Joining technologies and mechanical properties for a new kind of 3D wire structures

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1 Introduction

Cellular materials are special types of materials where customized strength and low weight 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 close cell aluminium foams and steel hollow spheres.

Cellular metals regular arranged with truss-type inner structures like pyramidal lattice truss structures [1] or the wire-woven bulk kagome (WBK) [2] are a different type and called periodic cellular metals (PCM), where the construction is manufactured by assembling metal wires in a systematic way. A new kind in this PCM group is a 3D wire structure called strucwire® and is to be introduced in this paper. The 3D wire structure is developed in a joint project of Fraunhofer-Institute for Manufacturing and Advanced Materials (IFAM) Dresden, the Institute of Lightweight Engineering and Polymer Technology (ILK) of the Technische Universität Dresden and the Kieselstein Group (Chemnitz) and was firstly presented at the Metfoam-Conference 2008 [3]. The work was also supported by the Institute of Material Science (IfWW) of the Technische Universität Dresden as part of the project “Textilbasierte Polymer-Metall- und Metall-Metall-Verbundmaterialien”. Strucwire consists of wire spirals, systematic assembled in the three directions in space in several steps. The wires are form-closed interconnected in its two typical cross points/nodes. The selected assembly of the wires the structure has an anisotropic character. The structure is equal in x- and y-direction but different in z-direction (see Figure 1).

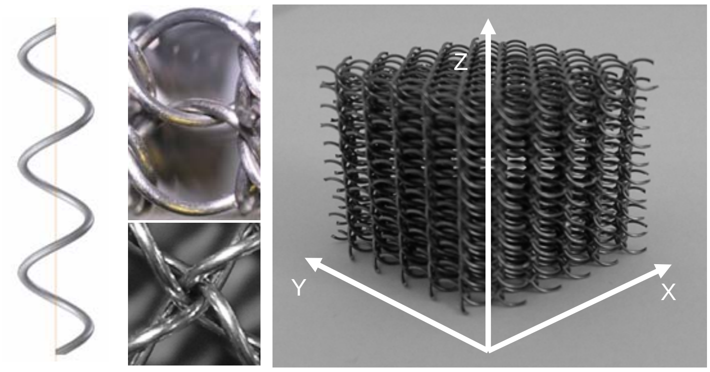

Figure 1. Wire spiral of 3D wire structure (strucwire®) and its typical cross points

Until now structures with an aperture (cell) size of 3, 5, 10 and 20 mm are realized. The structure can be built in an automatic process with every metallic material which can be formed to these spirals. As examples structures were manufactured of copper, titanium, aluminium and steel. Another benefit of the structure is the computability and design ability with exact dimensions because of the periodical cell structure and reproducibility. The densities and porosities are dependent on material, joining condition, wire diameter and cell size. For example a non-joined steel structure with a cell size of 5 mm and a wire diameter of 0,63 mm has a density of 0,65 g/cm³ and a porosity of about 90 %.

The aim of the study is to increase the stiffness and strength of these structures. Therefore the challenge is to join the cross points inside the structure with the perspective to treat these structures later on in an automatic joining process. The specimens fabricated from stainless and carbon steel wires, modified by different processes, are evaluated, tested under compressive loading und compared.

2 Joining of 3D wire structures

There are different solutions known to join the wires at the cross points of 3D wire structures. 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. In the present study selected brazing coatings which may be used for automatable brazing technologies are introduced.

2.1 Specimen Preparation

The first step to join the nodes of the structures is a specimen preparation to achieve a good wettability on the wire surface. Therefore the specimens were put in several bathes for repeated degrease (with alkaline cleaner) and rinse. A hydrofluoric solution was used to bath the stainless steel specimens and a hydrochloric acid (15 %) for the carbon steel. The dip coated (brazing paste) specimens were only degreased and rinsed with ethanol.

