JTTEE5 15:177-183
DOI: 10.1361/105996306X107977
1059-9630/$19.00 © ASM International

Technical Note

Cold Spraying: Innovative Layers for New Applications

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(Submitted September 2, 2005; in revised form January 31, 2006)

In recent years, results of many studies have been published that enhance understanding of the fundamental mechanisms of cold-spray coating generation and bonding as well as coating characteristics. From the points of view of a job shop in thermal spraying and of a user of cold-spraying equipment, a procedure being used in development of new applications is presented herein. In addition to the technical requirements, some general factors determining the success of industrial use of cold spraying are shown. Examples of cold-sprayed coatings are described to show both the possibility of rapid integration of this new technique in established coating jobs as well as exploration and use of new possibilities in cold spraying and development of applications that have not yet been a focus of thermal spray techniques. Suggestions for further research and development activities are made on the basis of practical cold-spray experience.

Keywords cold-gas dynamic spraying, influence of spray parameters

1. Introduction

In the last 12 years, great advances have been made in cold-spray technology. A variety of industrial applications are being pursued and are at different stages of commercial adaptation (Ref 1). In particular, some development departments in the aerospace (Ref 1, 2), defense (Ref 1, 3), and automotive industries (Ref 1, 4) as well as the electronics industry (Ref 1) are working on moving the cold-spray process from the research laboratories into commercial industry. The natures of the applications differ. Results of fundamental research work have been presented in a variety of papers (for example, Ref 5-22). The research efforts have focused on:

- Mechanisms of coating generation
- Characterization of powder feedstock and its effect on coating process and coating properties
- Effect of process parameters on coating process and coating characteristics (deposition efficiency and microstructure)
- Optimization of the spray system, especially the spray gun

The emphases of recent application development works are derived from several advantages of cold-spray process or cold-sprayed layers. Table 1 contains the decisive advantages for some applications.

For developing an industrial coating technology, much more information and experience is necessary than is available in the literature or from the equipment manufacturer. Therefore, various tasks, such as:

- Fundamental investigations
- Optimization of process parameters
- Developing of cold spray and handling systems
- Powder supply and development
- Publishing, promoting, and acquisition activities

have to be executed as represented consecutively.

2. Cold-Gas Equipment for Industrial Coating Processes

The basic requirement for industrial application of the cold-spray process is a reliable and easy-to-use spray system.

In December of 2003, a Kinetic 3000 system from CGT GmbH (Cold Gas Technology GmbH, Ampfing, Germany) for spraying with nitrogen and helium was installed in the Fremat GmbH production plant. Fremat GmbH is one of the first industrial enterprises in Germany to integrate the cold-spray process into its production run. The company is not only a job shop for thermal spraying, but thermal spraying is its key technology. In addition, several casting, forming, joining, and machining techniques are used for manufacture of products such as sputtering targets, which require a high level of materials technology knowledge.

A vast number of tests for fundamental investigations, for coating and application development, for series production development, and for prototype coating and batch production are in progress. Suitability for series production processes in long-term or continuous operation conditions is being investigated and developed.

The compact design and the mobility of the cold-spray system promote its integration into the production shop. Each spray booth and handling system can handle several spraying techniques. Consequently, utilization of production facilities can be improved with this new and supplementary device.

The original version of this paper was published in the CD ROM *Thermal Spray Connects: Explore Its Surfacing Potential*, International Thermal Spray Conference, sponsored by DVS, ASM International, and IIW International Institute of Welding, Basel, Switzerland, May 2-4, 2005, DVS-Verlag GmbH, Düsseldorf, Germany.

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Table 1 Properties, materials, and applications of cold gas sprayed layers

Application/purpose of the cold sprayed layer	Typical materials	Advantages of cold spraying and coldsprayed layers
Corrosion protection	Zinc, nickel, brass	Little porosity
Conductor, thermal management	Copper	Little porosity, low oxygen content
Repair, structural coatings	Aluminum, copper, steel, nickel, alloys	Little porosity, no phase changes
Solder/braze depot	Soldering/brazing alloys	Strong bonding, no phase changes, low oxygen content
Solderability	Copper	Low oxygen content

Thus, it is possible to generate coating systems by the subsequent application of different spray techniques (such as plasma, flame, arc, high-velocity oxyfuel spraying) in the same booth.

