TEXTILE BASED METAL SANDWICHES AND METAL-MATRIX-COMPOSITES REINFORCED WITH 3D WIRE STRUCTURES PART II: JOINING TECHNOLOGY AND INTERFACE MODIFICATION FOR MMC

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Abstract
A new kind of periodic cellular metal will be presented. These special three-dimensional cellular metals are built by wires with a modified textile weaving technique. The aim of this study (Part II) was to realize a well joined porous structure with the possibility to create a new kind of metal matrix composite (Mg matrix) via infiltration techniques. To join these special structures with its many intersections and nodes a procedural path had to be found. In thise study carbon spring steel was used because of its advantages like low cost, adjustable strength and the possibilities of brazing. The first results of this research will be presented in this work and a conclusion and an outline of future work will be given.

1 Introduction
3d wire structures
Cellular materials are special types of materials with customized strength and low weight. It can be adjusted by the specific integration of pores. In the last years a lot of research and development was done for metallic cellular metals. Well known examples for that kind of materials are open and closed cell aluminium foams and steel hollow spheres.
Regularly arranged cellular metals with truss-type inner structures like pyramidal lattice truss structures [1], wire-woven bulk kagome (WBK) [2] or 3D wire structure called strucwire® [3] are called periodic cellular metals (PCM). These constructed materials are manufactured by assembling metal wires in a systematic way. A new kind in this group is a three dimensional wire structure manufactured with a modified textile weaving technique with a

high potential for automatic manufacturing. For further information please refer to "Textile based metal sandwiches and metal-matrix-composites reinforced with 3D wire structures. Part I" in the same proceedings. Two pictures of the first developmental stage of this new textile 3D wire structure are shown in Figure 1 to give an idea of the geometric characteristic of these new materials.

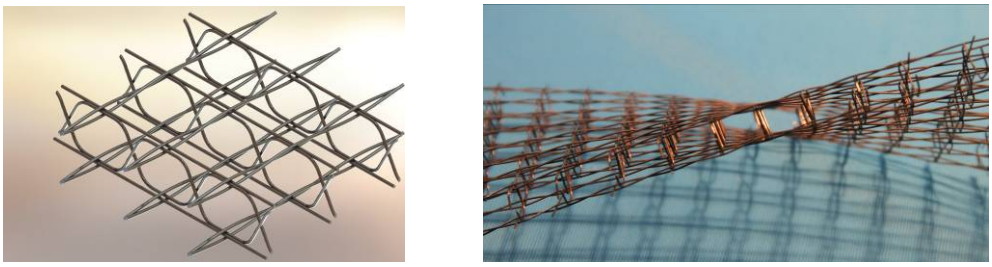

Figure 1. (left picture) CAD picture of the textile wire structure; (right picture) photograph of a structure after manufacturing

The aim of the study is to increase the stiffness and strength of these structures because of their low structure stability after the textile manufacturing process, like shown in the right picture of Figure 1. For this purpose the challenge is to join the wire crossing points or nodes inside the structure with the perspective to treat these structures later on in an automatic joining process. The specimens are fabricated from carbon steel wires with a diameter of 0.6 mm. To realize the joining of the wires inside the structure, different ways of brazing were tested and compared to each other.

Another research topic is the development of a manufacturing process to increase the fracture toughness of light metals (especially magnesium alloy) by infiltration of the porous wire structures. The steel wires with their higher stiffness and strength help to increase the toughness of the light metal. To create a good bonding between the carbon steel wires and the magnesium alloy AZ91, which was chosen for this study, a bonding agent is necessary because of the fact that there is no chemical interaction between these two metals. To integrate this type of porous structures in an automatic metallic casting process like die casting to get an MMC material, it is necessary to generate a metallic connection between the wire structure and the cast alloy. To analyse the interface reaction, a special experimental casting setup was used to simulate a very short reaction time like in technical die casting processes.

2 Experimental

2.1 Specimen preparation and brazing techniques

Conventional technologies like welding and brazing with gas torch e.g. seem not to be suited for an automated process because of the limited accessibility inside the wire structures. In the present study selected brazing technologies for 3D textile wire structures, which can be used for automatable brazing technologies, are introduced.

