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Hardfacing on High Strength Steel for Lightweight Wear Protected Structural Materials

Venti Oelde

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Fig. 1
Separate wear-plates applied to structural material on a worn industrial fan [2]

Wear and tear on machines and plants results in billions worth of damage yearly. Components which are exposed, during operation, to extreme wear and tear are often not directly hardfaced. Instead, pre-fabricated wearplates are manufactured using welding coating processes, adapted to the structural materials, and then either welded or bolted to the parts requiring protection. The consequence of this method is that the protected components are very heavy, which, particularly where fast-rotating fans, subject to wear, are concerned, is not expedient. Applying hard-facing directly onto high-strength structural materi-als, however, using conventional GMAW processes, where high dilution, a high energy input and an extensive heat-affected zone are typical, is not advisable, because the required mechanical properties of the high-strength steels are irrevers-ibly lost.

By using modern controlled dip transfer (short arc) welding processes, it is possible to considerably lower the heat input into the base material. A new field of application is the hardfacing of high-strength steels with the goal of ensuring an effective wear protection and also of retaining the mechanical properties of the hardfaced steel. The aim of this concept is: to encourage lightweight structural materials, resulting in a cost benefit for the com-plete plant.

Within the framework of this article, the possibility of hardfacing high-strength grade S960 steels using the controlled dip transfer (short arc) welding process will be discussed. The mechanical properties of the base steel as well as the behavior of the applied wear protective layers will be examined. This technol-ogy can be applied in the area of structural compo-nents for fast-rotating fans which are subject to wear and tear.

1 Introduction

Wear and corrosion are significant factors in the failure and breakdown of components in the industrial sector. In Germany, downtime and repair work cause losses amounting to 2–4 % of the Gross Domestic Product (GDP), averaging about 85 billion Euros [1]. In view of these enormous costs, researchers are continuously in search of new materials capable of withstanding the loads better and longer and, thereby, reducing costs.

Industrial fans, also, are affected by wear during their service life, necessitating regular maintenance and repair work. One way to reduce the occurring wear, is to use pre-fabricated wear-plates, which can be obtained from specialist suppliers.

They consist of a substrate material, onto which hard-facing layers, usually with a ferrous or nickel base, are applied by various welding processes. The finished plates are then shaped to the contours of the fan and bolted or welded to the fan structural components, where required – **Fig. 1**. The range of available materials is, however, limited. For example, no alloys with a (high)-boron content are used in this field on the composite wearplates, because these layers tend to flake off when being shaped. Besides which, the hard phase morphology (especially the hard phases distribution and particle size as well as the uniformity of the microstructure) is not as achievable using conventional OA/GMAW processes as it is required by the fine particle erosion.

Further disadvantages are that the structural materials in the primary hardfacing are often not directly coated, because these, due to the available, conventional welding processes, such as Plasma Transferred Arc (PTA), Open Arc (OA) and Gas Metal Arc Welding (GMAW), are subjected to such a high heat input that their original mechanical-technical properties are irreversibly lost and, therefore, cannot be included as a stress bearing cross-section in the fan design calculation. This means that wear-plates must be used, extra weight thus being caused by the wear-plate substrate material, resulting in considerable additional effort and costs for transportation, energy consumption, building of foundations, etc.

A possible answer is the development of wear protection systems, which meet the demands made by both wear and the deposition processes, to hardface highly stressed structural components, made from high- and ultra-high-strength fine-grained steel, using modern controlled (low energy) welding processes for ultralight fans.

2 Erosion on Fans

2.1 Typical Abrasion and Wear Patterns

Wear on fans is caused by particles carried in the airstream, because the industrial fans are installed, for example, in cement or steel works, chipboard or plastics factories or in chemical plants and refineries in dust extraction plants for raw materials, to handle air containing fine, highly abrasive dusts. **Table 1**.

The particles carried in the airstream cause considerable wear damage when they collide with the structural materials of the fan, i.e. blades, backplate, shroud, **Fig. 2**.

