Influence of the wire diameter and particle fraction of Fe-Al₂O₃/ZrO₂ flux-cored wires processed by wire arc spraying on the abrasive wear properties of the coating

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Abstract. The embedding of ceramic particles of a certain size and concentration in a ductile matrix is a strategy for producing wear-resistant coatings. In wire arc spraying, flux-cored wires with a metallic sheath and particle-filled core can be used for this purpose. The influence on wear properties of wire diameter and particle fraction has hardly been investigated so far. Due to the high kinetics of arc and gas flow, there are considerable challenges with regard to reproducibility, homogeneity and material efficiency. As a basis for a significantly improved understanding of the process, the relationships between the wire diameter, the particle fraction used and the wear resistance of the produced coatings have been investigated. The objects of investigation were flux-cored wires with an iron sheath and a particle filling of Al₂O₃/ZrO₂. By using the ball-on-disc test and rubber wheel test, the wear resistance of the respective coatings was investigated.

1. Introduction
Thermally sprayed wear protection coatings are used in a variety of machine elements to increase the resistance to severe abrasive wear. The main objective is the use of cost-effective base materials enhanced by appropriate surface functionalization. To increase wear resistance, hard material particles in the desired size and concentration can be embedded in a ductile matrix [1, 2]. The matrix material consists mostly of an Fe, Ni or Co alloy. The reinforcing particles usually are metal carbides like WC or TiC [3]. Dallaire and Levert investigated the influence of TiB₂ particles with different volume ratios in wear-resistant austenitic stainless steel coatings produced by arc spraying of flux-cored wires. The flux-cored wires consisted of a sheath of 304 stainless steel, TiB₂ particles, 316L particles and inorganic additives. The wear resistance was investigated using the dry rubber wheel abrasion test. The coatings with a volume ratio of 18 vol.% TiB₂ showed the lowest wear volume loss, which was about 6.5 times lower compared to an austenitic stainless steel coating [1]. Fang et al. studied the coating microstructure and wear properties of TiB₂ reinforced stainless steel 304L and nickel-chromium alloy coatings produced by arc spraying of flux-cored wires with different particle fractions. Dry sliding wear tests were performed using a block-on-ring tribometer at room temperature according to the GB 12444.2-90 standard. The coatings with the finer particle fraction (1 - 10 µm) exhibited clearly lower volume loss compared to the coatings with the coarser particle fraction (10 - 100 µm). Due to the smaller volume, the finer particles are more likely to melt and distribute themselves more homogeneously in the coating [4]. As a result of the high and volatile prices as well as the restricted availability, there are strong efforts from both political and economic perspectives to develop suitable substitute materials for conventional reinforcement particles such as WC, Cr₂C₃ und TiC [5]. An appropriate cost-effective alternative is the use of iron-based matrices with oxide hard particles. Metallic oxides such as alumina...
(Al$_2$O$_3$) and zirconia (ZrO$_2$) provide high hardness up to 2100 HV and their compositions (subsequently referred as Al$_2$O$_3$/ZrO$_2$) provide high fracture toughness of up to 7.8 MPa-m$^{1/2}$ [6] exceeding even those of fused tungsten carbides [5, 7–10]. Hwang et al. investigated the influence of Al$_2$O$_3$/ZrO$_2$ (60 wt.% Al$_2$O$_3$, 40 wt.% ZrO$_2$) particles with different volume ratios (10–30 wt.%) in wear resistant stainless steel coatings produced by plasma spraying. The wear resistance was examined using the pin-on-disc test. The coating with a 20 wt.% of Al$_2$O$_3$/ZrO$_2$ particles showed the lowest volume loss under various load conditions of only 3–5% compared to the coating without particle reinforcement. The dominant wear characteristics were abrasive wear in the form of scratches and particle breakouts. The breakouts were initiated by particle/matrix interface cracks. The crack initiation is favoured by a high hardness gradient between the matrix and the particles [11]. Another critical aspect is the poor wettability of oxide ceramics like Al$_2$O$_3$/ZrO$_2$ with iron-based melts due to the low chemical interaction. This leads to insufficient bonding of the ceramic particles in the metallic matrix. Brust et al. improved the bonding between the particles of Al$_2$O$_3$/ZrO$_2$ and the metallic matrix by a CVD coating of the particle surface with TiN [2, 5]. The use of the wire arc spraying process in combination with flux-cored wires represents an attractive technique for the production of particle-reinforced metallic coatings [1, 12, 13]. The advantages of the process are the very low process costs, as only an atomizing gas such as nitrogen or compressed air is required [4, 14]. In addition, the process technology and process control enable an automated application [14]. When using flux-cored wires, however, special features must be taken into account. The composition of the wires varies due to the seaming used, the dimension of the sheath material and the proportion of particle filling. The ratio between the sheath material and the particle filling has a significant influence on the process as well as on the properties of the resulting wear protection coating. Due to the significant smaller cross-section area of the sheath material compared to solid wires, the resulting molten metal is considerably smaller. Due to the high thermal energy of the electric arc - especially on the anodic side - a significant volume of the comparatively low-melting metallic sheath material is not only melted but converted into gaseous phase and evaporates. The melted sheath material is sprayed onto the prepared substrate surface by the process gas. At the same time, the particles get extracted out of the flux-cored wire by the negative pressure of the process gas flowing past. A part of the oxide ceramic particles gets in contact with the electric arc and therefore melts partly or fully. Another part remains solid and penetrates the molten metal during the flight phase or by impacting at the substrate surface and is thus integrated into the generated coating [15]. A considerable disadvantage of using the wire arc spraying process is the loss of reinforcing particles during the coating application. Due to the non-perpendicular angle of impact of the particles to the substrate surface as a result of the wide expansion of the spraying jet in the wire arc spraying process, individual particles are not bound into the matrix but are reflected directly from the substrate surface [16]. By increasing the wire diameter, the ratio of sheath material to particle reinforcement decreases. A better understanding of the effects of different wire diameters, sheath-to-filling ratios and particle size fractions on the microstructure and the wear resistance of the generated coatings is the target of the presented research.

