Cellular Metals Based on Wire Structures

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1 Introduction

Wire based cellular structures have been investigated since several years [1]. Examples of this kind of materials are pyramidal lattice structures or wire woven Kagome structures (WBK) [2]. Due to their ideal construction, WBK structures are characterized by an isotropic material behaviour with good mechanical properties. The major disadvantage of the WBK is their complex and costly assembling process, which is done in manual labour. For industrial purposes it is necessary to develop cheap and easy to build three-dimensional wire structures with suitable mechanical performance. Therefore *Fraunhofer Fraunhofer-Institute for Manufacturing and Advanced Materials, Dresden*, the *Institute of Lightweight Engineering and Polymer Technology of the Technische Universitaet Dresden* and the company *KIESELSTEIN* developed a 3D-wire structure called strucwire®, which can fulfil these needs [3].

For this purpose helical wires made from stainless steel, titanium and aluminium alloys were taken to assemble structures with different cell sizes. The parameter cell size describes the centre distance between two adjacent layers of the 3D-wire struture. Because of the high flexibility in wire diameters (~0.1-2 mm) and material selection, 3D-wire structures can be manufactured in a wide range of cell sizes (3 – 20 mm) and structural densities (0.05 – 2.0 g/cm^3). Examples of manufactured structures are shown in Fig. 1.

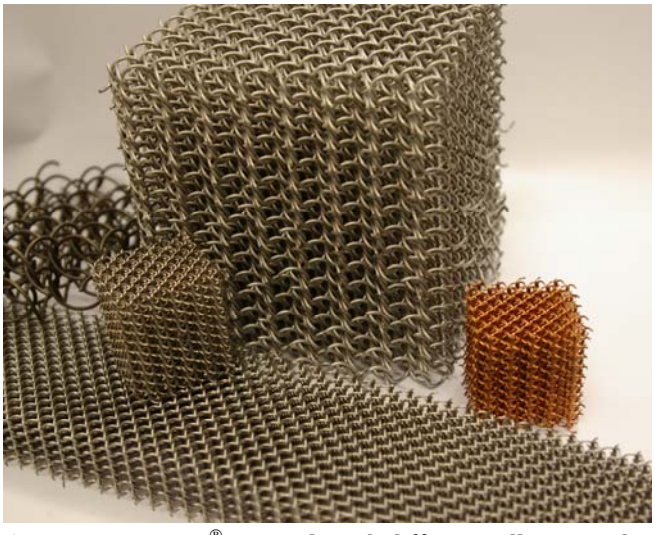

Figure 1: Strucwire® materials with different cell sizes and materials

Beside the technology development in manufacturing, research work has been performed comprising experimental investigations of the mechanical performance of the fabricated structures as well as the possibilities to adapt the structural properties by additional process steps. Furthermore, finite element simulations of 3D-wire structures were done in order to predict the properties of the real structure.
The aim of this study is to give an overview of the properties and possible applications with the main focus on structures made of stainless steel.

2 Manufacturing and FE-modelling

2.1 Manufacturing and experimental work

So far, helical formed wires from stainless steel 1.4301 were used to manufacture periodical structures with cell sizes of 5 mm. Structure details and the basic manufacturing procedure are described in an accompanying paper [4].
The properties of the starting materials allow the manufacture of different structure sizes from any wire material at reasonable costs. Due to the relatively simple assembling process the structures can be easily produced in a fully automatic process. To this end *KIESELSTEIN* is constructing a machine for the production of commercial structures with an edge length of 1000 x 1000 x 50 mm^3. The machine will be available in spring 2011.
For enhancing the mechanical properties, especially the stiffness, strength and the energy absorption capability, the structures were joined with adhesive bonding or brazing. The main coating methods were dip-coating, galvanic and chemical coating. The coating thickness of the bonding materials was varied to investigate the influence on the structural performance. All of these structures were mechanically tested under compression and compared with non-joined structures and other cellular metals. The experimental details can be found in the accompanying work [4].

2.2 Finite element modelling

Due to its periodic topology, the structural properties of strucwire® can be determined by analyzing the unit cell of the structure. The unit cell is shown with associated volume elements in Fig. 2. To simulate joined structures, the joining material is included by means of additional elements near to the crossing points of the wires. The interaction between wires and of wires and joining material is realized by appropriate boundary conditions. In the given example, the amount of joining material was chosen to be 4 % in volume. This method of having joining material only near the crossing points was a simplification compared to the real conditions, since the joining material covers and thickens the whole wire. In more recent investigations, this simplification is eliminated.

