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Thermally Sprayed Fiber-Reinforced MMCs

H. Kern, R. Kaczmarek, and J. Janczak

This article submits the synthesis of theoretical analysis and experimental investigation on the mechanical behavior of thermally sprayed continuous fiber-reinforced metal-matrix composites. Special attention is drawn to the relationships among processing parameters, fiber-matrix interface, and composite properties. The evaluation concerns austenitic steel fiber-reinforced NiCrAl alloys with up to 30% of filament volume content. For the selected model system, the tensile and flexural sample loading is performed. *In situ* scanning electron microscopy (SEM) bending tests were used to investigate crack propagation and failure modes in the composites. Theoretical predictions of composite mechanical properties are compared with experimental observations.

1. Introduction

Metal-matrix composites (MMCs) are rapidly becoming one of the strongest candidates for structural components. Satellite structures, storage battery plates, electrical contacts, bearings, compressor and jet engine fan blades, as well as antenna structures, helicopter transmission structures, and high-temperature engine elements, are representative examples of such applications.[1-3]

There exists a large number of techniques for manufacturing fiber-reinforced metals, each having its own advantages and limitations.[4-7] Some methods promise interesting results on a laboratory scale, but are very difficult to introduce into industrial production.[7] Others may have lower property potential, but good commercial possibilities.[7] Most of the above manufacturing methods, however, are very complex and time consuming.

More recent results in the manufacture of fiber-reinforced composites[8] recognize the thermal spraying technique as a simple and cost-effective alternative for large-scale production of MMCs with good mechanical properties. The maximum potential of manufacturing composites will only be realized when their mechanical behavior is understood. For example, knowledge about the load transfer and fracture mechanisms in a composite in terms of nature and strength of the interfacial bond has an important role.

This article examines the scientific features of manufacturing thermally sprayed continuous fiber-reinforced metal-matrix composites (TSMMCs) and points out those aspects decisive for the successful development of this composite group.

Key Words: development of porosity, fiber reinforcement, general over view, mechanical properties, metal matrrix composites

Dedicated to Prof. Dr.-Ing. H.-D. Steffens on the occasion of his 60th birthday.

H. Kern, R. Kaczmarek, and **J. Janczak,** Institute of Materials Technology, University of Dertmund, Dortmund, Germany.

2. Thermal Spraying Method for Fiber-Reinforced Composite Production

The origin of the thermal spraying technique dates back to the 1900s. Gerdeman and Hecht[9] indicate that the metallizing process was invented around 1910 by Max Ulrick Schoop of Switzerland. Applications of this coating deposition technique were extended to the production of fiber-reinforced composites in the 1960s with optimization work done most completely by Kreider in the aluminum matrix system.[10] The feasibility of the process for the formation of tungsten wire-reinforced rocket nozzle configurations has also been demonstrated.[11] Investigations concerning analytical modeling and optimization of mechanical behavior of thermally sprayed continuous fiber-reinforced MMCs were initiated by Steffens *et al.*[12] In the meantime, some successful industrial applications of the thermal spraying technique for composite manufacturing have been reported (see Table 1).

2.1 *Features*

The following advantages make this technique a viable approach for industrial applications: a simple route, versatility and wide range of processing materials, flexibility in shape and size, cost-effectiveness (less expensive than competitive powder metallurgy fabrication techniques), and good control of matrix thickness and accurate control of fiber distribution.