2. Experimental setup and materials
The investigated flux-cored wires were composed of an iron sheath and reinforcing particles of Al$_2$O$_3$/ZrO$_2$. The investigated wire variations differed in the diameter, the sheath geometry (width and thickness of the metal tape before seaming) and the contained particle filling fraction (fine (F) and coarse (C) fraction) specified by the manufacturer. The particle fraction is indicated by using d90 as well as d10, which means that 90% respectively 10% of all particles are smaller than this threshold. Thus, 80% of the particles are in between these two threshold values. For example, considering the coarse particle fraction -160/+63, 90% of the particles should be smaller than 160 µm and 10% of the particles should be smaller than 63 µm. A corresponding overview of the different wires and the used nomenclature is given in table 1.
The aluminium substrate surface was roughened by means of grit blasting. For this purpose, Alodur EKF-24 corundum with a particle size in the range of 600 µm to 850 µm was used. The grit blasting was carried out at a pressure of ca. 2 bar with a blasting angle of ca. 70° and a distance of ca. 150 mm. The samples were subsequently cleaned in an ethanol bath using ultrasound and then dried. The coating process was performed with a wire arc spraying system consisting of the VisuArc350 inverter and the Schub5 torch (both Oerlikon Metco, Pfäffikon, Switzerland). The torch was mounted on a five-axis robot. The process parameters, which were selected on the basis of preliminary investigations with the aim of achieving the lowest possible coating porosity, are given at table 2.

| name    | wire diameter (mm) | sheath width and thickness (mm x mm) | particle fraction d90/d10* (µm) |
|---------|-------------------|-------------------------------------|---------------------------------|
| FeF_16  | 1.6               | 10 x 0.22                           | -90/+45                         |
| FeC_16  | 1.6               | 10 x 0.22                           | -160/+63                        |
| FeF_24  | 2.4               | 14 x 0.30                           | -90/+45                         |
| FeC_24  | 2.4               | 14 x 0.30                           | -160/+63                        |

Table 2. Wire arc spraying process parameters of flux-cored wires.