Table 1
Average particle size of typical abrasives handled by fans [2]

Abrasive substance	Average particle size in μm
Raw meal dust	~ 8
Sinter dust	5-15
Dusts from steel production	< 20
Cement raw meal	8-15
Cement dust	10-20

Fig. 2
Disabling wear on industrial fans after use [2]
a) Erosion on a fan backplate
b) Erosion on fan blades

2.2 Conventional Wear Protection

Welded protective coatings are preferred as an answer to wear in fan construction, because of the required wear reserve, or rather, layer thickness, and the dynamic wear and tear to the hardfacing deposition. The wear-resistant materials consist of a relatively hard and tough mixed crystalline matrix, in which the wear-resistant, hard materials are embedded. High-alloy ferrous and nickel base alloys are used as wear-resistant alloys. **Table 2**.

These are normally applied to the substrate materials grade S235, S355, and in exceptional cases, S690 and S960, by metal-cored wire-type metal-arc or blended powder plasma welding processes. In this way, wear-plates with varying thicknesses are made. The coatings applied display a multi-phase microstructure, consisting of metallic carbides and borides or combinations of these hard materials, formed in situ or atypical and introduced. All alloys have in common that they are welded with a high heat input (PTA, OA and gas metal-arc welding (GMAW)).

While, in the cost-intensive PTA processes, costly powder hard-phase-reinforced nickel alloys with a dilution of normally under 10 %, are used, the main field of application of the lower-cost gas metal-arc welding (GMAW) and OA processes lies in the processing of Fe base materials. With the gas metal-arc welding (GMAW) and OA processes, a dilution of usually between 20 and 40 % is obtained; **Table 3**. The attribute “dilution” describes the ratio of the blending zone, comprising base metal and consumables, to the total surface of the weld cross-section. The quality of the coating increases with decreasing dilution grade, whereby a minimum figure of about 3 % is required so that layer bonding is ensured under dynamic load.

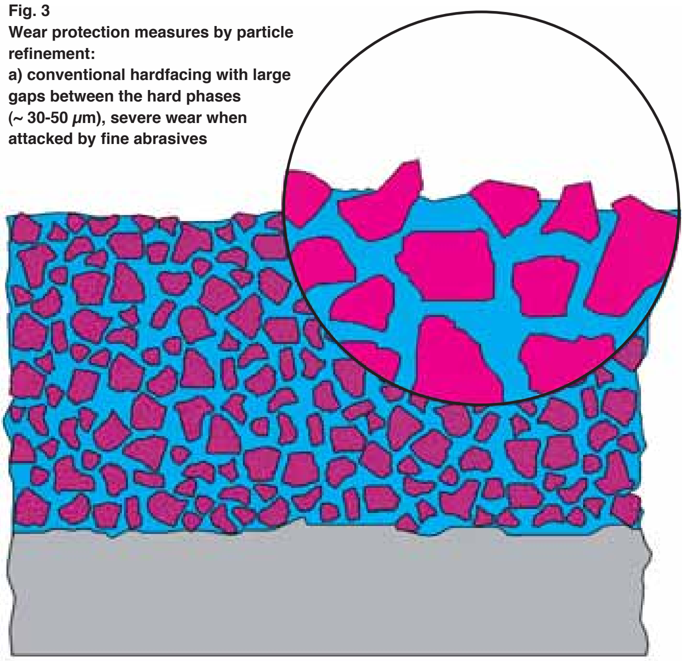
2.3 High Performance Wear Resistance Systems

The wear-resistance effectiveness of hard alloys relies on the hard and tough hard phases preventing the sharp abrasives from penetrating the matrix. If, however, the hard phases are more widely distributed than the average particle size of the abrasives, the matrix metal will be eroded and there will be considerable wear, **Fig. 3**.

The abrasives considered here, see **Table 1**, have, in comparison to other wear-protection applications, such as in mining, extremely small particle sizes, in the range of about 10 μm. In this case, therefore, irrespective of the base alloy, a finely dispersed distribution of the hard phases (≤ 12 μm), is absolutely necessary so as to obtain an improvement in wear-resistance.