3. Procedures in Coating Development

The Fremat cold-spray activities are targeted on layer design and application development.

Because cold spraying is a newly developed technology with particular characteristics and high application potential, several areas of development, such as spraying equipment, basic research, feedstock materials, and applications, are objects of intense study.

This cold-spray development work is aimed at extending technological competence and exploration of new applications for thermal spraying.

The authors are also developing solutions for automated line production. The nature and tasks of these development efforts are influenced significantly by the particular application.

Compared with conventional thermal spray processes, the powder specification is much more important for the cold-sprayed coating quality. Besides the higher particle velocity and the smaller particle size, the primary reason for this is that, in contrast to conventional thermal spray processes, the accelerated particles impact on the substrate surface in the solid state ("cold") and the deformation behavior both of the substrate and the particles strongly affects the build-up of the deposit. Therefore, the mechanical properties of substrate and powder feed stock determining the deforming process are very important for the coating deposition process and quality. The mechanical behavior can be described first of all by the material parameters of hardness and Young's modulus. Additionally, other parameters, such as particle shape, particle size distribution, content of oxygen, and material microstructure, influence the deforming and deposition behavior and, as a consequence, also the properties of the layer and the efficiency of the coating job. Several techniques of mechanical, thermal, and chemical powder treatment, such as sieving, sifting, or agglomerating, are available in-house to improve the respective properties of the commercially available powders.

For application development programs, the following tasks are important to varying degrees:

- Assessment of the state of the art and deposition approaches
- Investigation and development of powder feed stock (shape, particle size distribution, mechanical/chemical properties)
- Variation of spraying parameters (temperature, pressure, nozzle travel speed, step size, standoff distance, powder feed rate) and other factors (such as substrate surface topography and preheating) for optimization of the coating quality
- Determination of coating properties (porosity, bond strength, hardness, microstructure, etc.)
- Heat treatment and/or mechanical posttreatment of the coating
- Testing of coated components at different levels of real-system simplification (model tests, component tests, application tests)
- Determination of parameters for estimates (deposition efficiency, gas consumption, time consumption)
- Economic analysis
- Development of coating technology specification for series production including pre- and posttreatment, quality management, logistics, handling, etc.

Due to the comparatively high cost of cold-spraying powder feed stock and process gas, cold spraying is more competitive when alternative technologies are more complicated or expensive (for example, multistage joining technologies) or cannot provide the necessary quality (for example, low oxygen content).

4. Examples of Coating and Application Development

4.1 Nickel

Nickel coatings are widely used for corrosion and wear protection layers. Because of its low porosity, the low oxygen content, the ability to coat selectively and focused, and other advantages, cold spraying is an alternative option to established technologies, like electroplating.

Using the optimized nozzle 24 ("Stoltenhoff nozzle"), very dense coatings were achieved when nitrogen was used as the process gas (Fig. 1b). Corrosion-resistance tests are still in progress. Cold-sprayed nickel coatings can be used, for example, as base or intermediate layers because they are denser than conventional thermal-sprayed layers and less expensive than electroplated coatings.

Another interesting application of cold-sprayed nickel or further ferromagnetic metals and alloys is the cold spraying of induction heating coats on cooking appliances or cooking pots. In parts of Europe, a high market potential for induction cooking devices is assumed.

The induction heating layer is usually produced by brazing a ferromagnetic plate onto the nonferromagnetic cooking utensil. Using the cold-spray process, very dense and well-adhering thick induction heating layers can be deposited by a single processing step onto metallic or even nonmetallic cooking utensils. The coating properties, responsible for the inductivity and other