2.2 *Properties of As-Sprayed Matrix Materials*

The microstructure of thermally sprayed coatings, which is determined by rapid solidification of a succession of individual molten droplets, results in properties quite different from bulk materials formed by conventional processes.[33] For example, plasma-sprayed Nimonic 80A coating exhibits a tensile strength of 270 MPa, a Young's modulus of 120 GPa, and a tensile failure strain of 0.28%,[12] whereas bulk material is characterized by a tensile strength of 1.2 GPa, a Young's modulus of 205 GPa, and a tensile failure strain of 20%.[34] The tensile strength of a coating may be significantly lower than the average strength of the bulk material due to poor cohesion of the lamellae and porosity. For example, alumina coatings show a tensile strength of about 30 MPa, in contrast to bulk alumina with about 280 MPa[35] and arc-sprayed coatings produced from steel wire with a tensile strength of 1000 MPa possess a tensile strength of less than 300

MPa when thermally sprayed. A general trend is that fracture propagation becomes catastrophic with an increase in strength of the sprayed material. This is a major limitation of continued development of thermally sprayed coatings, as well as of expanding their range of application.[36] Moreover, the as-sprayed structures are not fully dense (2 to 15 vol.% voids) and contain a somewhat higher oxide content (1.5 wt.%) than the foil-type materials.[12,35]

3. Design Issues

Improvement of strength and/or stiffness of the bulk material is the main goal of manufacturing MMCs for structural applications. For conventionally produced MMCs, the composite ductility results from the metallic matrix, whereas the matrix of thermally sprayed composites primarily exhibit brittle behavior and cannot provide adequate fracture toughness properties for the composite. Therefore, in thermally sprayed metal-matrix composites used for structural applications, it is necessary to enhance both strength and toughness. Recent results, coming from the ceramic engineering area,[37-40] demonstrate the possibility of improving toughness and strength of brittle materials by fiber incorporation. Adoption of this toughening method for thermally sprayed metallic coatings promises to produce materials with distinctly improved mechanical properties.

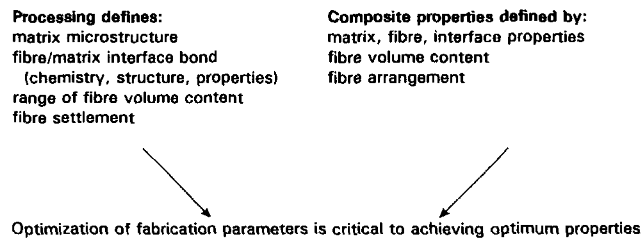

Figure 1 Macromechanical behavior of composites as a function of processing parameters.

Table 1 Review of Thermally Sprayed Composites and Their Applications

Matrix	Fibers	Comments	Reference
Al	W	Plasma spraying; product form: rocket nozzle configurations	13
Al	B	Plasma spraying	13, 14
Al	C (fiber coatings: SiC, TiC, TiB_2)	Vacuum plasma spraying	15, 16
Al18136, AlMg5	Steel	Plasma spraying; product form: tube	17
Al	Glass	Plasma spraying	18
Al, Ti	B + stainless steel, Borsic + Mo(a)	Application: aerospace industry	19
Al	SiC	Plasma spraying; product form: missile body casings, structural panel, Z-stiffeners	17
Al alloys, Ti alloys	IN909, 304 stainless steel	rf plasma spraying	20
Ti	SiC (SCS-6)	Plasma spraying; designed for applications in turbine engines and high-performance aircraft	21-23
Ti	B	Plasma spraying	18
Ti-6Al-4V	B	Plasma spraying; product form: ring structures	7
Ti-6Al-4V	Borsic	Plasma spraying; product form: plate	7
Ti-6Al-4V	SiC	rf plasma deposition/HIP consolidation	24
Ti-6Al-4V, Ti-6Al-2Sn-4Zr-2Mo	SiC (SCS-6)	Low-pressure induction plasma spraying	25
Ti-6Al-4V, Ti-15V-3Cr-3Sn-3Al	SiC	Plasma spraying; application: fan blades, gas turbine disks, load transfer tubes	26
Ti-11.5Mo-6Zr-4.4Sn	Borsic	Plasma spraying; product form: plate	7
Be or alloys with Ca, W, Mo, Fe, Co, Ni, Cr, Si, Cu, Mg, Zr	SiC	Plasma spraying; application: aerospace and nuclear industries	19
W	W	Plasma spraying; product form: rocket nozzle inserts	13, 7
Cu	W	Arc spraying; product form: combustion liners	7
Nb	W (ST300, 218CS)	Arc spraying; application: heat generation systems (cladding for nuclear fuel pins, heat pipes and tubing), energy conversion systems	27
Nb, Nb-1Zr	W	Arc spraying; product form: plate, tube	7, 28
FeCrAlY, Incoloy 907, 316 stainless steel, Waspalloy	W	Arc spraying; product form: plate	7
Kanthal	W	Arc spraying; product form: tube	7
Fe-base superalloys	W	Arc spraying	29
Ni-Cr alloys	Austenitic steel	Plasma spraying; product form: plate	12, 30
Ti_3Al + Nb	SiC	Plasma spraying; High-temperature applications	31
Be_4B, Be_2B	Cu, Cu-Be, Be	Plasma spraying	32
Si_3N_4	W, Mo	Flame spraying	32
Al_2O_3	Mo, W	Plasma spraying	32

