TEXTILE BASED METAL SANDWICHES AND METAL-MATRIX-COMPOSITES REINFORCED WITH 3D WIRE STRUCTURES. PART III: MATERIAL CHARACTERISATION

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Abstract
3D wire structures are predestined for the use in lightweight structures due to their high mechanical properties and temperature-resistance at a low specific weight. After the development of the textile wire structures and suitable joining technologies for sandwich applications have been presented in part I and part II of the paper, this article focuses on the experimental investigation of material properties and the failure behaviour of textile based metal sandwiches and the metal-matrix-composites with wire reinforcement. For this purpose, extensive static and dynamic tests have been performed. The mechanical properties are compared to commercial lightweight materials of the same class as a benchmark.

1 Introduction
The extensive requirements on modern structural lightweight materials lead to new classes of high performance composite materials. Requests for a high material efficiency increasingly require the development of sandwich composites because materials with different stiffnesses, strengths and densities can be combined according to the particular application. Significant disadvantages of conventional sandwiches like composites with honeycomb core are the low temperature stability especially of the synthetic core material and high manufacturing costs. By using metal as a sandwich core material, these disadvantages can be avoided. Nevertheless, the high densities of eligible metals usually contradict the lightweight design objectives.
Novel ideas to overcome this conflict arise from the field of cellular materials. Here, especially so-called “wire-woven bulk kagome” structures [1-3] have proven the capability to combine high specific mechanical properties with a low specific weight. However, an immanent problem of those structures – and also of other relevant cellular metal materials – is related to the inefficient manufacturing processes.
In this context, the “European Centre for Emerging Materials and Processes” (ECEMP) in Dresden adopts an approach that combines both efficient manufacturing technologies and

joining processes as well as high mechanical properties [4-7]. The developed textile based metal composites in multi-material design offer a huge application potential. Particularly, the excellent adjustable energy absorption of these 3D structures is an essential condition for an efficient design of structures that are loaded by impact or crash without a loss of performance. Beside a deep knowledge of the material behaviour, the design of such complex 3D wire structures requires three development steps: (a) a novel textile technology that enables a reasonably efficient manufacturing of 3D wire textiles (3DWT) with a high reproducibility and homogeneity, (b) an advanced technology for joining the 3D wire textiles with metal plates to the final sandwich material, and (c) novel experimental and theoretical approaches to evaluate the properties of such materials. The first two scientific issues are discussed in [8] and [9], respectively. This article focuses on the determination of relevant material properties for the given applications by suitable quasi-static and dynamic experiments.

2 Sandwich materials with metal surfaces and 3D wire textile cores

Beside the already mentioned thermal stability of the novel sandwich structures with 3D wire textile cores, their individually adjustable property profile, their good energy absorption capabilities and the high ductility of the core textile have to be mentioned as key properties in order to realise novel lightweight solutions. 3D wire textiles have proven to be particularly suitable for impact and crash applications since they can be manufactured to curved structures without major drawbacks. Figure 1 shows the preferred textile (left) and the final sandwich material (right). The preferred setup consists of steel plates (material 1.0605) of 0.6 mm thickness as surface layers and a woven textile core of approx. 10 mm thickness. The core has been woven with 0.6 mm spring steel wires by reshaping them to trapezoidal wires in the weft system.

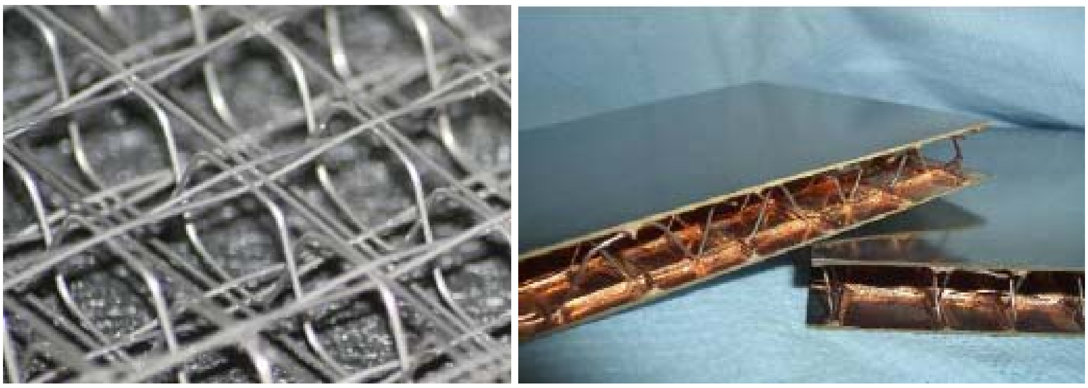

Figure 1. Novel wire based 3D textile (left), sandwich after joining (right)