The first step to join the nodes of the structures is a specimen preparation to achieve a good wettability of the wire surface. Therefore the specimens were put in several bathes for repeated degrease and rinse. The chosen process steps to braze the wire structures are:

- galvanic degreasing with a special alkaline bath
- rinse with water and ethanol
- application / integration of the brazing material

- heat treatment in argon atmosphere.

To braze the whole metallic wire structure, several technologies like metallic coatings, brazing pastes and the integration of brazing wires were tested. At the end two ways seemed to be practicable. The first is the galvanic coating technology because of its possibility to bring a brazing metal on the wire surface with a defined thickness. In the galvanic coating processes the deposition of pure metal films like copper, nickel or silver on the structure surface is possible. Basically, copper is the most used braze for stainless and carbon steels [4] because of its very good wettability and ductile character (no brittle phases). For the coating process the work piece (cathode) and the coating metal (anode) are put in an electrolytic bath. The process is controlled by the electric current. Figure 2 shows a galvanic cell and a copper coated wire structure after the galvanic process.

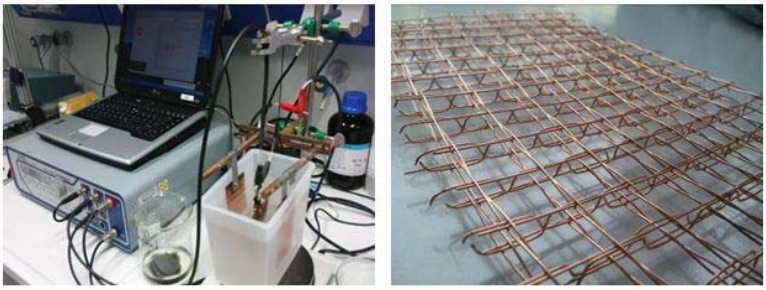

Figure 2. (left) galvanic cell – laboratory size, (right) copper coated textile wire structure

The other possibility is to integrate a special brazing wire into the weaving process. In this work a thin copper wire with a diameter of 0.4 mm was integrated in the fill direction of the weaving process.

2.2 Metal matrix composite with 3D wire structures

To realize a good metallic connection between the carbon steel wires and the magnesium alloy AZ91 (9 wt% Al, 1 wt% Zn; Ts: 580 °C) a metallic coating on the wires is used. The diffusion process between the wire, metallic coating and the magnesium alloy has to be very fast because of a short reaction time (seconds) where the alloy is in a liquid condition due to the rapid cooling in die casting. Therefore also copper, the brazing material that stabilized the wire structure during the cast process was chosen. The experimental setup to analyze the reaction at the interface between the wire and the magnesium alloy is given in the following list:

- galvanic copper coated carbon steel bar with a diameter of 6 mm
- a cylindrical carbon steel casting die with a inner diameter of 10 mm and a outer diameter of 12 mm
- magnesium alloy AZ91
- inductive heating
- argon inert gas atmosphere (closed furnace).

To simulate a very short process and reaction time, the magnesium alloy melt in the die under inductive heating conditions up to 620 °C under a argon inert gas atmosphere. After that the coated steel bar (being at room temperature) was inserted into the magnesium melt and the inductive heating was shut down immediately for rapid cooling. The solidification time of the magnesium melt was about 2 seconds.

The material bonding between steel bar and cast alloy was analyzed with optical microscopy and scanning electron microscopy. The element distribution in the boundary layer measured

by energy dispersive x-ray(EDX). X-Ray diffraction (XRD) was chosen to identify the formed crystallographic phase of the final cast structure.

3 Results

3.1 Results of the brazing experiments

The brazing solder mainly increases the stiffness and strength of the three dimensional semi finished part. The reason for this is the design of the structure itself. The brazing metal coats the wires and fills the space between the wires at the nodes and makes the structure much stiffer for further processing like sandwich constructions or integration in an infiltration process to create a metal matrix composite. Figure 3 shows some microstructures of galvanic copper coated wire surfaces for and after the brazing process.

