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HIGHLY DAMPED MACHINE TOOLS WITH METAL FOAM

Reimund Neugebauer, Thomas Hipke, Jörg Hohlfeld, Rocco Thümmler

Fraunhofer Institut für Werkzeugmaschinen und Umformtechnik Chemnitz

Abstract - Metal foams will soon make it possible to achieve lighter parts with good stiffness. Given today's steel constructions, one can also design lightweight parts for machine tools. The decisive advantage of metal foams - produced as a steel-aluminium foam sandwich - is their excellent dynamic behaviour.

This article focuses on possible applications of metal foam use in mechanical engineering. Some applications with interesting measuring results are shown. For example, a very large cross beam of a milling machine for tool and die making was tested. The other examples are taken from a high speed cutting machine.

It was shown demonstrated that sandwiches fulfil all the requirements of mechanical engineering.

Keywords: metal foam, machine tools, damping

1. INTRODUCTION

In order to implement lightweight construction concepts, new materials are sought again and again in all types of industry (e.g. mechanical engineering, the automotive industry). Cellular metal materials belong to a material group with a great potential for lightweight construction. Analogously to the examples from nature (bones, wood), one advantage of these highly porous materials is that they are very stiff despite their low specific gravity.

Thus, closed-porous and open-porous metal foams as well as hollow sphere structures belong to the category of cellular metal materials. Mainly the metals Al, Mg and Ti are used for production, since they have a low specific gravity. But steel, with its excellent properties – the material is not only very stiff, but also tough at the same time – is also increasingly attracting attention.

In mechanical engineering, closed-porous aluminium foams are preferentially applied in cases demanding lightweight construction and good damping of vibrations simultaneously. The producible sandwiches and also the profiles foamed out can be joined to large constructions. As a result, almost all frame assemblies in mechanical engineering are feasible. This statement can be impressively underlined by prototypes, which have been manufactured and tested at the metal foam centre of the Fraunhofer Institute for Machine Tools and Forming Technology (IWU) in Chemnitz [1-3]

2. METAL FOAMS

Powder metallurgic techniques are among the most highly developed metal foaming methods, since they have some decisive advantages over the other process chains. Before dealing with this topic in detail, it is useful to explain the procedural sequence:

- Mixing metal powder (e.g. Al) and foaming agent powder (e.g. TiH_2); as a rule, the foaming agent volume added is less than 1 per cent of the mass.
- Precompacting the powder mix into blocks with one die axial press ; the density achieved ranges from about 80 to 90 % of that of the full material.
- Extrusion pressing of the precompacted blocks; the density values achieved correspond to almost 100 % of the full material.
- Filling the foaming mould or the component to be foamed out with the foamable prematerial;
- Heating up the prematerial to temperatures above the metal's melting point and the foaming agent's decomposition point;
- Cooling down the foaming mould or the component to be foamed out

From the procedural steps above, we obtain the previously mentioned advantages over other foam fabrication methods.

Homogeneous distribution of the powder-like foaming agent inside the mixing material as well as in the prematerial to be foamed is advantageous. This is the precondition for achieving a homogeneous foam quality.

Since the technique consists of several procedural steps, in powder metallurgical production, the individual parameters can be controlled well, whereas in other techniques, all influences act simultaneously. The profile to be foamed, which is produced during extrusion pressing and the follow-up forming stages, can be fitted to the geometry to be foamed out at a later date. Furthermore, it is possible to build up material composite structures that are foamed together.

However, the decisive advantage of the powder metallurgical techniques results from the possibility to foam out contours and moulds (oder aber: geometries?) in a self-controlled manner and to simultaneously build up pores.

3. METAL FOAM APPLICATIONS FOR SERIES

The machinery available at the metal foam centre of the Fraunhofer Institute for Machine Tools and Forming Technology IWU Chemnitz makes it possible to fabricate metal foam components of considerable sizes.

Two batch-type furnaces ensuring foaming in the batch mode with a usable space of 2, 200 x 1, 500 x 1, 200 mm^3 each are available. Working temperatures up to 1, 000 °C permit the foaming of many non-ferrous metals.

The continuous furnace, which will be completed by September, 2003, will enable us to process very long components and to run continuous foaming operations. A heat treatment zone of 8, 000 mm length and a passage of 1, 200 x 650 mm^2 provide good preconditions for this mode.

Prematerial necessary for foaming can be produced on the extrusion press of the metal foaming centre. Thus, for instance, vacuum chamber temperatures up to 500 °C make possible the processing of tin, zinc and aluminium. But it is also possible to press alloys with higher melting points, such as brass and bronze materials, in the facility.

In addition to the manufacture of metal foam or metal foam-composite parts , the metal foam centre also offers capacities for drafting, simulation and component design for foaming. The centre also provides analysis services – investigating the component's characteristics.

In earlier studies, we found that especially high damping of vibrations is of particular interest for machine tool building. We were able to find a 980% increase in damping in comparison with the original on a machine tool bed [2]. Also studies performed using foamed out steel profiles have shown that we may expect a double to threefold damping capacity in comparison to unfoamed steel profiles. [2].