The mechanical properties of the preferred sandwich design have been determined and compared to sandwiches which are commercially available (FRP honeycomb sandwich (FRP-HC), aluminium honeycomb sandwich (Al-HC), sandwich with strucwire core (see [7])). Exemplary, quasi-static compression tests and dynamic bending experiments are chosen for that comparison.

Quasi-static compression tests in thickness direction are usually chosen to evaluate the properties of cellular materials. As a result, a broad database for different cellular structures exists as a basis for the comparison. Such compression tests are used to determine the properties of the core material since the stiffness and strength of the surface layers is usually much higher. Specimens of 50 x 50 mm² are cut and tested (Figure 2). The novel 3DWT-sandwiches show a distinct plateau in the stress-strain curve after leaving the linear-elastic part. Classical elastic-plastic material behaviour can therefore be assumed on the macro-level.

In order to assure a better comparability of the results of different sandwich materials, the measured compressive strengths have been normalised to the relative density of the core material (Figure 2). Due to the very low relative density of the novel sandwich structures, the compression strength shown in Figure 2 does not reach the values of the other structures tested. Consequently, the increase of the absolute values of the mechanical properties by adapting the wire arrangement must be the subject of further investigations.

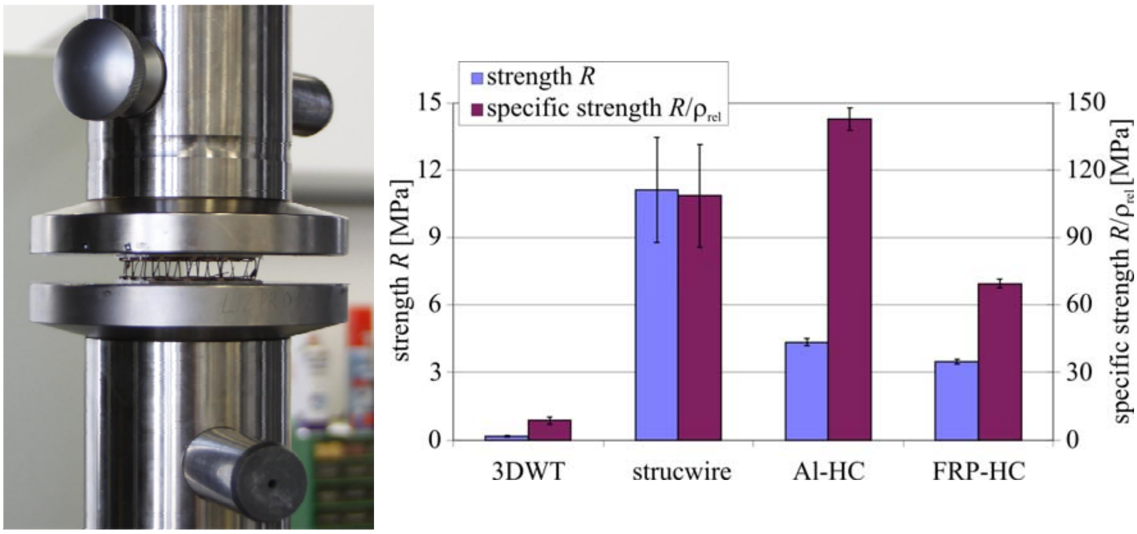

Figure 2. Quasi-static compression test (left), strength comparison of different sandwich materials (right)

Dynamic bending experiments enable a first evaluation of the impact and crash properties of the sandwich material. The chosen test velocity of 1 m/s adapts the local loading of a typical containment structure when impact events of smaller objects are considered.
The measured force-deflection curves during the dynamic bending tests are used to determine the work executed by the specimen which is a good indicator for the absorbed energy. The determined properties are normalised to the relative density of the whole sandwich structure (Figure 3). The novel sandwich materials show similar properties compared to aluminium honeycomb structures. By using high-strength wires, the obtained properties can be significantly increased.