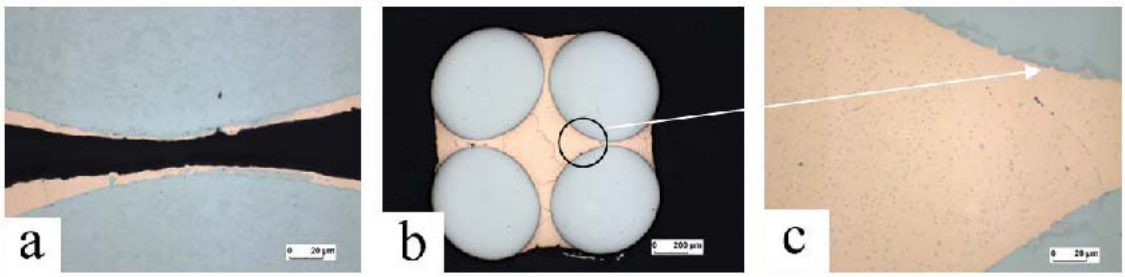

Figure 3. (a) steel wires after galvanic copper coating; (b) steel wires after heat treatment at 1130°C (Ar-atmosphere) with copper filled nodes; (c) good boundary layer between copper and a steel wire

Another way of joining of the wire structures is the integration of a brazing wire. This approach features two advantages. The first is a much easier process route because of the minimizing of the process steps. Furthermore it gives the opportunity to use standardized brazing wires with different compounds and performances. In Figure 4 a woven steel wire structure with integrated silver coated copper brazing wires in the fill direction before and after the heat treatment is shown.

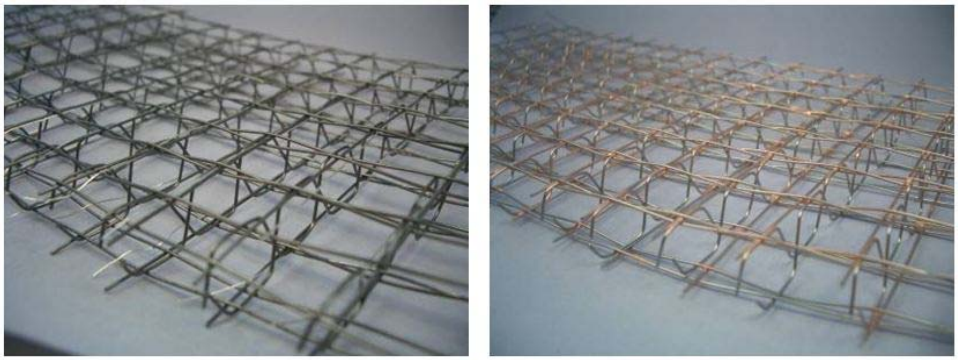

Figure 4. Carbon steel textile wire structure with silver coated copper brazing wires in the fill direction before (left picture) and after (right picture) the heat treatment (1130°C, Ar-atmosphere) to braze the nodes of the structure

With this first results it can be said that the stiffness of the structures is basically the same for both joining routes. For a further casting process where a metallic coated wire is needed to form a functional interface, the galvanically coated wires are the better solution because of a more homogenous coating of all wires of the structure.

3.2 Results of the casting experiments

In the following, it will be shown that a copper coated carbon steel wire can form a stable metallic interface without porosity with a magnesium alloy (here AZ91) even during a very short reaction time. Figure 5 shows an optical microscopy picture of a boundary layer section of the copper coated steel and the magnesium alloy matrix after the casting process.