As well as high-quality Ni-based alloys, there are alternative, less costly materials on a ferrous base. It is intended to hardface high-strength, high-grade steels, grades S690+ or S960+, used in fan construction, using modern, low-energy metal-cored wire-type

Fig. 3
Wear protection measures by particle refinement:
a) conventional hardfacing with large gaps between the hard phases (~ 30-50 μm), severe wear when attacked by fine abrasives



b) customized hardfacing with very small gaps between the hard phases providing resistance against fine-abrasive wear [4]

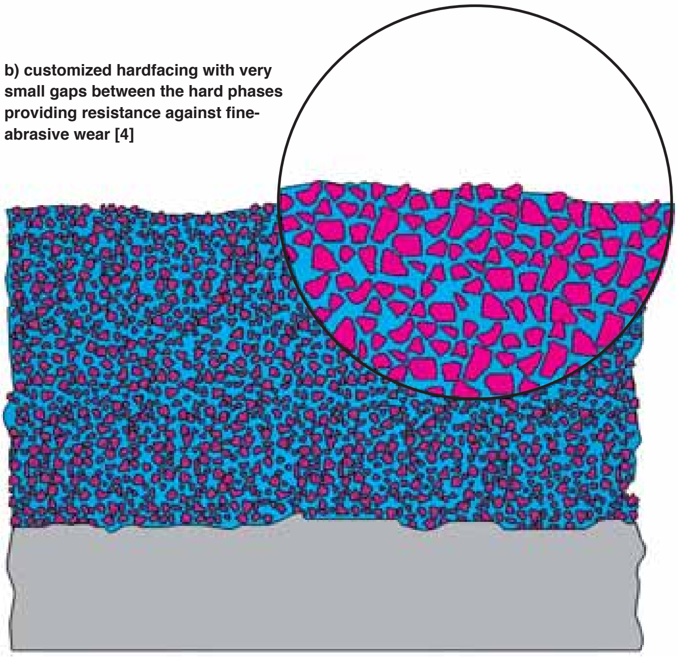


Table 2
Standard wear-resistant materials used in fan construction

Matrix	Hard phase formers	Welding process
Fe	Cr, (Nb, V, Mo, W), (C, B)	OA/GMAW
Fe	C, Cr, WSC	OA/GMAW
Ni	Cr, Mo, WSC	PTA, GMAW

Table 3
Standard processes for hardfacing in fan construction [3].

Welding-process	Deposition-rate in kg/h	Dilution in %	Layer thickness in mm
GMAW/OA	8-9	20-40	4-8
PTA	≤ 15	5-10	2-7

controlled dip transfer (short arc) welding processes, without the original base material properties being unacceptably impaired. This means that the hardfaced base materials can be used as high-stress structural materials, i.e. both lightweight structural aims are realized (retention of the base material properties) as well as considerable extension of the useful life being achieved (coating properties).

3 Short Arc Technology

Controlled dip transfer (short arc) welding processes only slightly affect the materials involved thermally, because on a whole there is a lower heat input (short circuit arc technology) and, therefore, the high short circuit currents are avoided. The controlled dip transfer (short arc) welding process was developed so as to be able to join thin sheet materials together by welding. So as to avoid heat input and uncontrolled spatter during interruption of the short circuit current, the output maximum on arc reignition is considerably reduced. This results in a noticeably lower thermal interference of the materials during the fusing phase [5].

As well as a joining process, this technology is also applicable to hardfacing welding [6–8]. For example, corrosion-resistant cladding plates are manufactured on a commercial scale using the controlled dip transfer (short arc) welding process [9].

When using the conventional short arc welding process, reduction of the heat input into the substrate material usually results in inadequate weld bead formation. In the controlled dip transfer (short arc) welding process, the short circuit current and the current increase on arc re-ignition after material deposition, are automatically controlled during the short circuit. Droplet detachment can, in addition, be mechanically assisted by an oscillating wire feeder. **Table 4** provides a selection of process methods available at present in conjunction with the variables used. Regarding current developments, attention is being focused on the modification of consumables as well as on the use of these processes for hardfacing on heat-sensitive materials. Studies of [6, 8, and 10] have already shown that a refinement of the hard phases in comparison with conventional methods is possible. In connection with this, an improvement in the performance of the coatings in the face of fine-abrasive or erosive loads is expected in practical use [11].