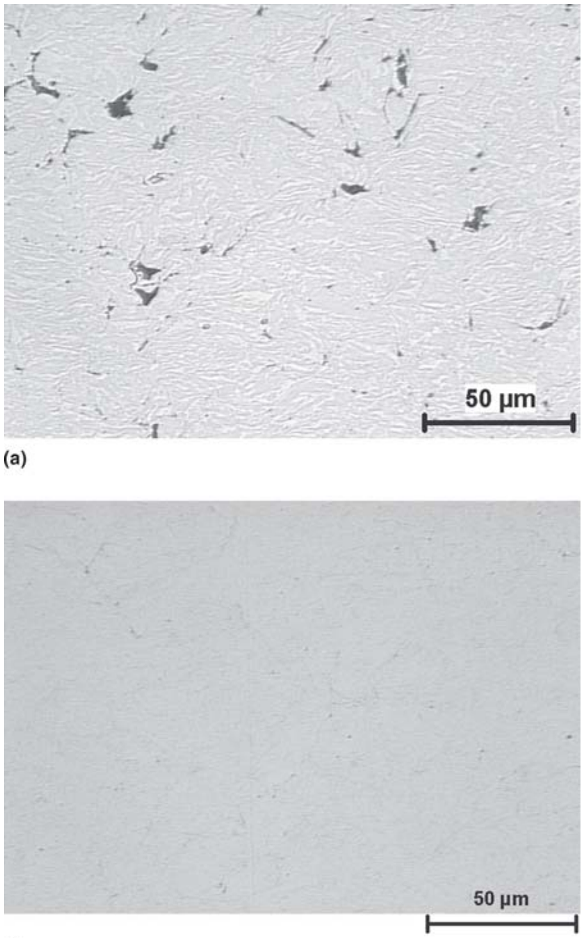

Fig. 1 Optical microscopy of the cross sections of nickel on steel: (a) nozzle travel speed doubled compared with (b) remaining parameters similar

important properties, like the coefficient of thermal expansion, can be modified, for example, by varying the feedstock material composition.

In a variety of cold-spraying experiments, it was detected that the adjustable system parameters, such as powder feed rate, step size, and nozzle travel speed, could influence the microstructure and bond strength of the coatings to a very high degree. In fundamental research reports, such examinations are difficult to find. In Fig. 1, the optical micrographs of cold-sprayed nickel coatings indicate, that, with decreasing nozzle travel speed, porosity can be reduced conspicuously. Of course, to achieve high process efficiency, the powder feed rate and travel speed should be as high as possible. So, for every substrate-powder combination or application, a specific economic optimization must be carried out because the material properties have a much greater influence on the coating development process and spray results than is known in conventional thermal spray processes.

4.2 Tantalum

Tantalum is used, for example, for chemically resistant layers in the chemical industry. The material is very expensive. Therefore, a high value of deposition efficiency is required.

Cold spraying of tantalum is an alternative technique to the currently used vacuum plasma spraying. Due to the nature of the process, especially the low particle temperature, practically no change in the chemical composition from powder feedstock to the coating is detectable.

Tantalum powders from different suppliers were investigated. The feedstock powders were cold sprayed at similar parameters onto steel plates with nitrogen used as the process gas. Among other things, the deposition efficiency was determined and the quality of sprayed coatings was investigated. Depending on the powder charge used, the values of deposition efficiency varied from 14 to 89% at constant process parameters. The differences in the following properties could have been the causes of these different behaviors:

- Hydrogen content
- Contents of other contaminations
- Particle size distribution
- Shape of powder feedstock particles

The oxygen content of all powders investigated was very low and in the same range. Powder No. 2 with the same d_{50} value (15 µm) as powder No. 1, but a higher content of larger particles, had a more spherical shape (Fig. 2). Most of the particles had been agglomerated. Powder No. 2 appeared sharp-edged and with a higher content of small particles. Because of the high density of tantalum, it has been assumed that the powder with the higher content of larger diameter particles will be deposited with a lower efficiency. Actually, powder No. 2 had a higher deposition efficiency (89%) than did powder No. 1 (58%). The coating produced by deposition of powder No. 2 showed no visible cracks and only few pores (Fig. 3).