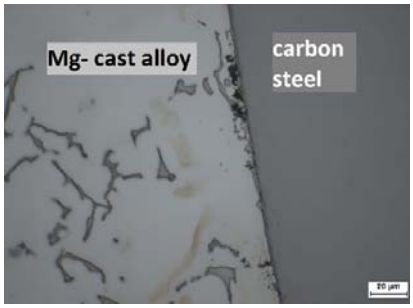

Figure 5. Optical microscopy picture of a boundary layer section between a copper coated steel bar and the magnesium alloy matrix AZ91 after casting (620 °C, Ar atmosphere, carbon steel bar at 25 °C); the copper coating is in solution with the Mg alloy

In order to gain further information, EDX mappings were done to determine the element distribution at the interface. This became necessary because the copper coating was no longer optically identifiable after the casting procedure. Figure 6 shows the distribution of the elements involved in the diffusion process like Al, Fe, Cu, Zn and Mg. It shows that the copper from the coating completely reacts with the magnesium melt, especially with the aluminum to form a new phase within the cast structure.

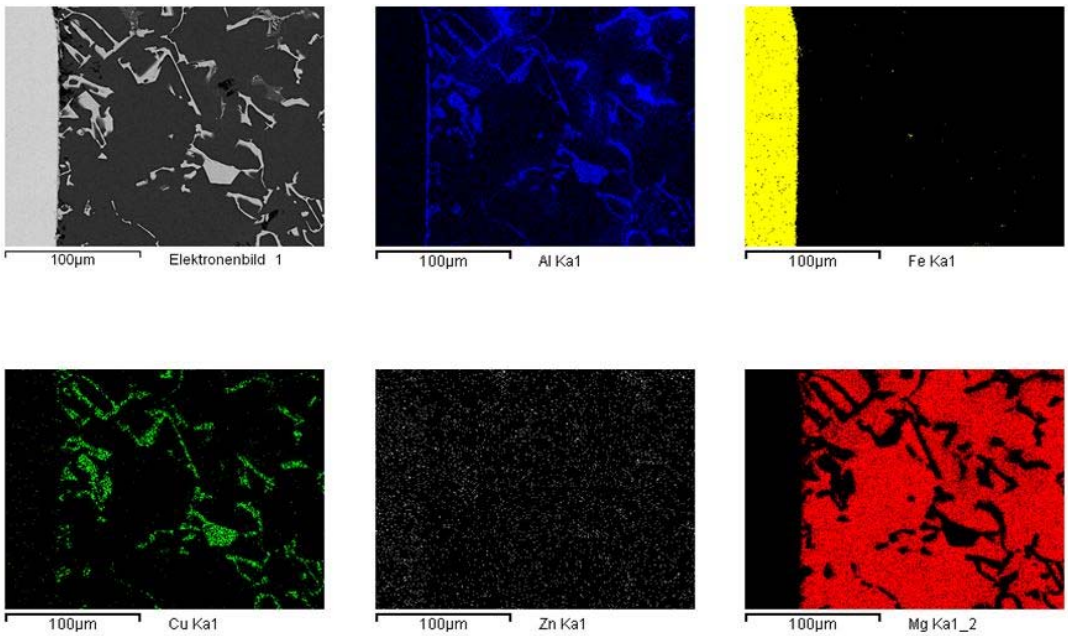

Figure 6. EDX mapping of the element distribution near the boundary layer of the carbon steel bar and the magnesium cast alloy

To specify the crystallographic phase of the new formed low melting phase/s in the magnesium matrix, an XRD analys was performed to confirm the EDX results. The XRD results are shown in Figure 7. The analysis shows that the phase Al_2Cu is formed as the new phase.