Table 4
Selected controlled dip transfer (short arc) welding processes acc. to manufacturer [10]

Controlled dip transfer (short arc) welding	Manufacturer
Electronic control	
AC-MIG	OTC Daihen Europe
coldArc®	EWM Hightec Welding
CP (Cold Process)	CLOOS
RMD™ (Regulated Metal Deposition)	Miller Electric
SST (Surface Tension Transfer)	Lincoln Electric
Electronic and mechanical control	
CMT (Cold Metal Transfer)	Fronius International
CSC (Controlled Short Circuit)	Miller Electric

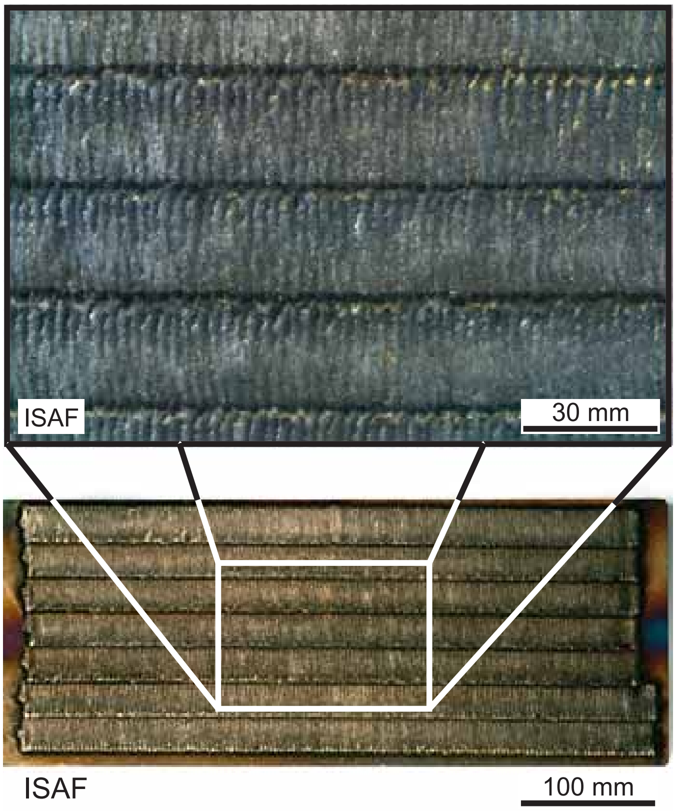


Fig. 4
Structural component coating Fe-base + Cr-Boride + VC applied by controlled dip transfer (short arc) welding process

4 Experimental Set-up and Procedures

Hardfacing was applied, using the controlled dip transfer (short arc) welding process, to fine-grade structural steel, grade S960QL. The consumables used were metal-cored wire-based Fe-based alloys (Ø 1.6 mm), with typical hard phases.

Also used were a high-chromium/high-boron hard-alloy, a Cr-boride-forming Fe-based alloy with VC and NbC as additional alloy content and, as a reference wear-resistant material, a conventional high-chromium/high-carbon Fe-base material, type FeCrC. The generated layers were examined metallographically and also regarding wear.

4.1 Hardfacings

Using the selected metal-cored wire consumables, extensive wear-resistant depositions were applied onto the structural material, in weave-bead technique with a weaving width of 20 mm, **Fig. 4**. A coating thickness of between 2 and 2.5 mm was applied. An argon-CO_2 mix was used as shielding gas.

Pure weld metal samples were taken from the welded coatings, by means of spark erosion, and the material density was measured using a pycnometer, **Table 5**.

The generated composite layers were metallographically examined and, as well as determination of the coating hardness (Rockwell hardness test, Scale C), low-load hardness measurements were taken in the area of the heat-affected zone.

4.2 Metallographic Analysis

The hardfacing microstructure type FeCrB, after being applied by the controlled dip transfer (short arc) welding process, shows a random hard phase distribution of the hard chromium-borides with very small hard phase gaps, **Fig. 5**.

The newly developed wear-resistant material type FeCrNbVBC also possesses additional hard phases of vanadium carbide, which are deposited in the matrix between the boride hard phases and thus further reduce the size of the gaps between the hard phases, **Fig. 6**.