| name    | current (A) | voltage (V) | relative traverse speed (m/s) | spraying distance (mm) | carrier gas pressure (MPa) | spray path offset (mm) | carrier gas |
|---------|-------------|-------------|------------------------------|-----------------------|---------------------------|------------------------|-------------|
| FeF_16  | 150         | 35          | 1                            | 150                   | 0.6                       | 5                      | Air         |
| FeC_16  | 150         | 35          | 1                            | 150                   | 0.6                       | 5                      | Air         |
| FeF_24  | 150         | 45          | 1                            | 150                   | 0.6                       | 5                      | Air         |
| FeC_24  | 150         | 45          | 1                            | 150                   | 0.6                       | 5                      | Air         |

Due to the increased dimensions of the iron sheath of the wires with 2.4 mm diameter the voltage was increased from 35 V to 45 V. To achieve a comparable coating thickness, the number of transitions varied between nine and eleven for the different wires. After four transitions, a cooling period of five minutes was implemented to reduce residual thermal stresses. The target coating thickness was 500 µm to 600 µm.

A detailed characterisation of the microstructure has been conducted for the flux-cored wires and the coatings. Metallographic cross-sections were produced using standard metallographic procedures. The analyses were carried out with the scanning electron microscope (SEM) LEO 1455VP (Zeiss, Jena, Germany). A backscattered electron detector was used to visualise the material contrast. The chemical composition was identified with the integrated energy-dispersive X-ray spectroscopy (EDS) system EDS GENESIS (EDS, Mahwah, NJ, USA). The phase composition of the wire sheath, the particle filling and the thermal sprayed coatings was studied by X-ray diffraction (XRD) with the D8 Discover diffractometer (Bruker AXS, Billerica, MA, USA) equipped with a LynxEye XE-T detector using Co Kα radiation with a tube voltage of 40 kV and a tube current of 40 mA. The diffraction patterns were measured for a 2θ range from 20° to 130°, with a step size of 0.02°. Using the Olympus GX51 inverted microscope (Olympus, Hamburg, Germany), the porosity and particle ratio of the coatings were determined using contrast-based quantitative digital image analysis within the Olympus Stream software. The determination of the area fraction of the pores or particles is in line with the usual procedure from the state of the art and serves as an approximation for the existing actual volume fraction. The particle size distribution of the ceramic particles of the flux-cored wires was measured through laser
diffraction analysis by a Cilas 920 particle size analyzer (Cilas, Orléans, France). The measuring principle is based on the diffraction of the laser depending on the particle size. The measuring range is 0.3 µm to 400 µm.

The wear behaviour of the coatings was determined under combined sliding and abrasive wear conditions. The surfaces of the coated samples were ground to Ra 0.3 µm in advance. For the evaluation of the sliding wear behaviour in the ball-on-disc test, the Tetra basalt tester (Tetra, Ilmenau Germany) was used. The wear test parameters were based on the ASTM G99 standard. The abrasive wear behaviour was carried out by the rubber wheel test. Test method E according to ASTM G65 standard was selected. The applied abrasive was dried quartz sand with a grain size of -300/+180 µm (d90/d10). Three samples of each coating were investigated for both tests. The applied wear parameters are listed in table 3.

Table 3. Wear test parameters.

| Ball-on-Disc Test | Rubber Wheel Test |
|-------------------|-------------------|
| Normal force      | Normal force      |
| 20 N              | 130 N             |
| Wear track radius | Wheel diameter    |
| 6 mm              | 229 mm            |
| Rotation          | Rotation          |
| 96 RPM            | 200 RPM           |
| Speed             | Speed             |
| 60 mm/s           | 2400 mm/s         |
| Wear track        | Wear track        |
| 596 m             | 718 m             |
| Counterbody       | Counterbody       |
| Al₂O₃ (ø 6 mm)    | Rubberised steel wheel |
| Abrasive medium   | Quartz sand       |

The evaluation of the loss of volume as well as the depth and width of the wear tracks was performed using the tactile measurement device Hommel-Etamic T8000 (Jenoptik, Villingen-Schwenningen, Germany) and the 3D profilometer MicroCAD compact (LMI, Teltow, Germany). The tactile measurement of the wear tracks was carried out perpendicular to the movement of the counterbody.

3. Results and Discussion
3.1. Flux-cored wire characterisation

Figure 1 shows the cross sections of two wires with a diameter of 2.4 mm and different particle fractions. It can clearly be seen that the coarse fraction contains considerably larger particles.