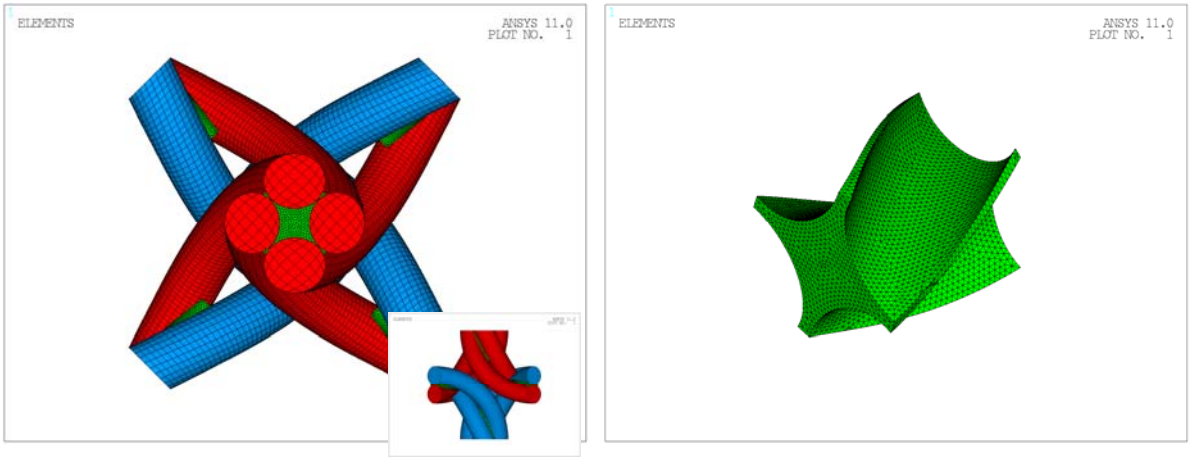

Figure 2: Unit cell of strucwire® structure viewed from z-direction (big left) and from x-direction (small left). The volume in between the wires of the big left picture represents the joining material and the middle part is enhanced in the picture on the right.

3 Results and discussion

3.1 Simulation

From the unit cell model, proper parameter combinations (wire diameter, median spiral diameter and spiral pitch) could be determined which allow the production of 3-dimensional wire structures. Furthermore, the upper limit of the relative density of the structure compared to solid material of the structure was calculated for non-joined structures ~12 %. In the present study, all real structures are characterized by similar ratios of the structural parameters and consequently by similar relative densities. The self-similar structures were only shrinked for smaller cell sizes and enlarged for bigger cell sizes.

To validate the created finite element models, compressive loading was applied onto the unit cell and the stress strain relationship was obtained. Fig. 3 shows the deformed unit cell for a cell size of 5 mm and Fig. 4 shows the stress strain relationship for two different cell sizes, both for compressive loading in z-direction. The calculated stress is defined as the ratio between the applied force and the total cross section area of the unit cell. The stress strain relation shows clearly that for similar relative densities the stiffness and strength of the structure remains the same, regardless of the cell size.

The compressive stiffness of the investigated unit cell is calculated to 850 MPa, which is consistent with the results of the experimental work (see Chapter 3.2). Furthermore, the received 1 % yield strength is comparable to the experimental measured strengths.

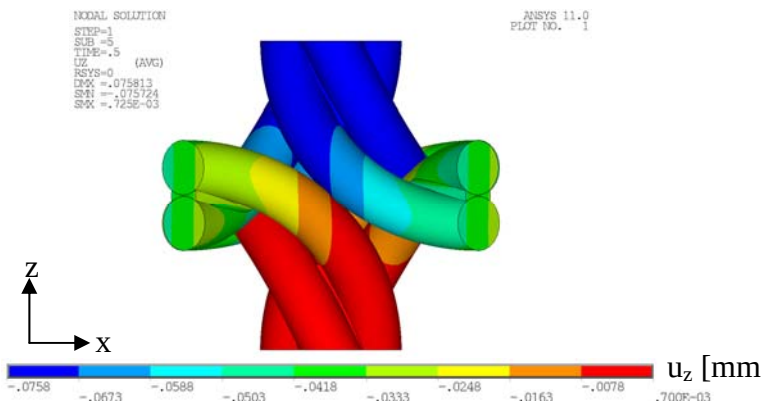

Figure 3: Simulation results under compressive loading in z-direction: Displacement in z-direction

In the future, this finite element model and the improved one with joining material covering the free wire zones will be used to study the influence of structural modifications like joining material amount, different wire material, alternative joining material, etc. on the mechanical performance of the strucwire® structure.