2.2 Brazing paste and coatings

To join the 3D wire structures at its cross points suited brazing material is applied to the whole structure surface and brazed by a subsequent heat treatment under inert gas atmosphere so that the molten soldering metal fills the nodes by exploitation of the capillary force. The coatings were achieved by dipping processes and alternatively metallic coating technologies respectively like galvanic and chemical deposition processes. The coating quality of the specimens (film thickness; wetting behaviour and behaviour after failure) was analyzed by gravimetry and metallographic methods after each process step. The following braze and coatings respectively describe only a selected part of the established and commercial available joining materials investigated within the project.

2.2.1 Dip coating with brazing paste

For the application of the brazing paste, the structures of stainless steel were dipped into the nickel-based brazing paste Ni102 (Umicore AG & Co. KG) to coat the complete structure. To recover the dispensable paste a separate process step has to be integrated like compressed air treatment or centrifugation. The application of pastes with a dip coating process appears simple but has disadvantages like inhomogeneous and incomplete coverage.

Figure 2 shows the surface and microstructure of a stainless steel specimen after brazing. A good adhesion of the solidified braze material to the wire, by the generated region of diffusion was proved for the investigated structures. The accumulated components of the soldering metal depending on process time builds defined brittle intermetallic phases.

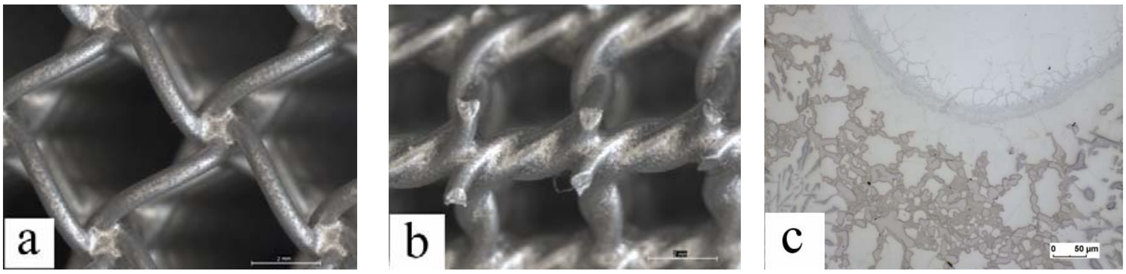

Figure 2. Specimens brazed with nickel based soldering paste Ni102; (a, b) nodes after brazing; (c) microstructure near a brazed node with brittle intermetallic phases

2.2.2 Chemical nickel coating

For the chemical nickel coating or plating process a nickel-phosphor alloy with a phosphor concentration between 2-15 m-% is used. During the process the specimens are put in an electroless bath with a nickel-phosphor electrolyte (11 m-% P) to ensure the deposition of a very homogeneous thin coat of Ni-P alloy [4]. Afterwards the coated specimens were heat treated to melt the NiP coating to realise the brazing process.

Figure 3 shows a joined node and microstructure after brazing. The analysis shows a very homogeneous coating over the whole structure. On the other hand for the carbon steel specimens a brittle brazing zone (Fig. 3b) with lots of Fe_2P/Fe_3P phases is identified with Energy-dispersive X-ray spectroscopy (EDX).

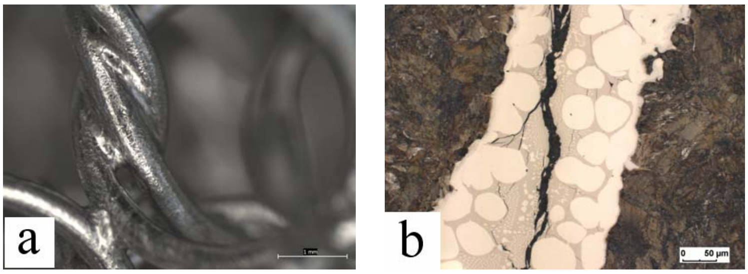

Figure 3. (a) Chemical nickel (NiP) coating at nodes of a brazed stainless steel specimen; (b) microstructure of the carbon steel brazing joint with crack between two wires after compression test

2.2.3 Galvanic coating

In galvanic coating processes the deposition of pure metal films like copper, nickel or silver on the structure surface is realised. Basically copper is the most used braze for stainless and carbon steels [5] 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. For the stainless steel wires a thin nickel undercoating is required before copper deposition. The prepared specimens were galvanic coated with copper for the subsequent brazing process.