4.3 Electronic Applications

For electronic or electrical applications, thermal spraying processes are rarely used. Because of its high ability to focus the particle stream, the high density, the high purity, and the low content of oxygen of the deposited coatings, cold spraying can lead to an extension of thermal spray applications beyond the limits of conventional component coating. For electronics, the following applications and development areas can be indicated:

- Generation of solderable surfaces on materials with poor wettability (for example, heat sinks, such as copper on aluminum)
- Deposition of electric screening coatings on plastics
- Generation of conducting structures on nonmetals
- Deposition of brazing and soldering alloys

4.3.1 Solder Depots. Investigation of cold-spray processing of brazing alloys especially for joining dissimilar metals in machine element applications are being pursued (Ref 1). For different electronic applications, cold spraying of solder alloy layers onto several substrates was tested. The primary advantage of cold spraying of solders is the dispensation with flux due to the supposed destruction of oxide layers by the impingement of solid particles having high kinetic energy.

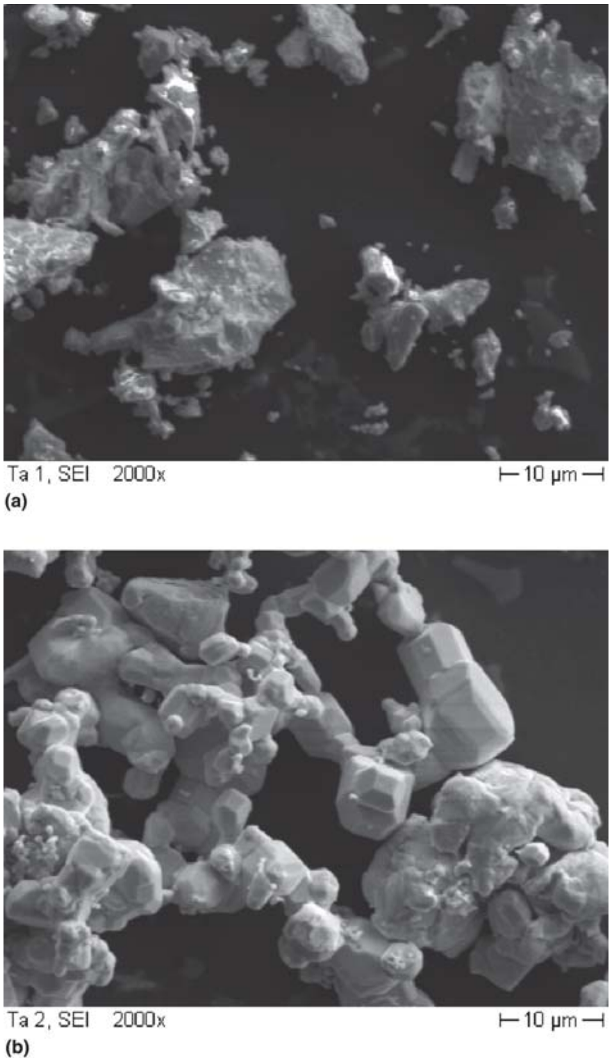

Fig. 2 SEM images of tantalum powder particles: (a) powder No. 1, (b) powder No. 2