4.3 Wear Analysis

To determine the erosion wear-resistance of the deposited coatings, blast wear tests were carried out in accordance with DIN 50332. This test setup consists in the main of the blasting chamber itself; a container and the dosing system to control the mass flow of abrasives, a

Fig. 7
Schematic diagram of the blast wear test setup

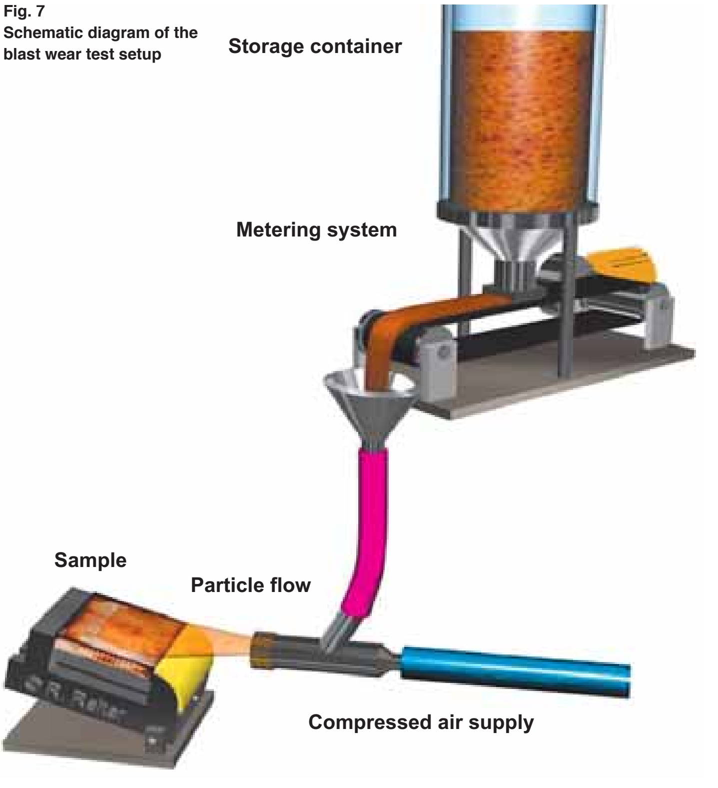


Table 5
Properties of the hardfacing layers

Type	Material density in g/cm³	Coating hardness in HR_C
FeCrB	7.2	56.6
FeCrNbVBC	7.1	65
FeCrC	7.6	63-66

Table 6
Test parameters

Wear test	Blast wear test (DIN 50332)
Abrasives	Cement dust
Stress angle	10° (Inclined blast wear)
Primary pressure	7.5 bar
Sample distance	20 mm
Mass flow of abrasives	140 g/min
Test duration	2 h

Fig. 5
Controlled dip transfer (short arc) welding process: FeCrB

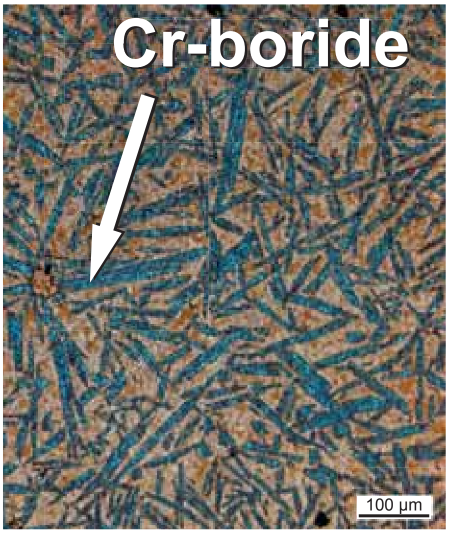
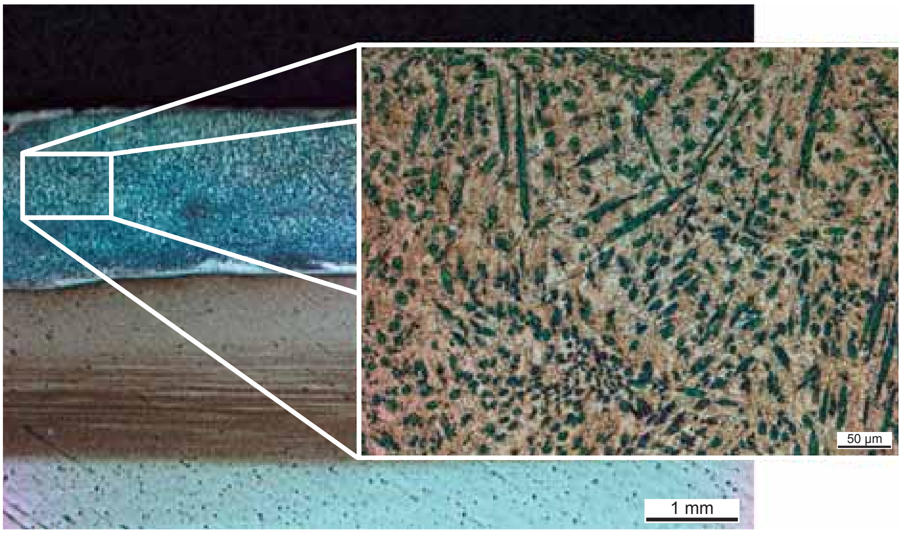