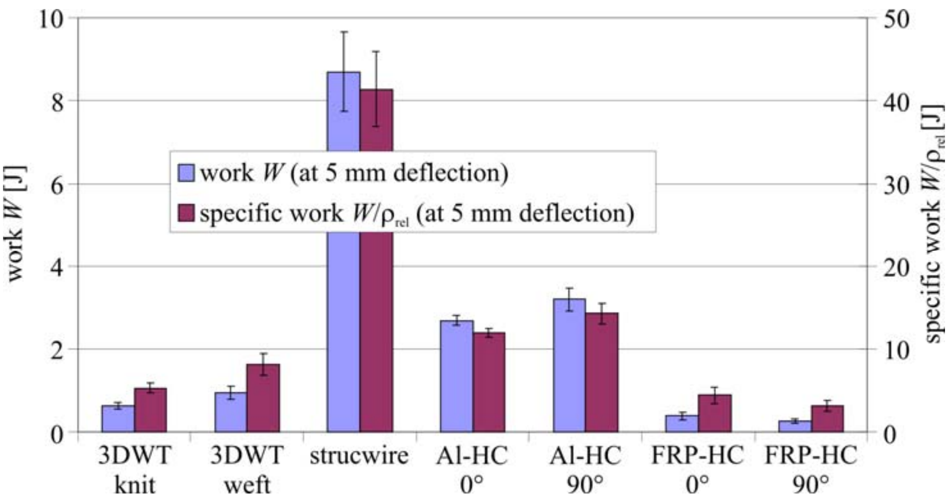

Figure 3. Mechanical work performed in a dynamic bending test for different sandwich structures

3 Metal-matrix composites with 3D wire reinforcement

3.1 Mechanical properties

Beside the developed sandwich materials with metal surfaces and 3D wire cores, metal matrix composites also have a considerable potential with regard to applications where thermo-mechanical strain rate dependent loading is relevant. For MMC's with high mechanical properties, a high-level manufacturing technology is of particular interest [10].

Magnesium as the lightest metallic engineering material has been chosen as matrix system. In detail, AZ 91 alloy was used due to its exceptionally good castability combined with high mechanical properties. Gas pressure infiltration technology was chosen for specimen manufacturing because of the high stability of the process and the high reproducibility of the time-temperature-pressure gradient [4,5].

Tensile tests, Charpy tests and impact experiments have been performed in order to evaluate the capabilities of the material. Four different materials are investigated: pure magnesium (AZ 91), magnesium unidirectionally reinforced with steel wires, magnesium bidirectionally reinforced with steel wires, and 3D-reinforced magnesium (reinforced with strucwire structures, details see [7]). Within the quasi-static tensile test, strain measurement was realised using optical measurement. The performed investigations have shown a strength increase in fibre direction. The increase of 22 % was realised by a steel fibre volume content of only 3.65 %. When specific strength values are compared, the strength increase still amounts 9 %. In off-axis direction, the strength of the MMC's is slightly lower compared to pure magnesium due to the weakening effect of the interface (Figure 4). The measured Young's moduli correspond to the values that can be predicted analytically by simple rules of mixtures.