(a) Combination of high-strength ductile and brittle fibers

4. Processing-Composite Behavior Relation

It is now an axiom concerning materials science that there is a strong relation between materials microstructure, their properties, and processing.[9] All aspects of processing, composite macromechanical behavior, and interface micromechanical properties are strongly connected and determine materials performance. In the case of fiber-reinforced composites, the process defines matrix microstructure, fiber-matrix bonding, range of fiber volume content, and precision of fiber setting. The composite properties are determined by the matrix, fiber and interface properties, fiber volume content, and fiber arrangement (Fig. 1). Therefore, investigation on the relationship between processing technique and composite mechanical behavior enables optimization of composite quality and characteristics. Here, manufacturing parameters are critical control parameters, as they predominantly influence matrix microstructure and interface properties.

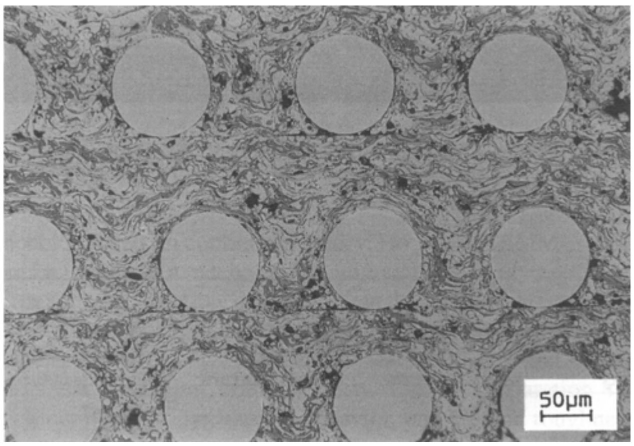

Figure 2 Microstructure of thermally sprayed metal-matrix composite.

Nevertheless, there is a discrepancy between theoretical analysis and experimental work in the field of thermally sprayed composites. The relation between processing parameters and mechanical properties for fiber-reinforced composites made by thermal spraying has not been fully investigated.

5. Theoretical Prediction of Composite Mechanical Properties

Usually, TSMMCs are manufactured with brittle matrix materials.[41] Thus, the failure strain of the matrix is distinctly lower than the failure strain of the fiber.[12] Therefore, the linear rule of mixtures, proposed by Kelly for prediction of MMC tensile strength,[45] is not valid for typical TSMMCs. Because the matrix is brittle for thermally sprayed composites, then the model assumptions should be similar to those for ceramic matrix composites (CMCs).[42] The rule of mixtures has to be modified for calculation of the expected tensile strength concerning

