] | 87 - 118 | 65 - 110 | 75 - 150 | 92 - 113 |

In the limits of the conducted experiments crack formation could not be avoided, when using macrocrystalline WC, fused tungsten carbide or WC/Co compounds, **figure 6**. In case of macrocrystalline WC and fused tungsten carbide dispersed surfaces cracks occur exclusively in places with minimum thickness of the reinforced layer, while cracks in WC/Co compound dispersed surface layers occur in random places. In any case crack orientation is vertical and cracks propagate both through tungsten carbide based particles and metallic matrix. Only for use of nickel clad fused tungsten carbide as reinforcing material crack formation can be avoided completely. However, use of too high laser power levels that cause excessive dissolution of the clad fused tungsten carbide particles can still result in crack formation.

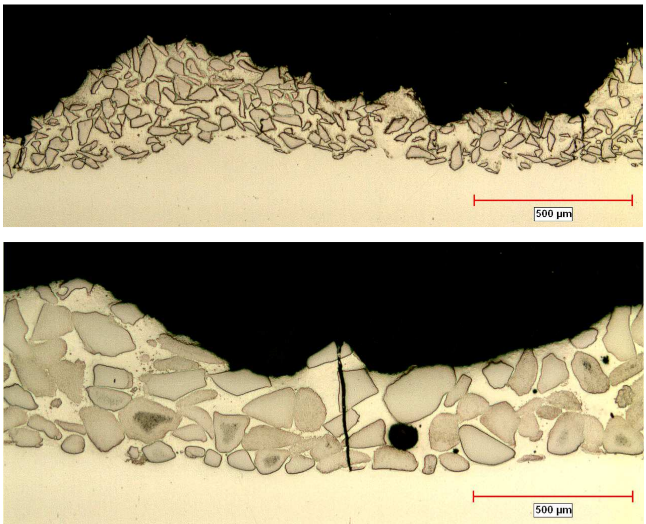


**Fig. 6.** Crack formation in S355J2G3 surfaces that were laser dispersed with fused tungsten carbide (top) and WC/Co compounds (bottom)

### 3.2 Laser dispersing of AlSi10Mg

Displacement of reinforced melt from the centre to the sides is observed for dispersing with both silicon and silicon carbide even for use of only 4 l/min carrier gas flow rate, **figure 7**. However, when using even lower carrier gas flow rate stable feeding of powders cannot be ascertained anymore and there is risk of feed line blocking.

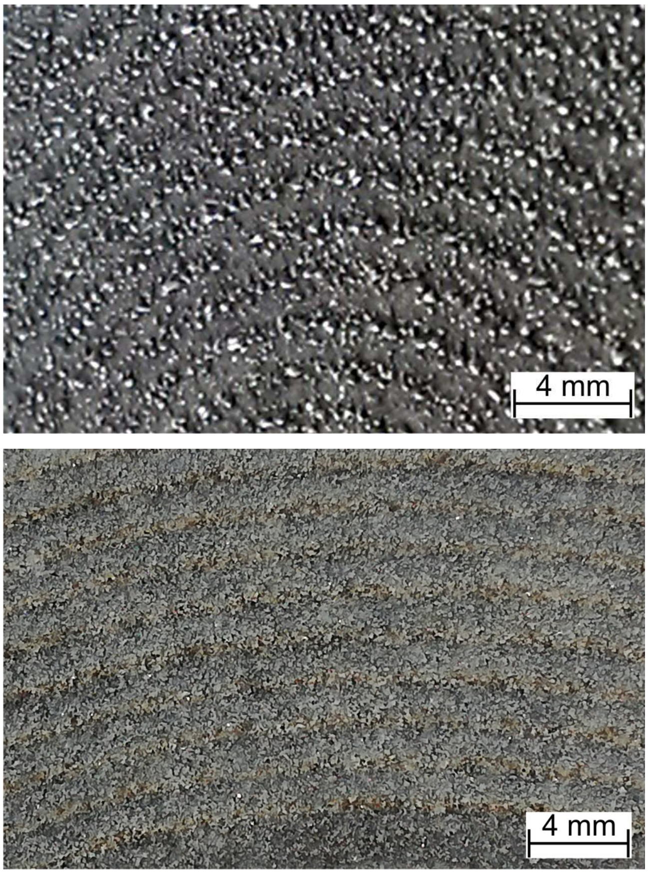


**Fig. 7.** Surfaces of AlSi10Mg alloyed with silicon (top) and dispersed with silicon carbide (bottom)

In the limits of the investigated parameters rough surfaces are produced, but no continuous surface layers with reinforcing phases are formed. Instead reinforcing phases form spikes on a layer of remelted substrate material that shows extremely fine microstructure due to process inherent high cooling rates, **figure 8**.