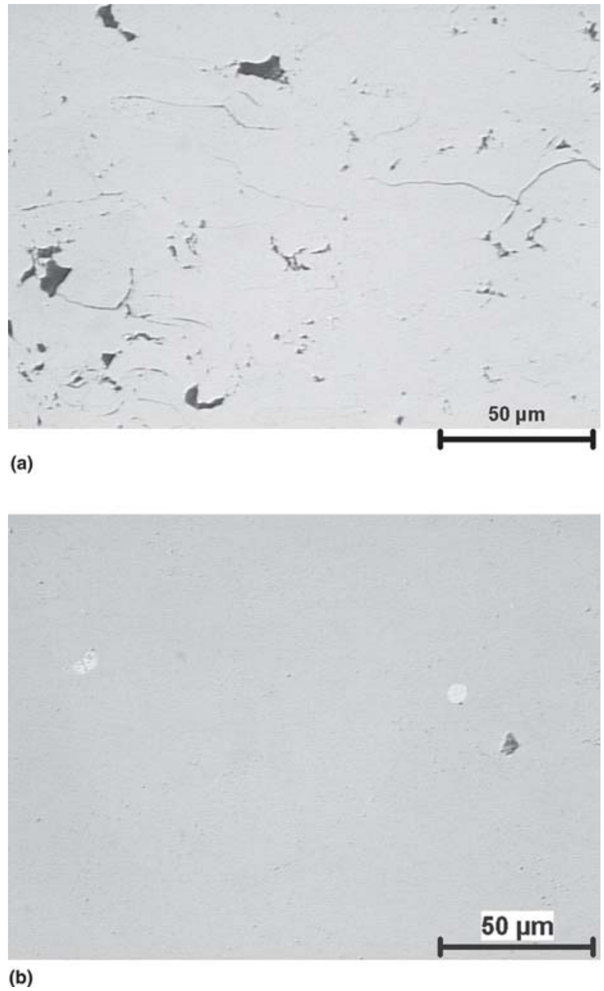

Fig. 3 Optical microscopy of the cross section of tantalum coatings made from two different powders: gas, nitrogen; (a) powder No. 1, (b) powder No. 2

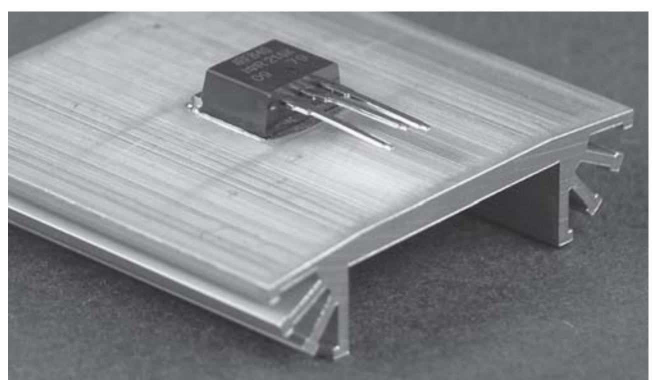

Fig. 4 Soldered power transistor on an aluminium heat sink with a cold-sprayed copper layer

Selective solder deposition can be realized by using mask sheets or layers.

4.3.2 Solderable and Conducting Coatings. Deposition of copper onto a heat sink made of aluminum as a base layer for subsequent soldering processes was one of the first serial applications of cold-spraying technology (Ref 23). The cold-sprayed copper layer removes the natural oxide film and provides a solderable surface for the tin- or copper-plated area of electronic parts. In addition, the copper layer conducts the heat very rapidly from the electronic part to the heat sink.

Cold-sprayed layers require adapted soldering technologies or surface posttreatment. Compared with coating technologies, which are usually used for coating electronic components, the cold-spray process generates another surface topography and roughness.

For adaptation development of joining technologies, the authors have made use of a diagnostic department and a laboratory for joining technologies, where, for example, soldering processes can be developed using industrial facilities and several tests, like thermal cycling tests, can be performed.

By application of a vacuum in the vapor-phase soldering process instead of standard atmosphere, the number and size of failures in the soldered interconnecting layer between a cold-sprayed copper coating and a power transistor (Fig. 4) could be reduced to low and acceptable levels.

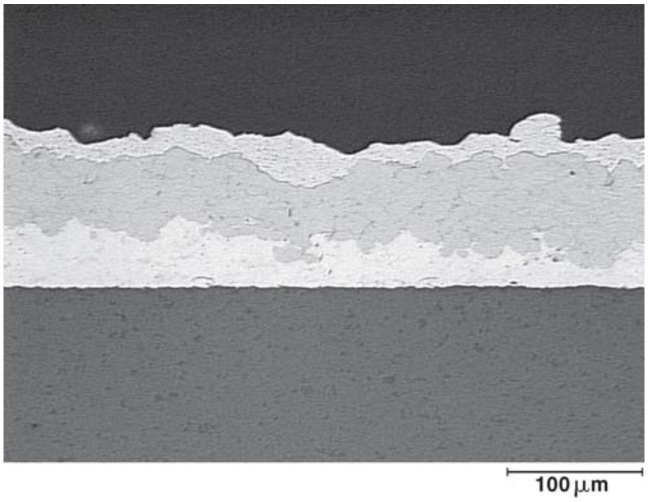

Fig. 5 Optical microscopy of the cross section of Al_2O_3-substrate and cold-sprayed multilayer system (from the bottom: aluminium, copper, solder alloy)