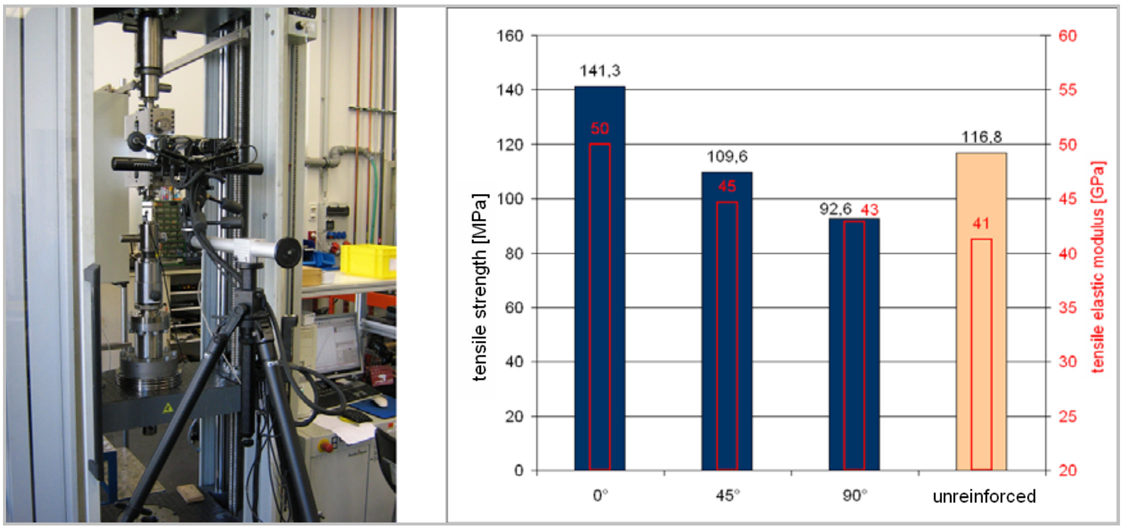

Figure 4. Tensile test device with optical strain measurement (left), stiffnesses and strengths of UD-reinforced MMC's compared to pure magnesium

The evaluation of Charpy impact tests enables to find conclusions about the energy absorption of the MMC's. Due to the higher strain at failure and the high Young's modulus of the reinforcing steel wires, the total energy absorption of the UD-reinforced MMC's increases by 18 % (Figure 5). Moreover, the ductility of the material increases, too. This can be a decisive advantage when the MMC's should be applied for applications in explosion prevention environments or crash structures because a fragment hazard has to be avoided.

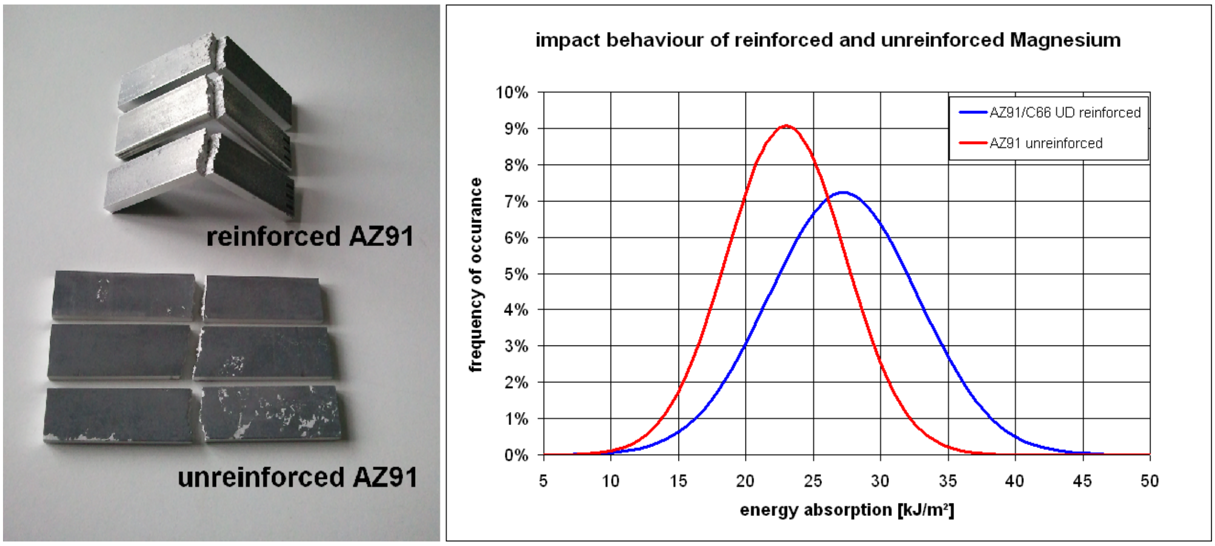

Figure 5. Phenomenology of failure of MMC composites and magnesium after Charpy tests (left), related energy absorption (right)

Classical impact penetration tests enable an advanced assessment of the energy absorption capability and thus of the crash behaviour of the new materials. Compared to the Charpy tests, the specimens are loaded over a larger area so that the energy redistribution after the impact event can be analysed. In order to characterise the strain rate dependent material behaviour, the impact penetration tests have been performed with different impact velocities. Based on the integral over the force-displacement curve, the absorbed energy during the impact event can be determined. Figure 5 shows that the absorbed energy significantly increases even if only a unidirectional reinforcement is used. The energy absorption can be further increased when optimised reinforcements or high-quality materials are used. Figure 6 also indicates a quadruplication of the energy absorption for the optimised set of so called strucwire 3D reinforcement which is made of helical wires made from stainless steel and a volume fraction of about 10 %.