Fig. 6
Controlled dip transfer (short arc) welding process: FeCrNbVBC



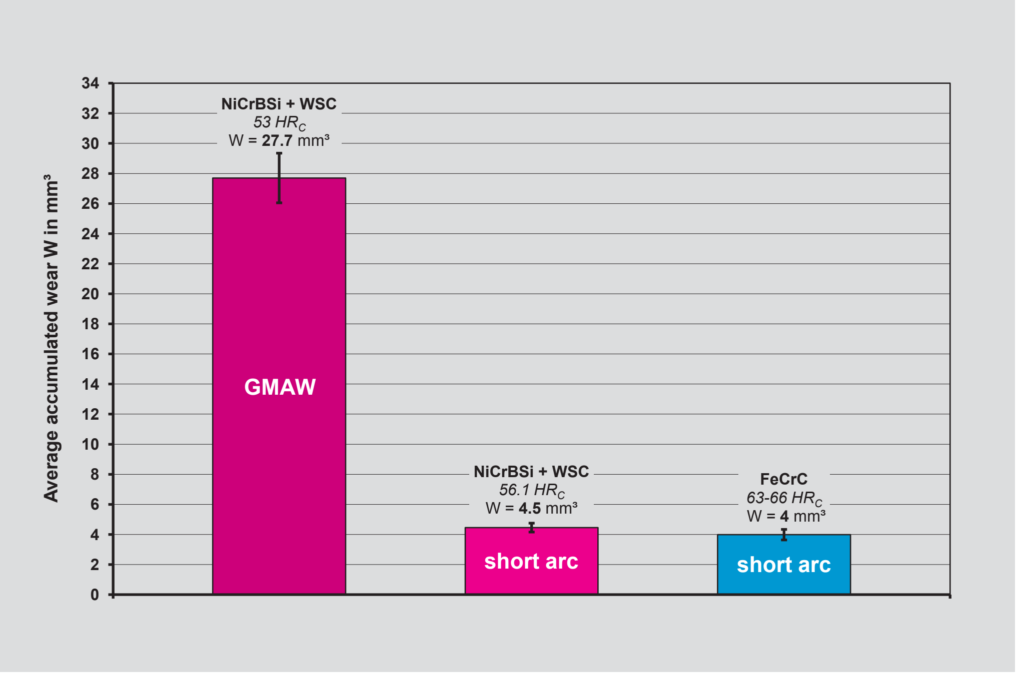
compressed air supply, an injector and the sampling, see **Fig. 7**. Via the dosing system, a set amount of the abrasives, non-varying for the complete test run, flows out of the container and is led to the injector. The free-travelling particles in the gas-bearing blast cause impact and/or abrasive material damage, depending on the load angle.

For the tests, a blast angle of 10° (inclined blast wear) on the weld transition was selected, because practical experience has shown this to be a particularly weak point. The test was carried out in the direction of the weld using cement dust as abrasives. A particle size analysis of the abrasives used, showed an average particle diameter of $d_{50} \approx 16\ \mu m$. Variable test parameters are the primary pressure and the mass flow of the abrasives as well as the distance between material sample and injector outlet, **Table 6**.