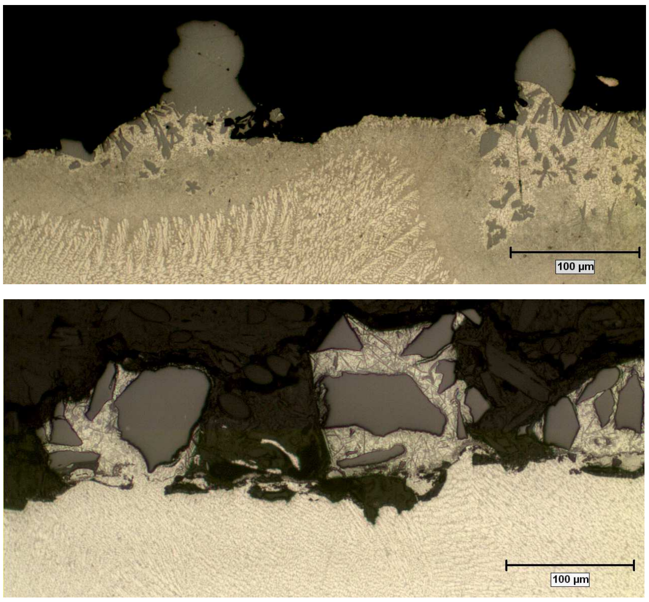


**Fig. 8.** Surfaces of AlSi10Mg dispersed with silicon (top) and silicon carbide (bottom)

Use of silicon as reinforcing material results in partial dissolution in the aluminium alloy melt and precipitation of primary silicon during cooling process as a result of hypereutectic silicon content in respective areas. The part of silicon particles that is not dissolved forms metallurgically well bonded spikes on the surface of the aluminium alloy.
In contrast silicon carbide is easily wetted by aluminium alloy melt and does not form pure silicon carbide spikes on the surface. A part of silicon carbide dissolves and results in precipitation of needle shaped aluminium carbides during cooling of the accordingly alloyed melt. Silicon carbide reinforced aluminium areas are partially separated from the underlying remelted aluminium alloy by thin oxide bands. Formation of such oxide bands during laser dispersing of aluminium alloys with silicon carbide has been reported for treatment of wrought precipitation hardened high strength aluminium alloys before [6]. In these studies separating oxide bands could be avoided by pre-heating to 150 °C and by adding 50 vol.-% AlSi40 to silicon carbide. The content of silicon in the here investigated aluminium cast alloy is too low to achieve such effect - at least without pre-heating.
Although surfaces with silicon and silicon carbide reinforcement show very different microstructure comparable roughness is observed. Typically $R_a$ between 20 - 25 µm and $R_z$ between 100 - 120 µm is achieved.

## 4 Summary

Laser dispersing is suitable for manufacturing of rough surfaces with high durability. Both for dispersing of S355J2G3 with different tungsten carbide materials and for dispersing of AlSi10Mg with silicon or silicon carbide roughness $R_a$ exceeding 20 µm and $R_z$ exceeding 100 µm can be achieved.
In the limits of investigated process parameters macrocrystalline tungsten carbide, fused tungsten carbide, sintered and crushed WC/Co as well as nickel clad fused tungsten carbides all formed surface layers with even distribution of reinforcing tungsten carbide based particles in S355J2G3. But, only use of nickel clad fused tungsten carbide permits avoiding crack formation completely.
Dispersing of AlSi10Mg with high hardness silicon carbide is accompanied by metallurgical problems. On the one hand dissolution of silicon carbide results in precipitation of needle shaped aluminium carbides and according embrittlement. On the other hand oxide bands that separate reinforced surface layers from remelted base materials are embedded with according detrimental effect on bonding of the reinforced surface layer. In contrast silicon is metallurgically fully compatible and bonds perfectly to alloyed surface layers that form as a consequence of partial dissolution of silicon in the aluminium alloy melt. Hypereutectic composition of the alloyed surface layer results in precipitation of primary silicon and accordingly strengthens surfaces which support silicon particles that form spikes.
In order to avoid displacement of melt to the sides of seams and accordingly wavy surfaces carrier gas flow rate needs to be minimized, but must still ascertain continuous feed of reinforcing particles. Powder nozzles with large working distance are particularly suitable with respect to this goal.

## 5 Perspectives

Further investigations are planned concerning dispersing of steel surfaces with vanadium carbide. It is expected to avoid crack formation even more secure than for use of nickel clad fused tungsten carbide due to advantageous re-precipitation behaviour of dissolved vanadium carbide from steel melt during cooling process.

## 6 Literature


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