![Figure 1. Scanning electron microscope (SEM) images (BSD) of flux-cored wires with a diameter of 2.4 mm (left: fine particle fraction; right: coarse particle fraction).](image-url)
For an exact determination of the particle distribution, the particle fillings were taken from the wires with a diameter of 2.4 mm. Contrary to the manufacturer’s specifications, the particle fractions used are significantly larger. The fine fraction has a particle range \( (d_{90}/d_{10}) \) of \(-83/+8 \, \mu m\) and the coarse fraction of \(-225/+24 \, \mu m\). Both fractions have a very high proportion of very fine particles, which is beneficial to wire stability and thus to wire feeding. As shown in figure 2, the particles have a very edged and irregular structure.

![Figure 2. SEM images (BSD) Al₂O₃/ZrO₂ particles (left: overview; right: in detail).](image)

By using the backscattered electron detector (BSD), the composition of the particles becomes clearer. The heterogeneous composition of the particles was investigated in detail by EDS measurements on the cross sectioned particle shown in figure 3. These showed that the grey areas consist of Al₂O₃ and the white areas of a lamellar structure of Al₂O₃ and ZrO₂. The chemical composition of the lamellar structure is 60 at. % O, 30 at. % Al and 10 at. % Zr. However, due to the difficulty of measuring light elements like oxygen by EDS measurements, the oxygen content should be understood as a rough orientation.

![Figure 3. Detailed view of a sectioned Al₂O₃/ZrO₂ particle with red arrows indicating Al₂O₃ particles and eutectic areas of Al₂O₃ and ZrO₂.](image)

3.2. Phase formation and chemical composition

The XRD patterns of the flux-cored wire sheath, particle filling and sprayed coatings of the 2.4 mm wires are presented in figure 4. The flux-cored wire sheath consists solely of ferrite with a body-centred cubic structure. The particle filling inside the flux-cored wire is composed of alumina (Al₂O₃), zirconia (ZrO₂) with monoclinic structure and aluminium zirconium oxide \((Al_{0.52}Zr_{0.48}O_{1.72})\) with tetragonal structure. The sprayed coatings contain iron as well as aluminium oxide, zirconium oxide and aluminium...
zirconium oxide like the flux-cored wire. During the spraying process the iron sheath undergoes oxidation which causes additional iron oxide (FeO) with cubic structure in the coatings. Compared to the XRD measurement of the particle filling only small proportions of \( \text{Al}_2\text{O}_3 \) and \( \text{ZrO}_2 \) were detected within the coatings although they are clearly visible within the cross-sections.

![XRD patterns of the flux-cored wire sheath and particle filling as well as the sprayed coatings.](image)

**Figure 4.** XRD patterns of the flux-cored wire sheath and particle filling as well as the sprayed coatings.

The chemical composition of the coatings was examined by area measurements and are presented in table 4. The investigations show a higher iron content and slightly lower content of aluminium, zirconium and oxygen for the coatings with the finer particle fraction regardless of the wire diameter. The FeF\(_{24}\) coating presents the lowest proportion of aluminium and zirconium, which is even lower compared to the FeF\(_{16}\) coating. This could be due to the increased ratio of sheath material to particle filling (2:3) compared to the smaller wire (1:1). In addition, the use of the thicker wires leads to a widening of the spraying jet, whereby more particles hit the substrate surface at a lower angle and after a longer flight phase. Both of these factors reduce the chance of the smaller ceramic particles being integrated into the coating.

| Sample        | Fe   | Al   | Zr   | O     |
|---------------|------|------|------|-------|
| FeF\(_{16}\) coating | 41.0 | 20.1 | 1.5  | 37.3  |
| FeC\(_{16}\) coating  | 38.4 | 21.5 | 1.8  | 38.3  |
| FeF\(_{24}\) coating  | 41.6 | 18.2 | 1.3  | 38.9  |
| FeC\(_{24}\) coating  | 35.8 | 22.1 | 1.9  | 40.2  |

**Table 4.** Chemical composition of wire arc sprayed coatings in at. %, measured by energy-dispersive X-ray spectroscopy (EDS).
The FeC\textsubscript{24} coating contains the highest composition of aluminium, zirconium and oxygen leading to the assumption of the highest particle ratio of all four coatings. The particles of the coarse particle filling fraction are significantly larger and therefore heavier, which means that they are less strongly distracted by the process gas and therefore increased their chance of impacting the substrate surface perpendicularly. This could favour the inclusion of the larger ceramic particles in the coating. The increase of the elements aluminium and zirconium in the chemical composition of the coatings could be an indicator for a higher particle ratio of the coatings with the coarse particle filling. As mentioned before, the detection of light elements like oxygen by EDS measurements is not as accurate.

