

Embedding of Alumina Reinforcing Elements in the Composite Extrusion Process

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Keywords: Composite extrusion, Alumina, Embedding

Abstract. Extruded aluminum profiles are essential for lightweight constructions in contemporary transport and automotive applications. The reinforcement of such aluminum-based profiles with high-strength materials offers a high potential for weight reduction and an improvement of functional and mechanical properties.

In comparison to conventional composite extrusion using fiber or particle reinforced billets, the alternatively developed process for the embedding of endless reinforcing elements provides enormous advantages regarding extrusion forces, load-adapted reinforcement, and tool abrasion. In this extrusion process with conventional billets, modified tools with portholes are used to position reinforcing elements from outside the pressing tool and to embed them into the material flow during the pressing operation.

This composite extrusion process is part of the research work started in 2003 and carried out within the scope of the Collaborative Research Center SFB/TR10. To increase the potential of composite extrusion with endless reinforcing elements, the manufacture of composite extrusion profiles with high-strength non-metallic alumina wires is planned. Due to the wires' specific properties, e.g. high stiffness, their deflection behavior must be analyzed to guarantee a stable feeding-in process. In this paper the specific behavior of alumina reinforcing elements regarding the feeding-in process is analyzed by experimental investigations. The main influencing factors are determined and a process window is deduced.

Introduction

The production of composite extrusion profiles with continuous reinforcing elements, which are embedded in an aluminum matrix, is an innovative process for manufacturing structural components in automotive and aerospace engineering. A high-strength reinforcing material is inserted into the welding chamber in the form of metallic wires and the wires are bonded with the material flow during the extrusion process [1].

To increase the reinforcing effect and to reduce the weight still further, it is judicious to use non-metallic reinforcing elements which have a higher specific strength and stiffness than metallic components (Table 1). One possibility of combining the lightweight material aluminum with endless non-metallic components is provided by alumina fibers. However, on the one hand alumina fibers have a high tensile strength, but on the other hand the fibers are brittle and rough considering bending forces. During the composite extrusion process, the reinforcements are redirected before they reach the welding chamber. Because of the wire's material properties with the non-distinct plastic material behavior and the applied bending stresses, which arise during the feeding-in of alumina elements, experimental investigations are necessary to guarantee a stable infeed without tearing of the reinforcement.

Material	R_m [MPa]	E [GPa]	ρ [g/cm ³]	E/ρ [GPa·cm ³ /g]
Spring steel 1.4310 (Ø 1mm)	> 1950	185	7.8	23.7
Nickel-based alloy (Ø 1mm)	1300-1600	205	8.1	25.3
Alumina fibres	until 3100	until 400	4.0	until 100

Table 1: Mechanical properties of reinforcing elements [2]

Process Principle of Composite Extrusion

In the composite extrusion process, a homogenous billet is used as base material and the hybrid is formed inside a special tool by feeding a second material into the metal flow during the extrusion. The billet material splits in front of the sealing plate into upper and lower strands, which join again in the welding chamber (Fig. 1 left). The reinforcing elements are fed from the sides into the tool where they are deflected towards the press direction within a cartridge provided with channels, still separated from the billet material. The elements get in contact with the base material in the welding chamber where the two different materials bond under high pressure and temperature [3, 4].