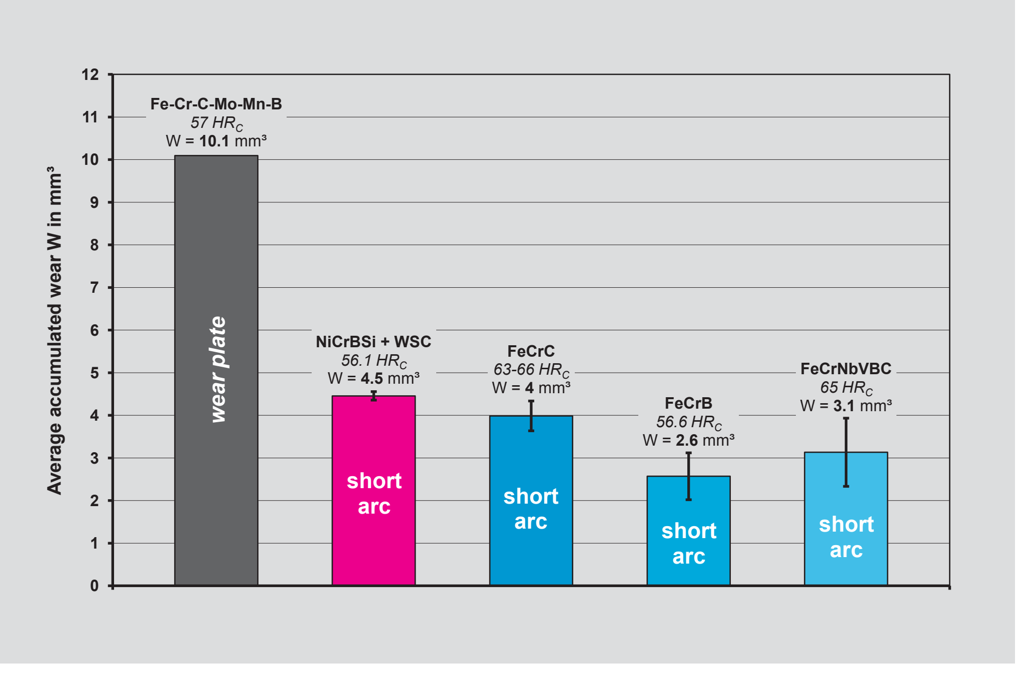
The analysis showed that the wires which had been welded using the controlled dip transfer (short arc) welding process performed much better with regard to wear-resistance than the cored wires which had been welded using the gas metal-arc welding (GMAW) process (here using the example of NiCrBSi + WSC), **Fig. 8**. The increased wear-resistance can be explained by the microstructure formation, specific to the process. With the alloy NiCrBSi + WSC, used in the controlled dip transfer (short arc) welding process, there was a reduction of the occurring carbides dissolution, or rather, of the formation of WC, and, thereby, an increased wear-resistance when subjected to a fine-erosive load, obtained through the process-related lower heat input.

The hardfacing with innovative wear-resistant materials, its hard phases embedded tightly in the matrix, together with very small gaps between the hard phases, in conjunction with the low-heat controlled dip transfer (short arc) welding process (dilution < 10 %), provided, in comparison with normal wear-resistance solutions (Fe-Cr-C-Mo-B-wear-plates), an increase in useful life of 325 % to almost 400 %, and when set against conventional coating materials, also applied by the controlled dip transfer (short arc) welding process, an improvement of 150 % to 175 %.

Fig. 8
Average accumulated wear abrasion below 10° – inclined blast wear.
a) Hardfacing with GMAW vs. controlled dip transfer (short arc) welding



b) New types of high-performance wear-resistant systems



5 Lightweight Construction Potential

So as to achieve the goal of a lightweight construction, coating thicknesses of between 2 and 2.5 mm were aimed at. The extent of the heat-affected zones was about 3 mm for all welds and, therefore, in comparison with conventional composite layers, had a stable width of considerably < 5 mm, whereby the stress bearing residual cross-section was clearly increased. In conjunction with a dilution zone of < 1.5 mm, a preservation of the base material properties can, therefore, be assumed for all coatings. In addition, low-load hardness measurements (HV 1) were taken in the area of the heat-affected zone, see **Fig. 9**. Using the low-energy controlled dip transfer (short arc) welding process, it was possible to clearly reduce hardening in the heat-affected zone and in the heat-sensitive base material in comparison with the GMAW process (using FeCrC here as an example). An increased hardness was ascertained in the weld metal in both the conventionally used FeCrC alloy and the newly developed high-performance wear-resistant alloy. Reduction in the extent of the heat-affected zone when using the controlled dip transfer (short arc) welding process was confirmed by the hardness continuum.