3.3. Coating microstructure

The microstructure of the thermal sprayed coatings of the flux-cored wires was investigated by SEM to visualize the material contrast of the different elements. Figure 5 shows representative microstructural images. The coatings exhibit a porosity of ca. 3 % to 5 % which is typical for wire arc sprayed coatings. The bright areas are made out of iron, the light grey out of oxidized iron (FeO), the dark grey sections are made out of the Al\textsubscript{2}O\textsubscript{3}/ZrO\textsubscript{2} particles and the black particles are made out of Al\textsubscript{2}O\textsubscript{3}. It can be seen very clearly that the particles did not retain their original form. Within the coating, they have a very irregular shape. Sometimes they form a lamellar structure, as it is characteristic for thermal spray coatings. This indicates that the particles are partially or completely melted during the process. Due to the great variation in particle sizes, the particles in the coating are also of very different sizes.

Figure 5. SEM images (BSD) of thermal sprayed coatings (upper left: FeF\textsubscript{16} coating; upper right: FeC\textsubscript{16} coating; lower left: FeF\textsubscript{24} coating; lower right: FeC\textsubscript{24} coating).

Over the entire coating the particle distribution is comparatively homogeneous. When looking at individual areas, however, significant differences can be observed. Like shown in figure 6 there are areas with a large number of particles and areas where hardly any particles are embedded.
Figure 6. SEM images (BSD) of thermal sprayed FeF$_{24}$ coating showing locally inhomogeneity of the particle concentration with high particle concentration in the upper left image corner and low particle concentration in the upper right image corner.

On closer inspection, the particles also have different microstructures. As already shown in figure 3, the particles usually consist of a fine lamellar structure formed by ZrO$_2$ and Al$_2$O$_3$. Some particles additionally integrate Al$_2$O$_3$ particles into the lamellar structure. In accordance with the results from Brust et al., cracks are visible in the interface between the particles and the iron matrix like shown in figure 7. These indicate an insufficient adhesion between the two materials.

Figure 7. SEM images (BSD) of thermal sprayed FeC$_{16}$ coating (left: coating overview; right: enlarged view of the white rectangular area with arrow indicating the area of particle/matrix interface cracks).

The particle ratios of the coatings as well as the loss of the particles during the spraying process are given in table 5. The values are in a similar range for all four coatings. Although the particle-filled volume of the thicker wires is significantly higher than that of the thin wires, their coatings do not contain a significantly increased particle ratio. The FeF$_{24}$ coating shows the highest loss of particles during the spraying process. This could be due to the increased ratio of sheath material to particle filling as well as the widening of the spraying jet of the thicker wires like mentioned before. Although the use of thicker wires regarding the fine particle filling results in a similar particle ratio in the coating, the loss of particles is higher. For this reason, thick wires are only a more economical alternative to a limited extent.
Table 5. Particle ratio of the wire arc sprayed coatings using flux-cored wires and loss of the particles during the spraying process.

| Sample            | Particle ratio of the coating | Loss of particles during the spraying process |
|-------------------|-------------------------------|---------------------------------------------|
| FeF_16_coating    | 24.7 ± 2.1 %                  | ~ 51 %                                      |
| FeC_16_coating    | 24.2 ± 4.8 %                  | ~ 52 %                                      |
| FeF_24_coating    | 24.5 ± 1.7 %                  | ~ 60 %                                      |
| FeC_24_coating    | 28.8 ± 2.8 %                  | ~ 53 %                                      |

3.4. Microhardness and wear behaviour

The microhardness of the iron sheath and the Al₂O₃/ZrO₂ particles as well as that of the coating consisting of the iron matrix and the Al₂O₃/ZrO₂ particles embedded in the matrix for the FeC₂₄ flux-cored wire and coating was investigated. Furthermore, the surface hardness of all coatings was determined. The measured values are summarised in table 6. The hardness of the iron matrix as well as the iron sheath is significantly lower compared to the embedded reinforcement particles. The hardness of the iron matrix increased due to the spraying process and the oxidation of the iron sheath. The higher standard deviation indicates the heterogeneous matrix of Fe and FeO. The hardness of the Al₂O₃/ZrO₂ particles before and after spraying does not differ significantly. No significant differences in surface hardness occurred between the different coatings.