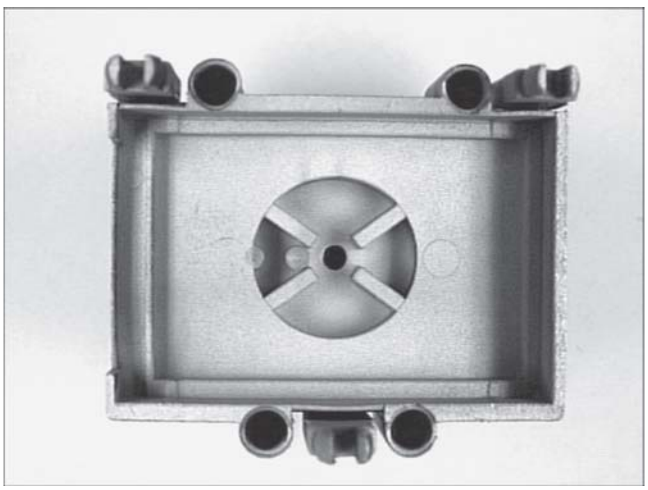

Fig. 6 Cold-sprayed electric screening coating on a thermoplastic housing.

Cold spraying of copper onto aluminium parts is already a proven application. Further development work will focus on process optimization for increasing reliability and process efficiency, on developing of layer structuring and masking techniques, and on enhancing the solderability of cold-sprayed layers.

Several tests have been performed to investigate the possibilities of coating deposition on nonmetal substrates. The result of coating deposition onto hard and brittle substrates depends to a higher degree on the process parameters than does deposition onto ductile materials.

The high bond strength of cold-sprayed aluminum layers on glass or ceramic substrates is well known.

On these substrates, cold-sprayed aluminum coatings can also be used as bonding layers for other top layers. Thus, with cold spraying, a complete multilayer system can be designed (Fig. 5)

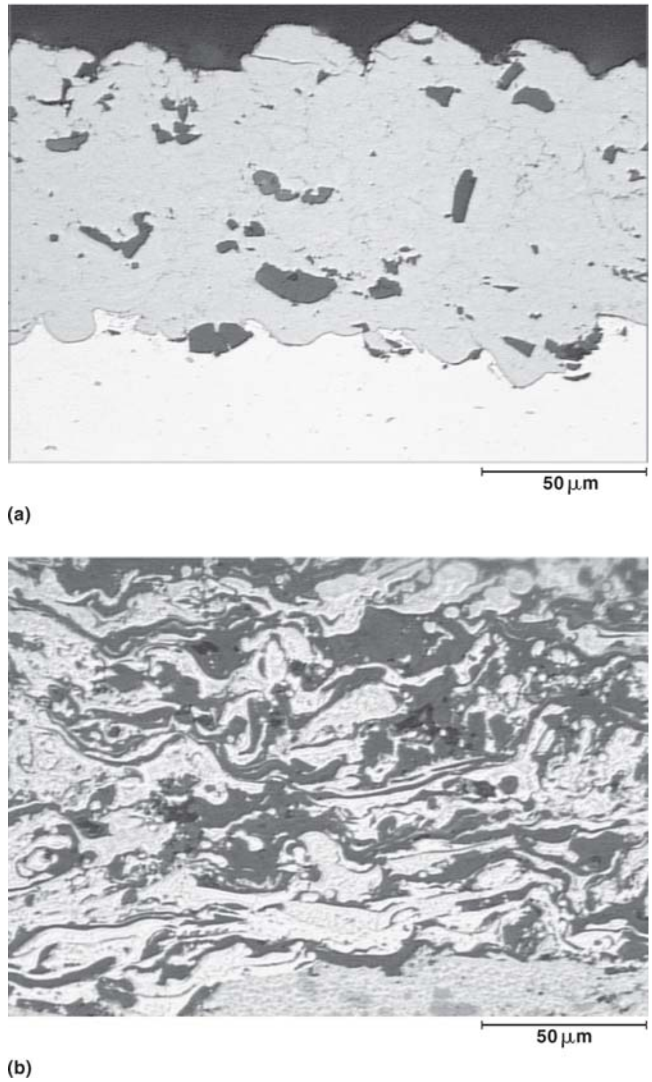

Fig. 7 Optical microscopy of a cold-sprayed (a: copper + TiO_2 on aluminium) and a plasma-sprayed (b: brass + TiO_2 on brass) MMC coating cross section

Another interesting application is the deposition of conducting layers on plastics. Because of the low temperature of the sprayed particles, thick metallic coatings can be deposited on technical thermoplastics, such as polyamides and others.