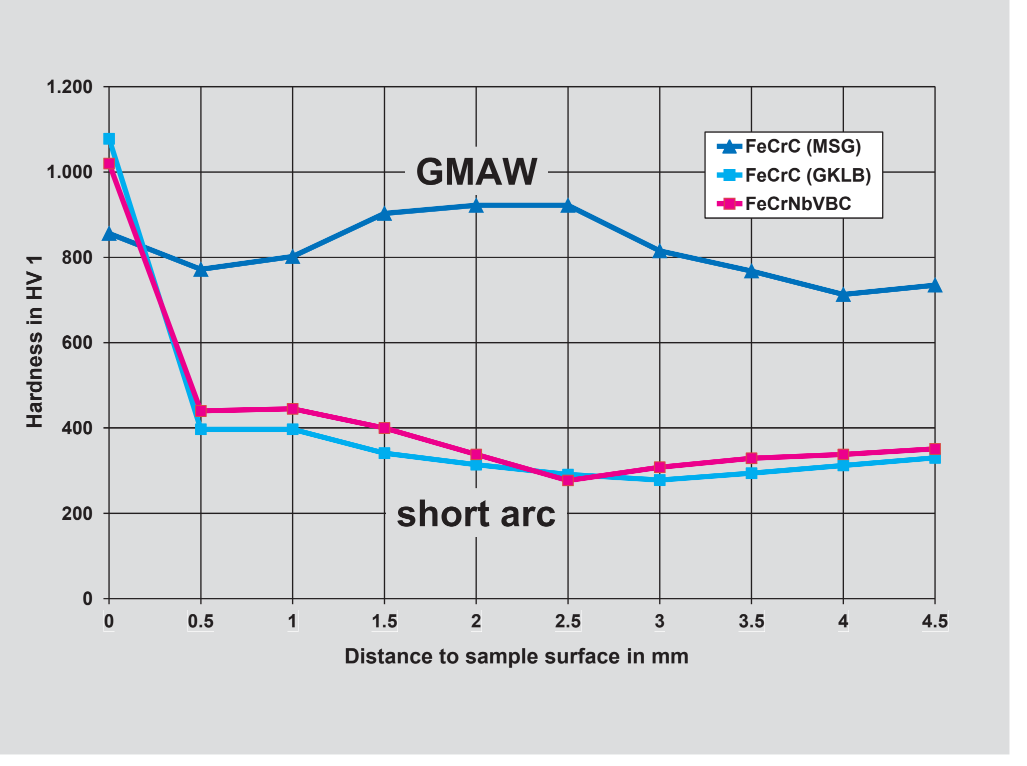


Fig. 9
Heat-affected zone hardness comparison GMAW v Controlled dip transfer (short arc) welding

6 Summary

Typical as well as innovative metal-cored wire-type high-performance wear-resistant alloys were welded, using a controlled dip transfer (short arc) welding process and these were partially compared with coatings, produced using a conventional GMAW process. It was found that, when using the controlled dip transfer (short arc) welding process with hard alloys with characteristic hard phases, a hard phase refinement occurs and when processing nickel alloys containing fused tungsten carbides (FTC), the occurring hard phase dissolution could be noticeably reduced.

During the blast wear test, carried out in accordance with DIN 50332. It was discovered, that this in turn, considerably increased the quality of the hardfacing layers and, compared to conventional hardfacing layers, there was a clear improvement of wear-resistance. The use of customized high-performance wear-resistant systems on a Fe base, consisting of a controlled dip transfer (short arc) welding process and newly developed wear-resistant alloys, offers optimum protection against finely erosive loads through the dispersion of the tightly embedded chromium-borides with very small gaps between the hard phases, and provides a technical and economic alternative to the costly Ni-based alloys.

Structural lightweight goals in fan construction are also noticeably enhanced by the low-energy controlled dip transfer (short arc) welding process, because, on the one hand, the extent of the heat-affected zone is small and the stress bearing residual cross-section is suitably large. On the other hand, structural components can be directly hardfaced. The use of composite wear-plates is unnecessary.

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