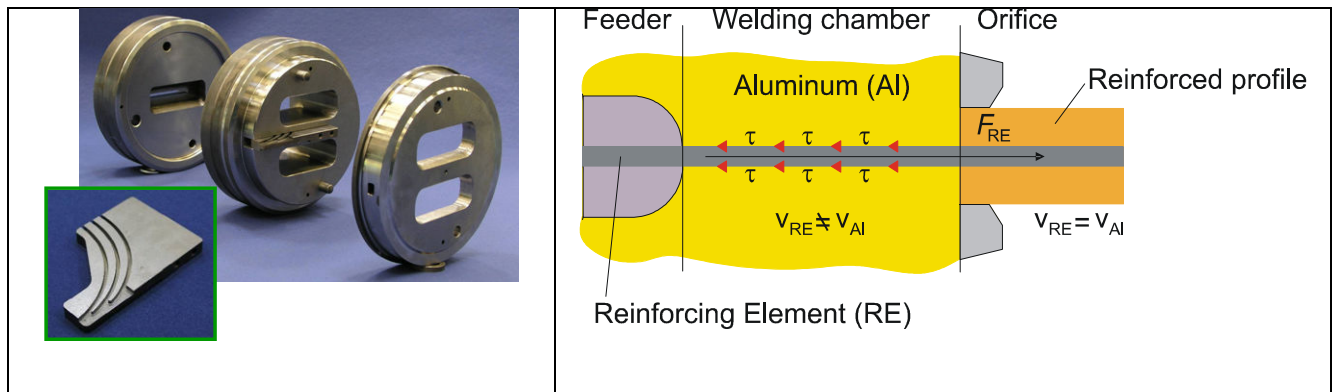


Fig. 1: Tool design and conditions in the welding chamber [5]

The reinforcing element is introduced at a 90° angle into the die (Fig. 1 left). Holes in the die direct the round reinforcement to integrate into the metal flow. During the extrusion process, no external force is needed to feed in reinforcing wires, because the metal flow leads to a tension stress in press direction on the wire surface [5] (Fig. 1 right).

To assure a stable manufacturing process of profiles with continuous reinforcing elements, it is important that the reinforcing wires are fed without tearing. In consequence of the redirection during the feeding, a bending moment appears on the wire. The occurring stresses for linear elastic loading depend on the radius of the cartridge channels, the diameter, and the Young's modulus of the used wires. The maximum bending stress σ_{\max} of a wire with a circular cross section of the diameter d and the Young's modulus E , which is controlled via a cylinder with the radius r , can be calculated with the following equation [6]:

$$\sigma_{\max} = \frac{E \cdot d}{2 \cdot r + d} \quad (1)$$

If the bending moment exceeds the yield stress, a plastic deformation of the reinforcing element will occur. Especially the feeding-in of ceramic wires involves special demands due to the fact that they are less flexible than metallic wires which are used for composite extrusion. Moreover, a small bending radius can lead to the fracture of the element.

Behavior of Alumina Reinforcing Elements

Ceramic fibers can generally not withstand the occurring shear and tensile stresses during the extrusion process without prior preparation due to the lack of internal load transfer inside the fiber bundle. An advantageous arrangement for using non-metallic wires in composite extrusion is represented by fiber-reinforced metal matrix composite wires. Composite wires could serve as a reinforcing element providing internal load transfers and helping to overcome the disadvantages regarding the extrusion process of fiber bundles. The reinforcing ceramic fibers are embedded in a light metal matrix by a continuous pressure infiltration process before extrusion. In addition, using the same matrix material for the composite wire and the extrusion process should prevent problems at the interface between the surrounding base material and the composite wire [7].

The non-metallic wire for the experimental investigations was provided by the IWK1 (Institute of Materials Science and Engineering 1, University of Karlsruhe). The composite wire has matrixes of almost pure aluminum and was reinforced by infiltration with approximately 40 vol. % ceramic alumina fibers (Al_2O_3). The wire has a diameter of 1 mm and oval Nextel440 fibers were infiltrated.

To guarantee a stable feeding of the composite wire into the composite extrusion process, the deflection has to be determined. In experimental investigations, the force which is needed to pull the wire out of the cartridge was measured to evaluate the deflection ability of the reinforced wire. Because during the extrusion process, the metal flow leads to a tension stress in press direction on the wire which pulls the wires into the welding chamber. For the experiments, a special cartridge with different channels with milled radii from 20 mm up to 100 mm in steps of 10 mm was manufactured so that the behavior can be determined for a variety of channels. The resulting tensile force was quantified with a piezoelectric sensor (Fig. 2).