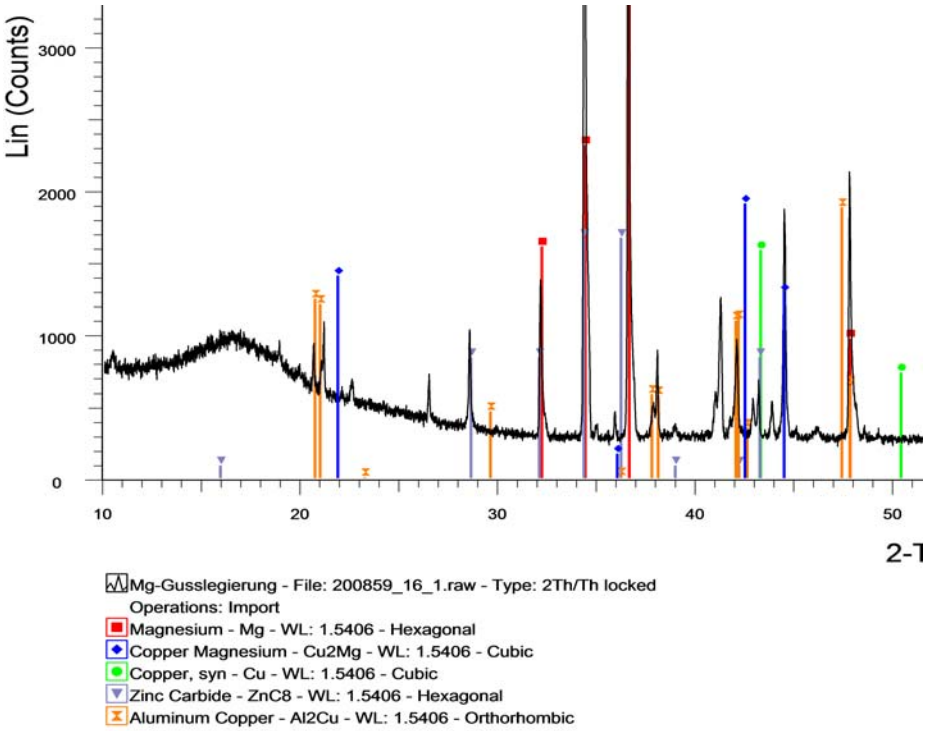

Figure 7. XRD plot of the magnesium cast alloy after the reaction with the cold (RT) copper coated carbon steel bar at 620 °C under Ar atmosphere for several seconds.

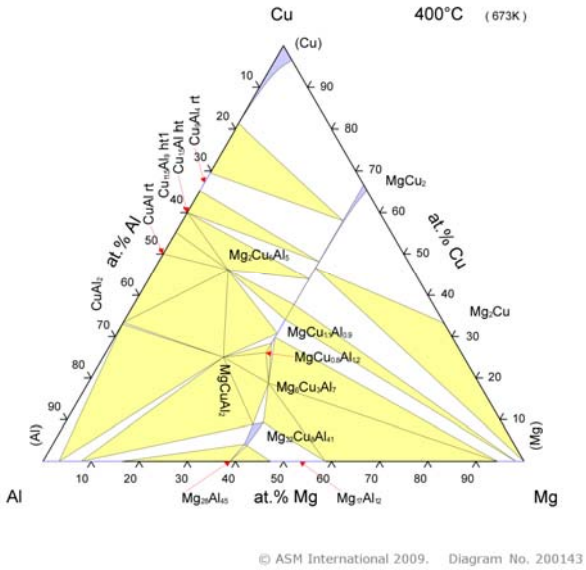

Figure 8. Al-Cu-Mg phase diagram at 400 °C

The Mg-Al-Cu phase diagram is given in Figure 8. From this ternary diagram it would be expected to find at least one of the ternary Mg-Cu-Al phases in the solidified cast instead of

the detected Al_2Cu phase. It is likely that the formation of this phase is preferred for kinetic reasons compared to the more difficult ternary phase formation.

Summing up, copper coated carbon steel substrates can interact with the magnesium alloy to create a good metallic interface like shown in Figure 5 even in a very short time during fast cooling.

4 Conclusions

The present study shows that it is possible to join 3D wire structure by brazing. It is proved that the cross points are filled with molten soldering metal due to the action of capillary forces. Furthermore it could be shown that the brazing metal can act as a coupling agent betweeen the carbon steel and the liquid magnesium alloy to create a good interface for a MMC with a magnesium alloy as matrix material. The study shows that is possible to use the joining material to bond the nodes of the wire structure in a first brazing step to generate a stiffer structure and to use it as a coupling agent between carbon steel and the magnesium alloy to create a new MMC material. In the future, different brazing materials and metallic coatings will be tested and compared to each other, and in particular the strength of the interface will be characterized by suitable mechanical testing.

5 Acknowledgment

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