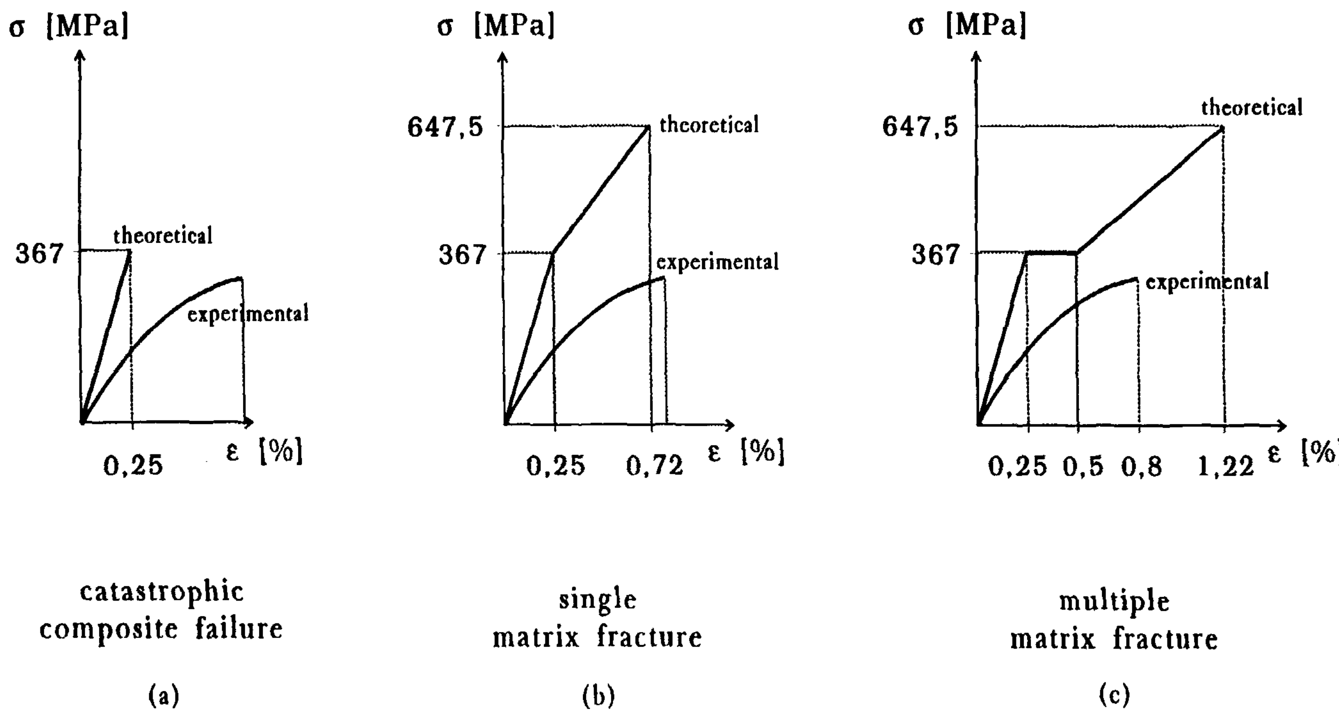

Figure 3 Comparison of theory versus experiment.

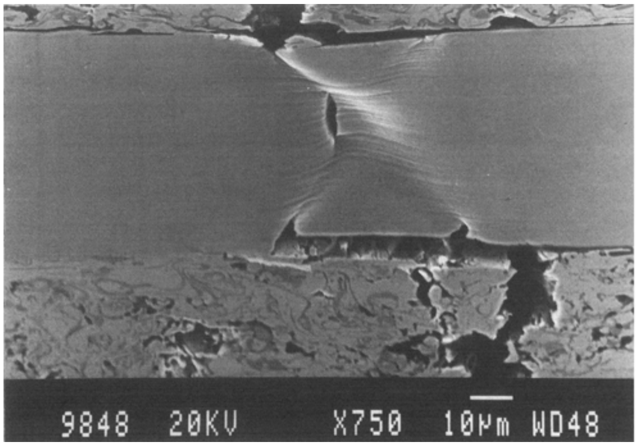

Figure 4 Typical fiber fracture, fiber yielding, necking, and local plastic deformation followed by fiber breaking.