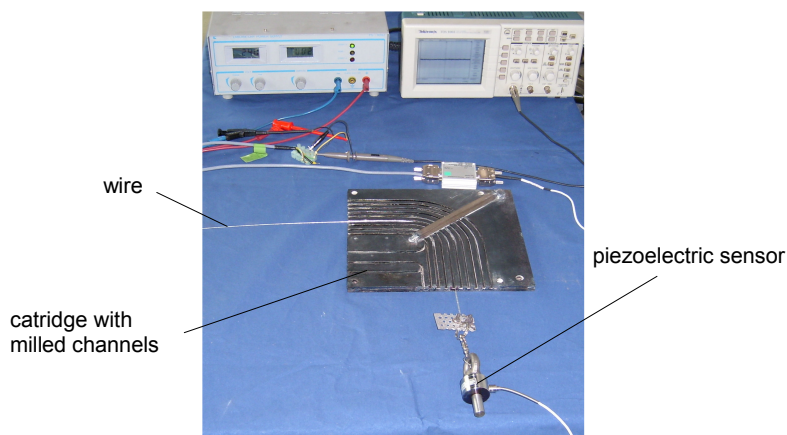


Fig. 2: Experimental set-up

The tests were done between room temperature and the maximal temperature of 500°C, which is equal to the maximally reached temperature inside the extrusion tool during the composite extrusion process. Because of the low dimension and the ambient aluminum matrix, the composite wire cools down to room temperature very fast so that the temperature-dependent experiments were done inside a furnace. Fig. 3 shows the cooling behavior of the double composite wire.

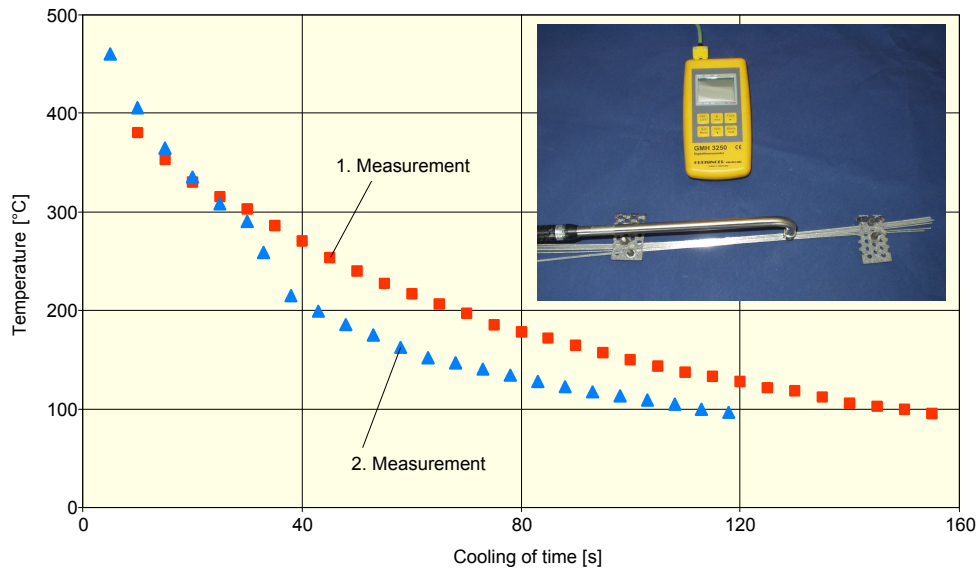


Fig. 3: Cooling behaviour

Fig. 4 shows the results of the measured forces which were needed to pull wires through the cartridge channels at room temperature. For comparison purposes, the experiments were also accomplished with spring steel (1.4310), which was already successfully used for the production of composite profiles with endless reinforcing elements. Per used wire and radius five tests were executed.