Figure 4 some microstructures of galvanic copper coated surfaces are shown. With the chosen optical resolution the undercoating cannot clearly be differentiated. Furthermore it is proved, that there are no brittle phases.

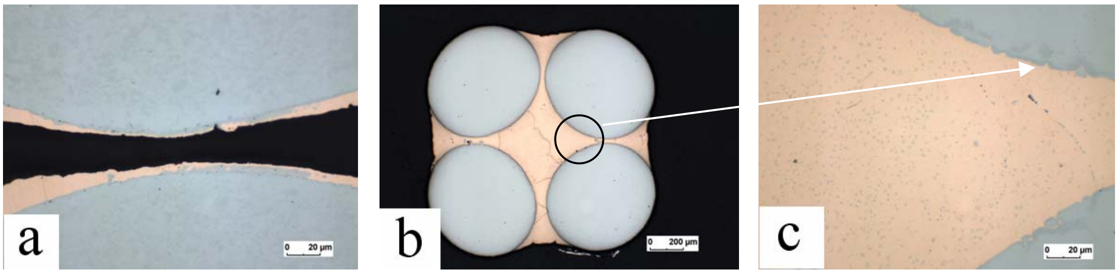

Figure 4. (a) Stainless steel specimens after galvanic copper coating; (b) specimen after heat treatment with copper filled nodes; (c) boundary layer between cooper and a steel wire

2.3 Assessment of brazing technologies

To melt the brazing materials the specimens were coating specifically heat treated. In general a short process time is advantageous. Important for a good wettability and adhesion of the brazing material is a non-oxygen atmosphere. The most important approved brazing process parameters are summarized for all coatings in Table 1. For the dip coating process, the obtained coating thickness is significant higher than those reached in the deposition processes. The most homogeneous coatings were achieved by the chemical nickel coating process.

Table 1. Brazing temperature, atmosphere, brazing time and coating thicknesses of the specimens

Coating	**Stainless steel**	**Carbon steel**	**Coating thickness**
Brazing Paste Ni102	1050 °C; H_2; 20`	-	>100 µm
Galvanic copper	1100 °C; Ar/H_2; 20`	1130 °C; Ar/H_2; 3`	~ 10 µm
Chemical nickel	1100 °C; Ar/H_2; 20`	950 °C; Ar/H_2; 5`	~ 10 µm

Obviously the density of the structures is increased because of the added coating. For the dip coating process with brazing paste the structure density is about 33 % higher compared to the non-joined structure. The galvanic and chemical coatings lead to an increased density of about 15 %.

Each tested process to braze the nodes has advantages and disadvantages referred to application. In Table 2 a comparison and assessment of the considered brazing technologies with respect to constancy, costs and reproducibility is given.

Table 2. Comparison of the tested coating technologies to join the nodes of 3D wire structures

Process	**Advantages**	**Disadvantages**	**Costs**	**Reproducibility**
Brazing Paste Ni102	- products available - high bonding strength	- very high viscosity - irregular coating - incomplete recovery - high material efforts	high	not achieved
Chemical coating (Ni)	- very homogeneous coat - low melting point (950°C) possible (NiP-alloy) - corrosion protection	- complex assurance of the chemical equilibrium of the bath - often brittle phases	middle	Yes
Galvanic coating (Cu)	- simple handling - ampere controlled - possibility for Ag/Cu multilayer braze	- high melting point - decreasing coat thickness at the middle of the structure - toxic fluids	low	Yes

3 Mechanical characterization and discussion

After brazing the specimens were tested under compressive loading. The joined and non-joined specimens have a cell size of about 5 mm. The wire spiral has a wire diameter of 0,63 mm with a spiral pitch of 6,75 mm and a median spiral diameter of 4,4 mm. As wire material stainless steel (X5CrNi 18-10; 1.4301) and carbon steel (C75; 1.1750) are used. The dimensions of the structures are about 40 x 40 x 40 mm for the stainless steel specimens and about 25 x 25 x 20 mm for the carbon steel specimens.