Table 6. Microhardness HV0.5 of the FeC₂₄ flux-cored wire and coating as well as HV1 of the coating surfaces.

| Sample            | Matrix | Particles | Surface |
|-------------------|--------|-----------|---------|
| FeF_16_coating    | -      | -         | 322 ± 22 |
| FeC_16_coating    | -      | -         | 347 ± 25 |
| FeF_24_coating    | -      | -         | 335 ± 38 |
| FeC_24_coating    | 315 ± 62 | 1607 ± 305 | 338 ± 21 |
| FeC_24 flux-cored wire | 236 ± 6  | 1686 ± 208 | -       |

The investigations carried out showed no significant differences between the coatings in terms of their chemical composition, their phases, their particle ratio and their coating hardness as a function of the wire diameter. This leaves mainly the particle size fraction used as a differentiation criterion between the coatings wear properties.

The results of the ball-on-disc and rubber-wheel test are summarized in figure 8. The wear behaviour under sliding wear conditions in the ball-on-disc-test is slightly influenced by the wire diameter. The coatings produced with the 1.6 mm wires exhibit a lower wear depth and wear volume. This could be due to the slightly higher proportion of Fe respectively FeO which could also act as a lubricant. They also show a significantly lower scattering of the measured values. For both wire diameters the fine particle fraction leads to a lower wear volume loss. This is in coincidence with the investigations of Fang et al. [4]. An explanation is the lower local overload of individual particles using a smaller particle fraction due to a wider distribution of the loads in the contact area to a larger amount of particles [17].

The abrasive wear behaviour of the coating using the rubber wheel test shows also an influence of the particle fraction. The wear depth of the coatings is smaller for the coarser particle fraction regardless of the wire diameter. However, the increased particle surface area, which improves the binding of the
particle to the matrix, is a possible explanation. This reduces the probability of the particle breaking out. Another reason is the lower mean free path between the particles. Similar results are presented by Tillmann et al. They discovered a better wear resistance of coatings with larger reinforcing particles under abrasive wear using the rubber wheel test [17]. The integration of larger particles considering a similar particle ratio leads to a smaller mean free path between the particles. The wear volume is only influenced by the particle fraction for the 1.6 mm wires. The coatings with the coarser particle fraction show a lower wear volume. The wear volume of the 2.4 mm wire coatings is at a similar level.

![Figure 8. Results of wear investigations of wire arc sprayed Fe-Al2O3/ZrO2 coatings (left: ball-on-disc test; right: rubber wheel test).](image)

### 4. Conclusions

The influence of the wire diameter and particle fraction of flux-cored wires on the wear properties of the sprayed coatings was examined. The wires were processed using the wire arc spraying technology. The use of flux-cored wires with a diameter of 2.4 mm was successfully demonstrated. However, the significant increase in wire diameter is reflected neither in a significantly higher application rate nor in a considerably increased particle density.

The microstructures of the coatings show 24.2 to 28.8 % of reinforcing particles in the matrix. Investigations of the coating microstructures showed a strong deviation of the reinforcing particle sizes. The particle distribution is comparatively homogeneous over the coating, with locally varying particle concentrations. The coating of the 2.4 mm flux-cored wire with the coarse particle fraction had the highest particle ratio of 28.8 %.

Investigations of the phases within the coatings and the flux-cored wires by XRD show the oxidation of the iron sheath by the process. Further investigations of the chemical composition by EDS showed a higher concentration of Al, Zr and O in the coatings with the coarse particle fraction. The particles of the coarse fraction are significantly larger and therefore heavier, which means that they are less strongly deflected by the process gas. This favours the inclusion of the particles in the coating.