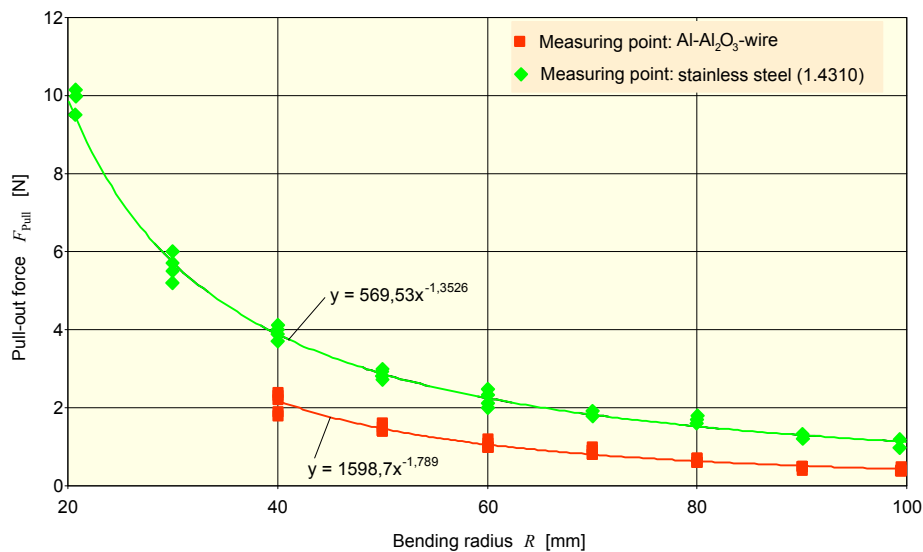


Fig.4: Pulling force at room temperature

The Al-Al₂O₃-wire breaks at cartridge radii less than 40 mm, as shown in Fig. 4. The spring steel was deflected without tearing for all tested radii and the needed forces were higher. Generally, the detected forces increased when reducing the radius of the supply channels. Analogue equation (1) the maximum stress raises with decreasing bending radius. The strength must be absolutely larger than the maximally reached bending stresses and the resulting friction forces so that the reinforcement wire will not break and can be supplied without failure. For aluminum-alumina composite wires with a fiber percentage by volume of 50 %, a tensile strength of approximately 1300 MPa can be expected [8]. Even at a temperature of 775°C, when the matrix is partially melted, strengths still ranging between 500 and 700 MPa are reached [9]. An accurate prediction of the wires' strength cannot be done because the amount of the ceramic fibers in the wires is not exactly known. The material properties in fiber direction strongly depend on the fiber quantity in relation to the total volume, the type of the fibers, and the characteristics of the fiber matrix connection and

vary accordingly in larger extent [9]. It is possible that small pores remained during the infiltration of the fiber bundle where the liquid matrix material was not able to penetrate and this phenomenon has a negative effect on the material properties of the wire [10]. Fig. 5 shows a polished micrograph section of the used Al-Al₂O₃-wire.

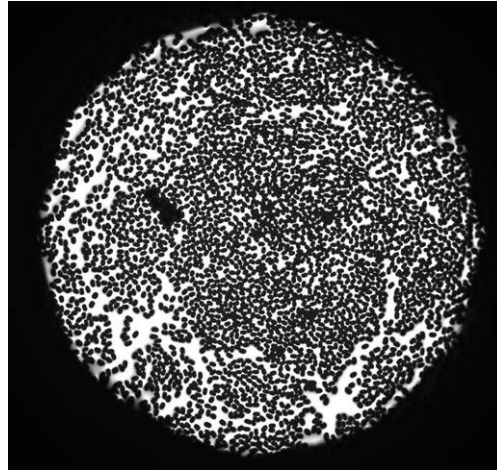


Fig. 5: Polished micrograph section (IWK1)

During the successive increase of the temperature, the aluminum base should weaken and permit small movements of the fibers, thus allowing a lower stress and pull-out force, which involves a better redirection ability. It cannot be assumed that the ceramic fiber bundles become more flexible at temperatures of up to 500°C because the melting point of alumina lies approximately above 2050°C [11]. Fig. 6 shows the results of the measurement up to a temperature of 200°C for a bending radius of 50 mm. The pull-out forces of the spring steel decrease continuously, which is a consequence of the falling Young's modulus. The Young's modulus of solid materials decreases usually with increasing temperature due to the decreasing atomic binding forces [12]. However, the composite exhibits another behavior, at first the pull-out forces became less, but in the further run of the curve the forces rise strongly. The minimum is probably due to the sinking Young's modulus, but the rise is justified by other effects, for example friction.