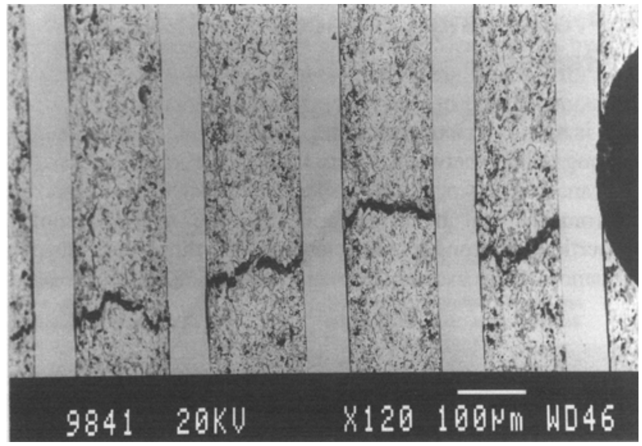

Figure 5 Composite failure process, matrix bridging by fibers.

Table 2 Comparison of Theory Versus Experiment

	Experiment	Porosity	Theory Type of failure Multiple matrix fracture	Single matrix fracture	Catastrophic composite failure
$\sigma_{c_{max}}$, MPa	302	(a)	648	648	367
		(b)	648	648	308
ε_c, %	0.8	(a)	1.15 to 1.33	0.72	0.25
		(b)	1.2 to 1.32	0.82	0.25
E_c, GPa	70	(a)	147	147	147
		(b)	123	123	123

(a) No matrix porosity. **(b)** Matrix porosity 20%.

TSMMCs. Thus, based on CMC theory and taking into account interface aspects, the composite tensile strength is given by the following expression:

$$\sigma_{c_{max}} = \sigma_F V_F \text{ for } V_F > \frac{\sigma_M}{\sigma_F - \sigma_F' + \sigma_M}$$

and adequate fiber/matrix bonding else:

$$\sigma_{c_{max}} = \sigma_M V_M + \sigma_{F'} V_F$$

where $\sigma_{c_{max}}$ is the composite tensile strength, σ_F is the fiber tensile strength, σ_M is the matrix tensile strength, σ_F' is the fiber stress at ultimate matrix failure strain, V_F is the fiber volume content, and V_M is the matrix volume content.

The maximum fracture stress and strain are expected when there is multiple matrix fracture. This occurs for high fiber volume content and weak fiber matrix bonding.

6. Composite Manufacture and Testing

Thermally sprayed fiber-reinforced metal-matrix composites can be produced as free-standing bodies with appropriately spaced continuous fibers helically wrapped on a specially prepared substrate. Afterwards, the matrix is thermally sprayed. When the required thickness is achieved, the composite is cut perpendicular to the wrapped fibers and removed from the substrate.[43,44] Figure 2 shows an example of a multilayer composite structure made by plasma spraying.

Tensile and bending tests are used for the evaluation of the load-bearing characteristics of composites. To evaluate crack growth and composite fracture behavior, *in situ* SEM bending tests on notched specimens have been performed.[12,20]

7. Theory-Experiment Relationship

7.1 *Mechanical Properties*

Comparison of theoretical and experimental results for a 25 vol.%-X12CrNi17 7/NiCr19Al6Si thermally sprayed composite, chosen as the model system, is depicted in Fig. 3 and Table 2.[42] The fiber material (1.4310 material number according to the German Industrial Standard) is referred to as AISI 301 and the plasma-spray powder used for deposition of matrix material was Amperit 296.090. In the theoretical considerations, different composite failure modes were taken into account because no precise information on the mechanical properties of the interface exist. In the three cases indicated in Fig. 3, there is a differentiation between theoretical and experimental results. The main reason for this divergence can be found in the model assumptions and experimental aspects. The applied theoretical