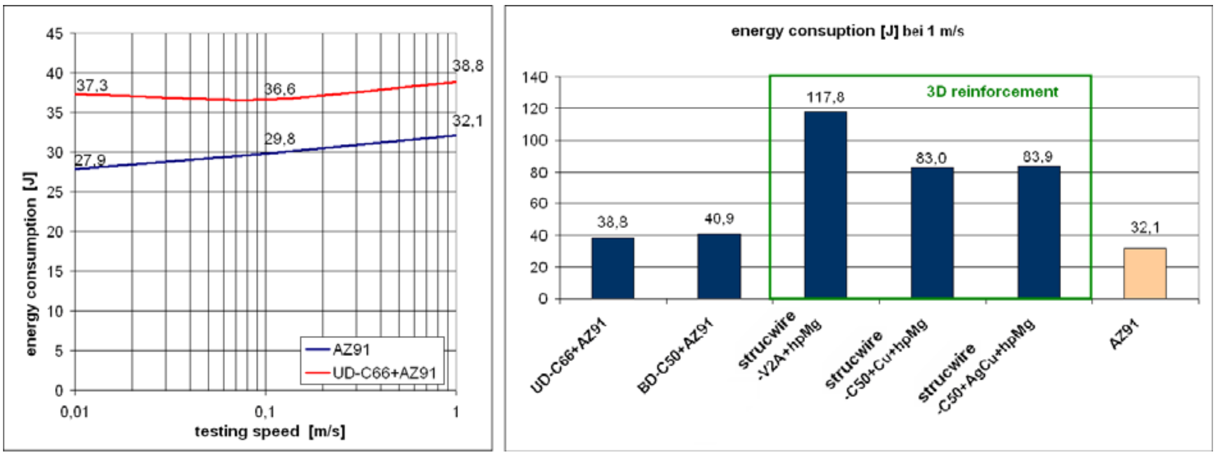

Figure 6. Energy absorption during impact tests depending on loading velocity (left) and materials (right)

3.2 Interface properties

The interface between the reinforcing wire and the light metal matrix is of vital importance for the mechanical properties of the MMC’s. A weak bonding results in higher delamination probabilities and thus in lower strenths. Wih a well pronounced bonding, the fibres are fully loaded without delaminations in the interface. For applications that require a high energy

absorption capability, the interface has to be designed in a way that mechanical energy as high as possible can be absorbed due to crack propagation without larger delaminations.
To study the interface properties, several material combinations have been investigated with regard to their interface properties:

- steel wires soldered up with copper filler,
- steel wires soldered up with copper filler and eutectic aluminium soldier AlSi12,
- zinc-coated steel surfaces with AlSi12.

The investigations have proven that a homogeneous copper layer as alloying element or as intermediate layer is basically suitable to guarantee a good bonding to aluminium and magnesium melts. With its melting point of approx. 420 °C and the ability to appear as mixed crystal creator for aluminium and magnesium, zinc provides good preconditions to guarantee a high-quality interface in the MMC.

4 Conclusions

Textile based 2D and 3D metallic wire structures have proven to be a suitable reinforcement for multi-functional composites. Within the described investigations, a systematic transfer of those materials into lightweight applications for automotive and mechanical engineering has been performed together with the development of efficient and economical manufacturing technologies and process chains. The metallic wire structures fabricated by a novel weaving technology are globally unique. After joining the wire structures, they are processed to sandwich composites with metallic surfaces or embedded in metal matrices.
Based on an extensive experimental test programme, the particular suitability of the developed 3D wire structures for impact applications has been shown. Impact experiments have shown that the energy absorption capability of wire-reinforced materials can be increased up to 600 % compared to conventional materials. Beyond that, with their low weight and high temperature stability, the novel materials are predestined for thermo-mechanically loaded structures in automotive applications.

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