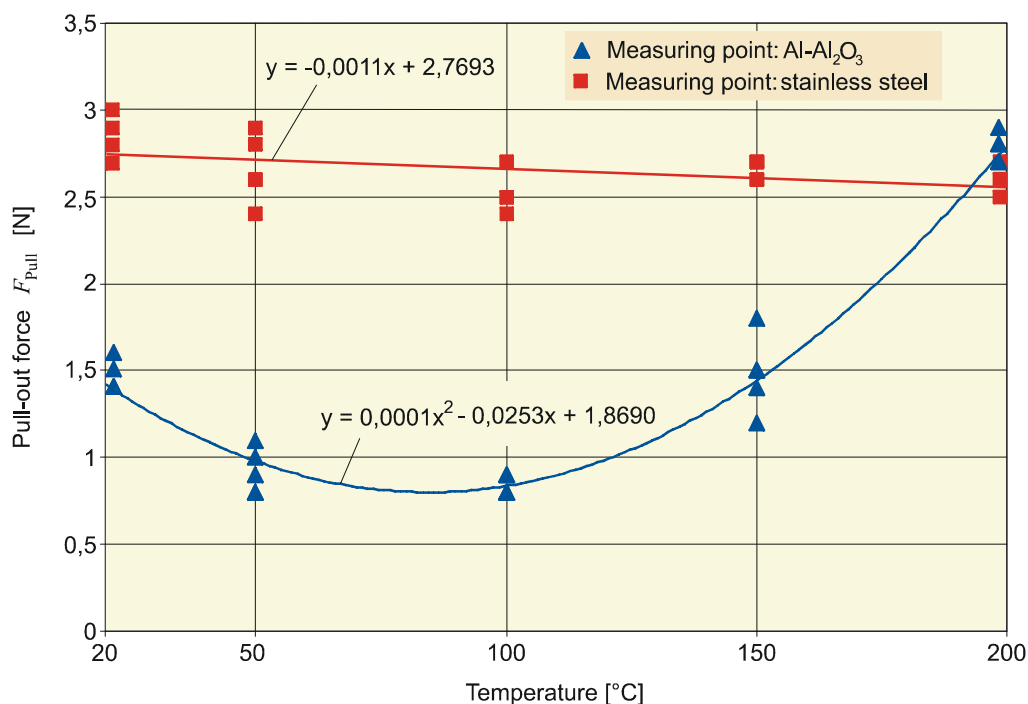


Fig. 6: Temperature-dependent deflection behavior up to 200°C

According to the friction model of *Coulomb*, the frictional force depends linearly on the regular force which affects the contact surface orthogonally. The regular force towards the supply channel bottom will not be considered by reason of the low death load of the composite wires. But the regular force in wall direction has an important influence on the friction due to the stresses. To analyze the influence of friction on the feeding-in process, tests with the lubricant boron nitride (α -BN) to reduce the friction and without lubricants were made. Fig. 7 shows the results.

The use of the lubricant boron nitride reduced the pull-out force significantly. During the test, it was not possible to guarantee a continuous lubricant film. That is the reason why the composites broke above a temperature of 450°C. Moreover, the oxide skin of the aluminum matrix has a strong influence on the frictional forces [13]. A rise in temperature leads to the oxide skin getting larger, which results in an increase of the surface roughness and finally to higher friction forces.