3.2 Experiments

In Fig. 4 typical measured results from compression tests in z-direction of non-joined (sample 201) and brazed structures are presented. The structure and therefore the mechanical properties are anisotropic, the z-direction shows generally higher stiffness and strength in compression than the x- or y-direction [3].
The samples 266-267 and 262-263 are comparable due to their same bonding procedure. The periodic structure combined with a well defined bonding process leads to good reproducibility.

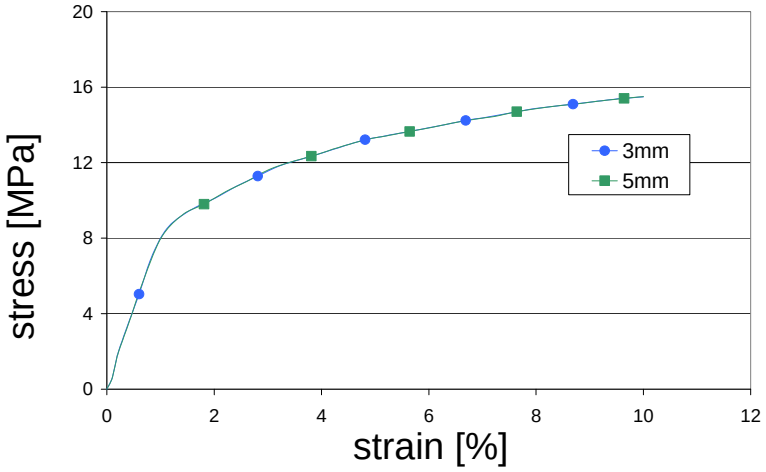

Figure 4: Simulation results under compressive loading in z-direction: Calculated stress strain relationship for different cell sizes

The measured mechanical properties in z-direction are shown in Table 1 and compared with other typical values from brazing and adhesive bonding. Generally, the brazed samples show the highest mechanical properties followed by the samples joined with adhesive bonding. The

differences between the brazed structures itself are caused mainly by different masses of the joining material in the structure, which is reflected in different densities of the samples. Another important influence is related with the differences in the joining material. More detailed information can be found in the accompanying work [4]. In Table 2 all measured samples from compression tests made of 1.4301 are concentrated. It is distinguished between non-joined, adhesive bonded and brazed structures. The wide range of property values gives an impression of the adaptability of the strucwire® material. Compared to other cellular metals the strucwire® material has competitive capability (Fig. 5).