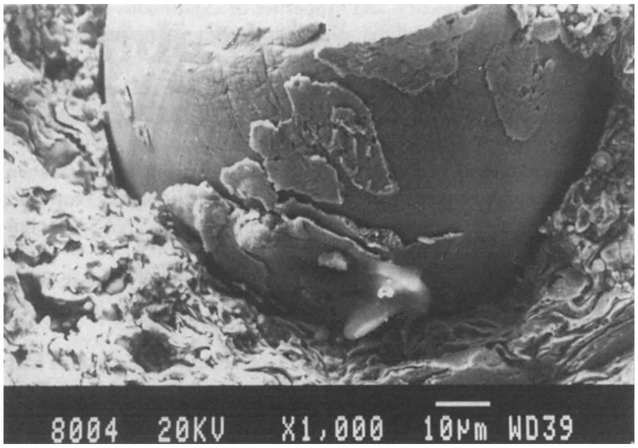

Figure 6 Fiber-matrix interface, local differences in interfacial bonding strength caused by lamellar matrix microstructure.

model is based on continuum theory. However, TSMMCs cannot be treated as a mechanical continuum due to fiber damage, fiber strength variation, deviation from theoretical fiber arrangement, matrix porosity, and irregular interface bonding strength, which are sources of discontinuity. Manufacturing and testing problems, including reproducibility, sample preparation for measurements of mechanical behavior, and surface roughness of the composite, represent typical experimental aspects that also contribute to the divergence between theoretical assumptions and laboratory measurements.

7.2 *Fracture Behavior*

The test results show that fracture behavior of TSMMCs is defined by different failure modes.[12] For the chosen model system, fiber yielding, necking, and local plastic deformation, as well as fiber debonding and pull-out, were observed. Single matrix cracks were also detected. A typical fiber fracture is shown in Fig. 4, and the composite failure process with fiber bridging is shown in Fig. 5.

7.3 *Interface*

It was found that the fiber-matrix bonding strength for TSMMCs is not perfect and varies locally. These interface failures are related to the matrix microstructure and porosity. Figure 6 shows fiber-matrix bonding imperfections in plasma-sprayed composites.

7.4 *Porosity*

Thermally sprayed fiber-reinforced composites reveal macro- and microporosity. The fine porosity resulting from the spraying process is in the range of 3 to 7%. The coarse porosity originates during composite manufacture as a consequence of a shadow effect of the fibers and roughness of the sprayed coating surface. Depending on the number of plies and the spraying technique, the volume fraction of macroporosity can reach up to 20%.[43] However, experimental techniques, such as spraying with a variable angle between substrate and spray direction, can be used to manufacture composite structures without coarse porosity.[30]

Table 3 Thermally Sprayed Continuous Fiber-Reinforced Metal-Matrix Composites in the Composite Family

	Composites MMCs	TSMMCs	CMCs
Matrix	Ductile	Low ultimate failure strain	Brittle
Fiber	Strength, stiffness	Strength, stiffness, toughness	Strength, toughness
Interface	Strong fiber-matrix bonding	Weak fiber-matrix bonding	Weak fiber-matrix bonding
Composite	No porosity, no cracks	Porosity, microcracks	Porosity, microcracks

8. Summary

Thermally sprayed fiber-reinforced MMCs have been manufactured with fibers having higher tensile failure strain than the matrix. This is unlike MMCs made by conventional manufacturing processes, but is similar to CMCs. Therefore, the design goals and optimization of mechanical behavior for TSMMCs are more complex than for MMCs made by other techniques, and most MMCs models used for prediction of mechanical properties are not suitable for TSMMCs. On the other hand, the fracture behavior of TSMMCs can be compared to fiber-reinforced ceramic or glass with load bearing controlled by the fiber-matrix interface. Taking this into account, the optimum between composite strength and toughness can be reached by tailoring the interface properties. As a conclusion, the position of TSMMCs in the composite family is presented in Table 3.

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