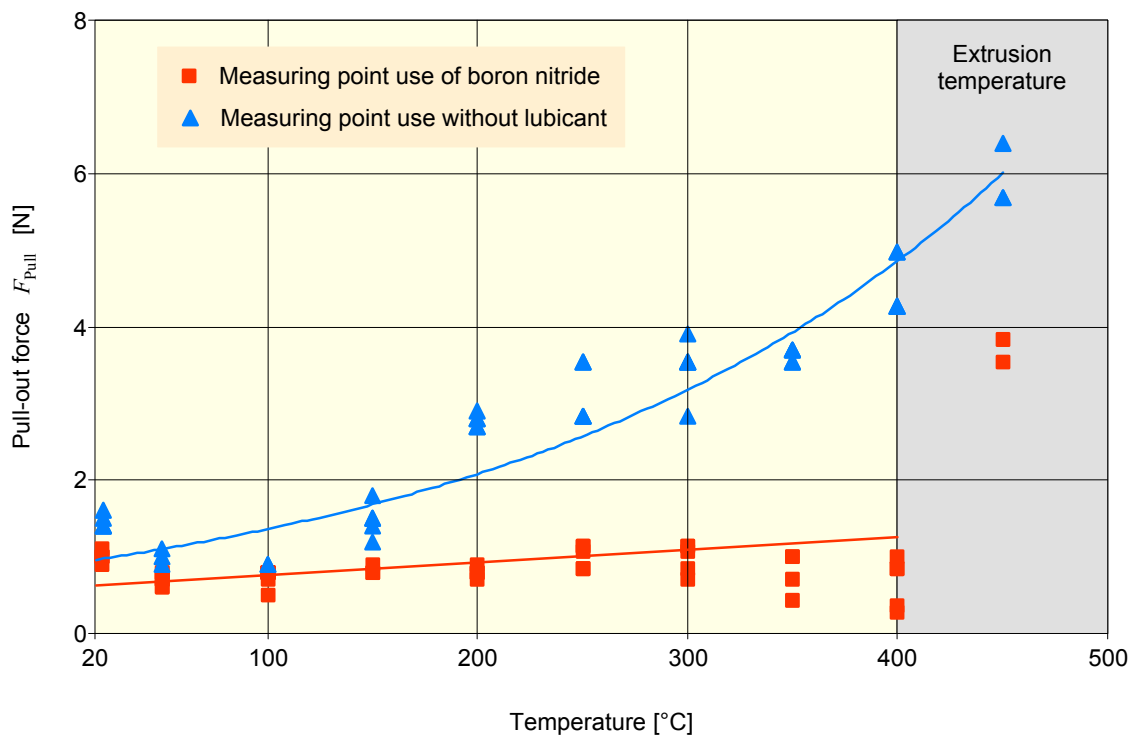


Fig. 7: Temperature-depending deflection behavior up to 500°C

Deduction and Analysis of a Process Frame

Influencing Factors. In the experimental investigations, only the break of composite wires appeared as observed disturbance. The reason for the break of the wires is stress above the maximum tensile and shear strength. The arising tensions depend directly on the bending radius of the cartridge, the tribological system, and the wire characteristics (Fig. 8). The friction, for example, can be reduced by a surface coating of the cartridge channels.