3.1 Compression Tests

To analyze the mechanical performance of the differently modified structures a compression test was realized corresponding to DIN 50134 [6] because of its relatively simple procedure and comparability to literature results. The tests were carried out on a universal testing machine ZWICK 1475. The deformation of the structure as well as the displacement of the compression platen was investigated with the optical 3D measurement system PONTOS of the GOM mbH.

Following Figures 5 and 6 show the results of the compression tests of the joined and non-joined (as-delivered) carbon and stainless steel specimens. Every test result is an arithmetic mean of two or three data. To obtain the stiffness of the 3D wire structures (shown in Figure 5) the required hysteresis of the stress–strain curve was defined between 70 and 20 % of stress plateau.

The failure behaviour under compressive loading (not further discussed within this study) depends on specimen condition and shows phenomena like brittle fracture of single wires, failure in discrete layers or homogenous collapsing of the whole structure.

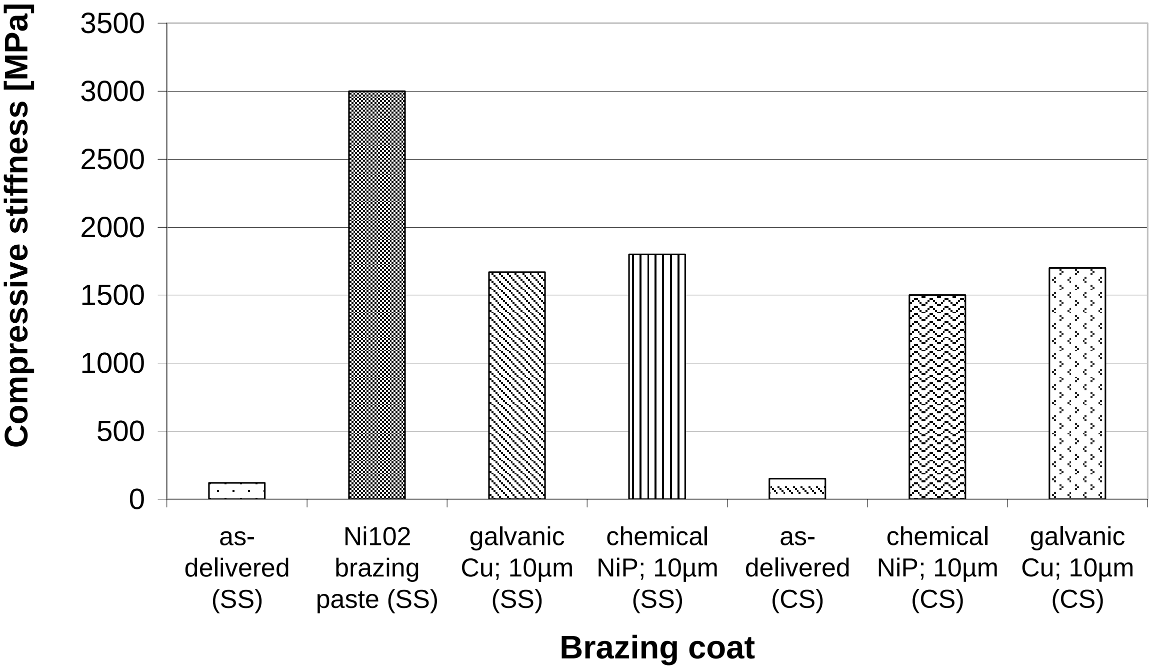

Figure 5. Compressive stiffness of 3D wire structures (non-joined (as-delivered) and joined specimens of stainless (SS) and carbon (CS) steel)