Potential applications are, for example, deposition of electric screening coatings on electronic component housings (Fig. 6) and the deposition of bond coats for further coating processes. In contrast to cold spraying, other metallizing techniques of thermoplastics are much more complicated.

4.4 Composite Layers

By cold-gas spraying of simple powder blends, composites of various metals and dispersants can be produced. Typically, the cold-sprayed metal-matrix composite (MMC) coating is dense, and the bonding between the metal matrix and the dispersant is strong. Microstructure is different from the typical structure that is obtained by other thermal spray processes, for example, by plasma spraying (Fig. 7). The figure illustrates that the

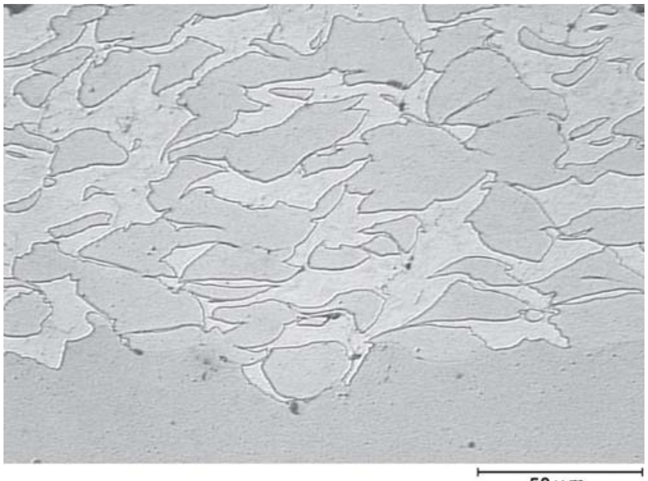

Fig. 8 Optical microscopy of the cross section of cold sprayed nickel-copper coating (gas: nitrogen)

total area of the interfaces between the metal and the dispersant in the cold-sprayed composite layer is much lower than in the plasma-sprayed layer.

Apart from metal-non-metal-composite layers, for several applications, metal-metal-composites are of high importance as well (Fig. 8). Such layers can be sprayed easily by using a simple powder blend feed stock. Applications of cold spraying of composites are, for example, layers for thermal management, for wear protection or bearing layers, and also solder layers.

5. Summary

The cold-spraying technology has attained a state of development that makes industrial applications, even in series production, possible. The cold-spray device has been integrated successfully into the existing production facilities of a conventional job shop. This device is also suitable for an automated single-purpose production line.

In contrast to research institutes, development activities of Fremat are focused on applications with high probability for commercial exploitation.

Experiments have concentrated on deposition approaches of new coating systems, on optimization of the cold spray process, and, to a small degree, on basic research.

Similar knowledge and skills in materials diagnostics, materials engineering, and process engineering are needed for both research and application development.

The applications for which the cold-spray coating technology is developed are diverse. The authors have developed customer-specific coating applications as well as solutions for their own thermal spraying shop. According to the particular coating-substrate combination and application, the emphases of the work differ. For extension of industrial cold-spraying applications, different topics must be worked on extensively, for example:

- Development and provision of cost-efficient powder feed stocks with adequate processing properties (feeding properties, deposition efficiency), which can generate coatings in the demanded quality (powder feed stock design)
- Development of the long-time stability and reproducibility of the cold-spray process
- Development of complete manufacturing processes: integration and optimization of pre- and post-treatment/machining processes/heat treatment; combination of different types of thermal spraying or coating processes

Acknowledgments

This research was supported in part by the European Fund for Regional Development (EFRE) 2000-2006, the County Saxony, and the Federal Ministry of Economics and Labour (BMWA, reg.-nr. 1205/03).

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