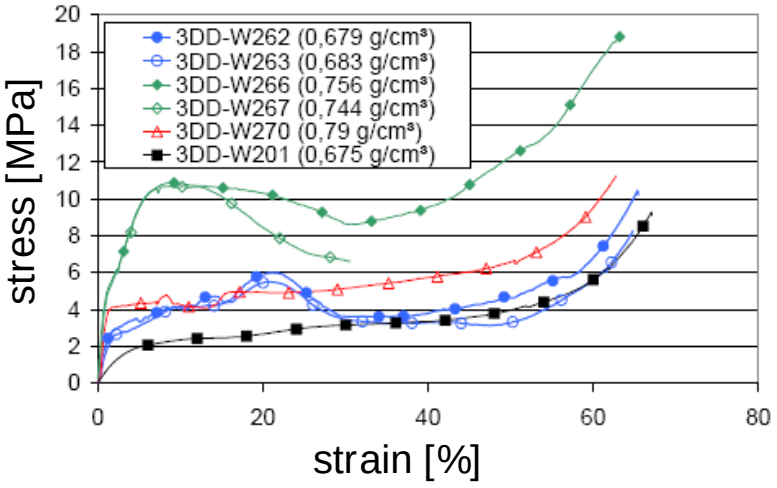

Figure 5: Measured stress strain relationship for different bonding conditions

Table 1. Mechanical properties of different strucwire® samples

sample name	density [g/cm³]	plateau stress [MPa]	energy absorption (60 % strain) [kJ/m³]	elastic slope [MPa]
W262/W263 (mean value)	0.68	4.2	2458	840
(chemical Nickel braze)				
W266/W267 (mean value)	0.75	8.3	6210	2504
(dipped Ni 1002 braze)				
W270 (dipped bronze brace)	0.79	5.2	3267	1224
W201 (non-joined)	0.67	3.1	1860	87
W271 (chemical Nickel braze)	0.72	14.8	9139	1485
W274 (galvanic Copper braze)	0.72	24.4	12414	1739
W281 (2k epoxy adhesive)	0.82	14.5	10198	622
W282 (2k acryl adhesive)	0.80	12.7	8582	582

Table 2. Combined mechanical properties of all tested samples in z-direction

Sample name	non-joined	adhesive bond	brazed
density [g/cm^3)	0.65-0.87	0.72-0.87	0.68-1.04
elastic slope [MPa]	77-120	98-632	840-4480
1 % yield strength [MPa]	1.4-2.3	1.5-8.6	2.3-14.5
energy absorption [MJ/m^3] (60 % strain)	1.8-2.5	2.6-10.9	2.4-19.2

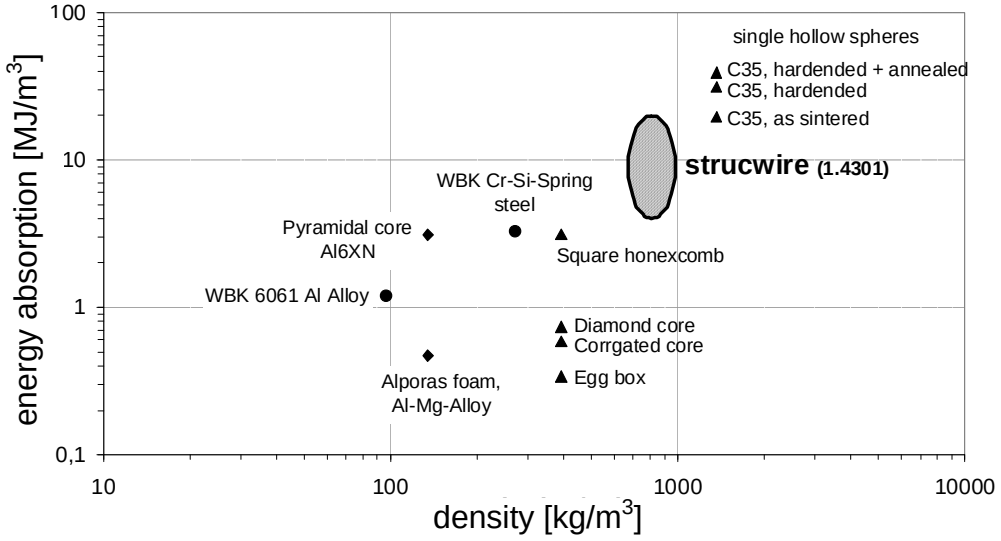

Figure 6: Comparison of steel based strucwire® with other cellular metals

4 Applications

The possible use of different cell sizes and wire materials can be utilized in various applications. Strucwire® material can be used as implant material with titanium wires or as containment material using cheap carbon-steel wires. An advantage of this new material is the relatively cheap starting material.

Due to its open cell structure it can be easily infiltrated by other materials. Promising applications in this field are as reinforcing structure in plastics or for enhancing the high temperature creep resistance of light metals like magnesium. Currently there are ongoing projects in automotive applications like damping elements, crash absorbers and heat exchangers.

5 Conclusions

With helical wires it is possible to assemble lightweight periodical porous structures with high mechanical performance. Strucwire® as cellular material has various interesting and adaptable properties, which are:

- High mechanical performance
- Periodic cell structure
- High material variety
- Cheap starting material
- Easy manufacturing

The mechanical performance of the structures can be tailored with a bonding process and is comparable with the mechanical properties of other porous metals. The results reveal that in comparison with the experimental results under compression, the FEM simulations yields reasonably good agreement. Especially because of the expected comparable cheap manufacturing it is supposed to fulfill the needs of the industry for cellular metals.

6 Acknowledgment

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7 References

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