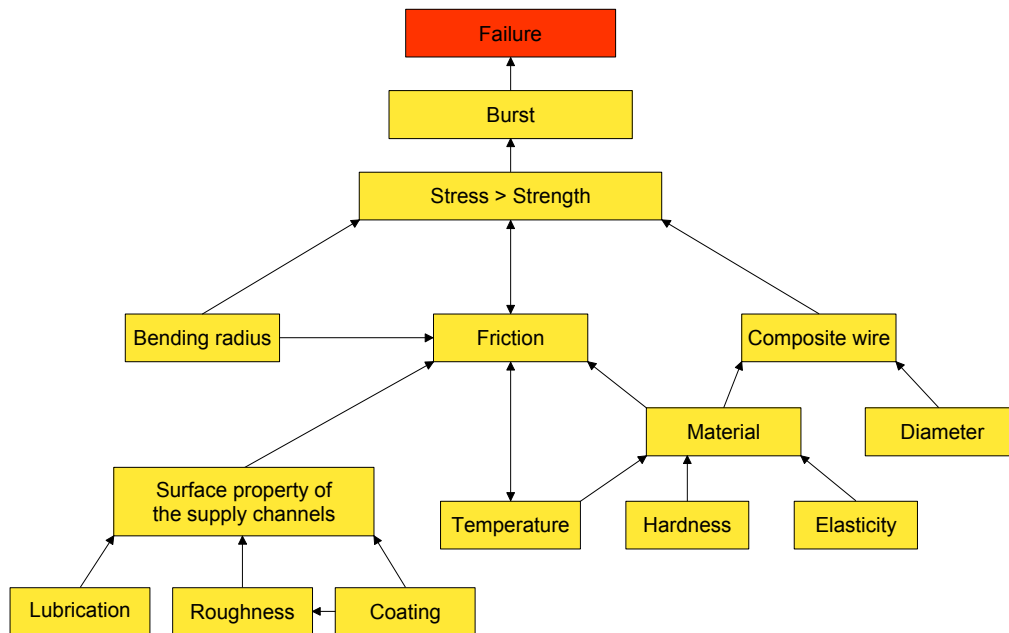


Fig. 8: Process-related influences

Process Window. Based on the pull-out test, a process window for the feeding-in of ceramic reinforced wires can be deduced. Fig. 9 shows a process window for a stable feeding-in process. For the composite extrusion process, only the range at temperatures between 400° and 500°C is relevant. The degradation of deflection characteristics during the rise in temperature is due to the increasing friction. To guarantee a high process stability, a minimum radius of 60 mm is needed. By the application of a suitable coating, the feeding-in up to a radius of 30 mm could be possible. But, on the other hand, a coating could be negative for the interface between reinforcing element and aluminum base, if the coating reached the welding chamber bounded to the wires.

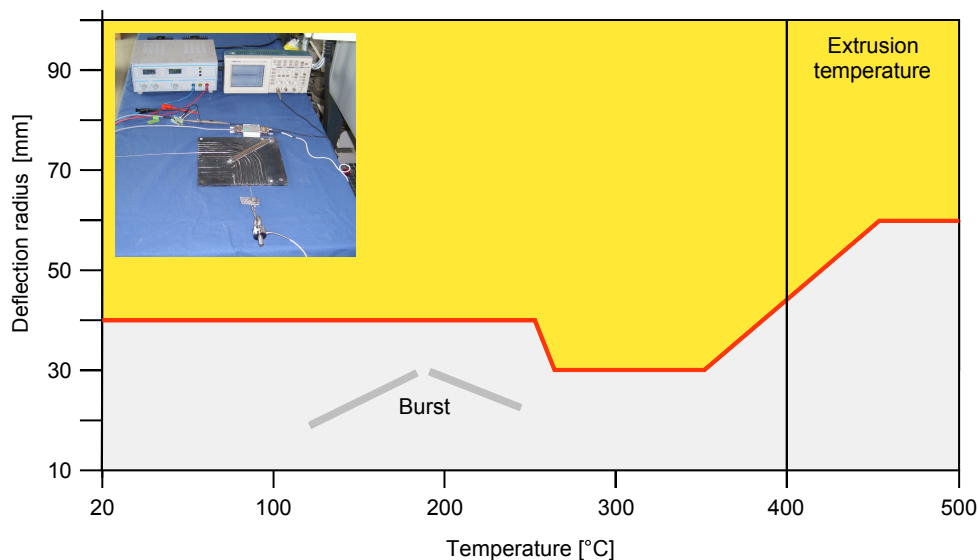


Fig. 9: Process window

Conclusion and Outlook

The production of continuously reinforced profiles by use of an aluminum matrix and reinforcing elements made of steel or ceramic wires offers a great potential for modern lightweight constructions. In addition, ceramic fibers feature a high specific strength and stiffness compared

with heavy metallic components. The feeding-in process of ceramic reinforcements demands specific requirements because of the high stiffness and brittleness. In the scope of the present paper, the deflection behavior of the composite wires was analyzed on the basis of the needed pull-out force. In general, the pulling force decreases with increasing radius. The deflection behavior also depends on the temperature, whereas friction has a great influence, too. Accordingly, a process window for a stable embedding could be deduced. At first, the rising temperature leads to decreasing process limits, but at temperatures above 350°C, the influence of the cumulative oxide skin dominates. To enhance the process limits, an adequate coating of the supply channels should be used to reduce negative tribological effects.

Acknowledgement

This paper is based on investigations of the Transregional Collaborative Research Center SFB/TR10, which is kindly supported by the German Research Foundation (DFG).

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