The hardness of the coatings is very heterogeneous due to the composition of particles and matrix material. The iron matrix reaches average values around 315 HV0.5. The reinforcing particles, on the other hand, have average hardness values around 1650 HV0.5. The hardness values of the coatings surfaces are in a similar range for all four coating systems without significant differences.

This is also reflected in the results of the wear tests. The investigation of sliding friction wear by means of the ball-on-disc test showed a slightly higher volume loss and a higher wear depth for the
coatings produced with the 2.4 mm wire. The use of the fine particle fraction resulted in a slightly lower wear volume for both wire diameters.

When investigating the abrasive wear behaviour with the rubber wheel test, the wire diameter had less effect. However, the use of the coarser particle fraction results in a lower depth of wear. The wear volume is also lower in the coatings of the 1.6 mm wires using the coarser particle fraction. No difference in wear volume can be detected in the coatings of the 2.4 mm wires.

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References
[1] Dallaire S and Levert H 1997 Development of cored wires for improving the abrasion wear resistance of austenitic stainless steel Journal of Thermal Spray Technology 6 456–62
[2] Brust S, Röttger A, Kimm J, Usta E and Theisen W 2017 Manufacturing of Hard Composite Materials on Fe-Base with Oxide Particles Key Engineering Materials 742 106–12
[3] Berns H 1998 Hartlegierungen und Hartverbundwerkstoffe: Gefüge, Eigenschaften, Bearbeitung, Anwendung (Berlin, Heidelberg, s.l.: Springer Berlin Heidelberg)
[4] Fang J-J, Li Z-X and Shi Y-W 2008 Microstructure and properties of TiB2-containing coatings prepared by arc spraying Applied Surface Science 254 3849–58
[5] Brust S, Röttger A and Theisen W New wear-resistant materials for mining applications International Conference on Stone and Concrete Machining pp 272–80
[6] Pastor J Y, Poza P, LLorca J, Peña J I, Merino R I and Orera V M 2001 Mechanical properties of directionally solidified Al2O3–ZrO2(Y2O3) eutectics Materials Science and Engineering: A 308 241–9
[7] Riedel R 2008 Handbook of ceramic hard materials (Chichester: Wiley)
[8] Lube T, Pascual J, Chalvet F and Portu G de 2007 Effective fracture toughness in Al2O3–Al2O3/ZrO2 laminates Journal of the European Ceramic Society 27 1449–53
[9] Carter C B and Norton M G 2007 Ceramic materials: Science and engineering (New York, NY: Springer)
[10] Wu D, San J, Niu F, Zhao D, Huang Y and Ma G 2020 Directed laser deposition of Al2O3–ZrO2 melt-grown composite ceramics with multiple composition ratios Journal of Materials Science 55 6794–809
[11] Hwang B, Ahn J and Lee S 2002 Correlation of microstructure and wear resistance of ferrous coatings fabricated by atmospheric plasma spraying Metallurgical and Materials Transactions A 33 2933–45
[12] Fauchais P L, Heberlein J VR and Boulos M I 2014 Thermal Spray Fundamentals (Boston, MA: Springer US)
[13] Zhu Y L, Ma S N, Yang C H and Fu R F 1999 Investigation on microstructure and tribological properties of cored wire arc sprayed Al2O3 coating Act Metallurgica Sinica 988–94
[14] Lugscheider E and Bach F-W (eds) 2002 Handbuch der thermischen Spritztechnik: Technologien - Werkstoffe - Fertigung (Fachbuchreihe Schweißtechnik vol 139) (Düsseldorf: Verl. für Schweißen und Verwandte Verfahren DVS-Verl.)
[15] Tillmann W and Abdulgader M 2013 Wire Composition: Its Effect on Metal Disintegration and Particle Formation in Twin-Wire Arc-Spraying Process Journal of Thermal Spray Technology 22 352–62

[16] Winkler R, Paczkowski G and Lampke T 2020 Optimisation of the hard material fractions of flux-cored wires with large diameters for arc wire coating Thermal Spray Bulletin 90–6

[17] Tillmann W, Hagen L and Schröder P 2017 Investigation on the Tribological Behavior of Arc-Sprayed and Hammer-Peened Coatings Using Tungsten Carbide Cored Wires Journal of Thermal Spray Technology 26 229–42