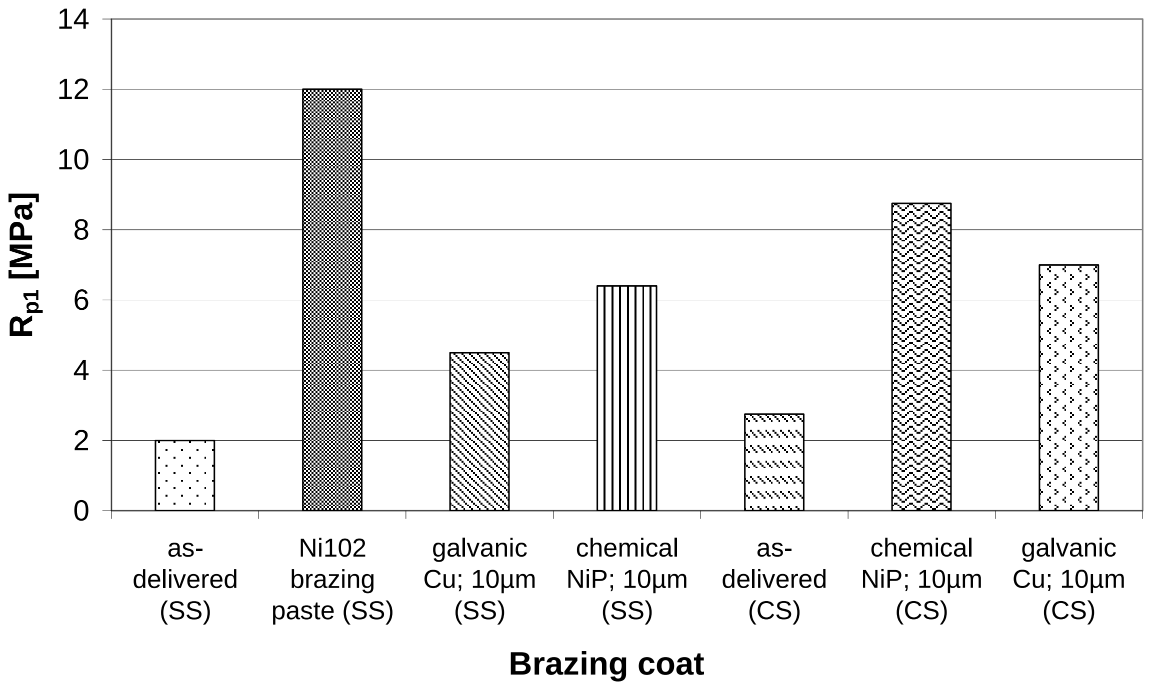

Figure 6. 1 % offset yield strength of 3D wire structures (non-joined (as-delivered) and joined specimens of stainless (SS) and carbon (CS) steel)

3.2 Discussion

The brazing solder mainly increases the stiffness and strength of the three dimensional semi finished product in general. The reason therefore is the design of the structure itself. The brazing metal coates the wires and fills the space between the wires at the cross points and makes the structure much stiffer. The results show that wire material itself seems to have no significant effect on stiffness and strength in the brazed structure. The used brazing paste Ni102 increases the stiffness at a factor of 25, galvanic copper and chemical nickel coatings at a factor of about 10 compared to the non-joined specimens. The factor of the offset yield strength is not as high as for the stiffness. The deciding reason for the much higher stiffness and offset yield strength of the specimens processed with brazing paste is the process related higher amount of applied brazing solder, so that the nodes as well as the free wires obtain a higher moment of inertia.

The only specimens showing a very brittle failure behaviour under compressive loading were the carbon steel coated with chemical nickel, because of the grown intermetallic Fe/P phases. These phases were not observed for the stainless steel specimens and thus no brittle failure behaviour occurred.

4 Conclusion

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 by exploitation of the capillary force. To compare these modifications, the 3D wire structure specimens of two different metals with non-joined and joined nodes have been analysed with regard to their mechanical performances under compressive loading. The results show that the joining lead to increased strength and stiffness of such structures. Highest stiffness and yield strength was achieved with brazing paste Ni102 (of Umicore AG & Co. KG) but the realized dip coating process is not as reproducible as e.g. the deposition processes.

For future prospects a good ductility under load is requested to obtain high energy absorption of such structures. Therefore ductile copper or copper-alloys seem to be promising brazing solders because no brittle phases in the joint were observed.

The gained results are an important step within the ongoing research project to create sandwich panels with 3D wire structures as core-layer were the metal coating can be used as bonding material to braze the structure itself and also the cover plates in one step. The present study serves for better evaluation which joining technology to choose for a good compromise between reproducibility, mechanical performance and economic processing.

5 Acknowledgment

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