In the following, we introduce projects, which first of all aim to utilize the excellent dynamical characteristics of aluminium foams.

a) Cross beam of a milling machine for large tool making

Machine tools have to fulfil extreme dynamical requirements. Current frame components always fulfil the statical stiffness values demanded despite extreme lightweight construction. However, vibration problems occur due to the thin walls of the components.

The combination of sufficient statical and dynamical characteristics can be realised by decomposing the massive steel structures into sandwich structures – for instance steel-aluminium foam-steel. Unlike the steel sheets of equivalent mass, sandwiches like these have the 30 to 40 fold bending stiffness due to the high area moment of inertia. In addition, the foam core strongly dampens vibrations.

Based on the advantages mentioned before, the sandwich construction principle was realised using two cross beams of a milling machine for large tool making (Figure 1). Front and base plates of each bar were massive steel plates, while all the other bar walls, as well as the supporting elements were performed with sandwiches. The area of the sandwich produced was 1, 179 x 1, 182 mm^2. From these panels, all sandwiches which had to be made smaller were cut out by water jet abrasive cutting. All elements were joined by welding.

Table 1 presents a comparison of the calculated characteristics of a conventional bar, which was only made of steel plates, and the sandwich construction. In the meantime, the calculated values of the sandwich structure were evidenced in metrological studies. The first bending vibrations determined in x and in z directions are 37.9 and 75.5 Hz. The damping values of the bending vibrations are 2.3 or 2.9 %, which is a very good result for welding assemblies. Usual values for welding constructions of this size range at 1%.

Table 1: Comparison of calculated characteristics - conventional steel construction and sandwich structure.

Variant	Conventional steel construction	Sandwich structure
Mass (t)	6.3	6.6
Deflection by mass (µm)	34	14

As the realisation of the sandwich principle using the milling machine's cross beam shows, it is possible to join standard foaming parts such as sandwiches and foamed out profiles to large constructions. Thus, we may rely on series parts rather than put in the tremendous efforts necessary to build a foaming mould and exactly tune the foaming parameters for each special case of application. This paradigm simplifies the manufacturing process as a whole, helps to reduce lead-time and contributes to cost reduction.

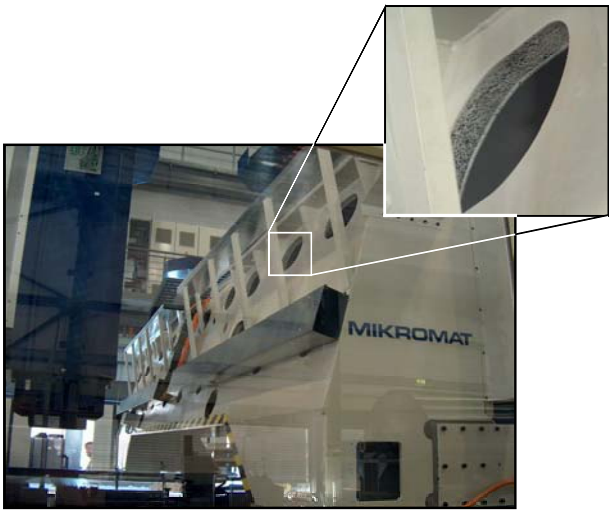

Fig. 1. Cross beam of a milling machine of steel-aluminium foam sandwiches;

Sizes: 5,900 x 1,400 x 940 mm^3

b) Cross beam of a laser cutting unit

Laser cutting of thin-walled sheets is characterised by travels with high acceleration values. Lightweight construction and damping of vibrations are unconditionally necessary to achieve the requirements demanded. For this reason, a cross beam for a laser cutting unit making use of aluminium foam was developed for the equipment manufacturer SITEC Industrieanlagen GmbH Chemnitz. The rail was redrafted and calculated. Some variants arising from differing density and wall thickness values had to be paid attention to. For design, we preferred to completely foam out a steel profile. The links of the guideways and engine parts were supported by massive steel plates (see Figure 2).

An acceleration of 10 m/s² in the x and y directions was assumed as the load for the masses accelerated at a time. The force of gravity is valid for the z direction. Manufacturing forces were not taken into account. The linear motors' forces of attraction in the x and y directions had some influence on the model.

The results are listed in Table 2. As can be seen, the deformations in the middle of the beam - less than 6 µm - are clearly below the required limit of 10 µm. In all variants, the stress values obtained - 3 to 4 N/mm² (outside the range of the motor link) are not critical. Necessary stiffness is provided by all variants.

We performed a modal analysis to calculate the natural and natural frequencies. The modal analysis was carried out in order to check the system's sensitivity to vibrations. We worked with a fixed beam, which means that the cross beam retains the location conditions from deformation calculation. The associated natural frequencies are typical for all variants 1 to 5:

- Natural frequency 1: The hanging masses oscillate. Due to specific geometries in practice, this frequency will have another value. But this resonant frequency will stay assigned to the first natural frequency.
- Natural frequency 2: Bending vibration of the beam in the x direction;
- Natural frequency 3: Bending vibration of the rail in the z direction;
- Natural frequency 4: Torsional vibration around the centered y axis;

The frequencies are independent of the acting forces, whereas the position of the hanging masses is of considerable influence. Summarising, we found that

- variant No. 3 with maximal wall thickness is characterised by the highest natural frequencies,
- the beam foamed out does not have any of the wall vibrations which have often been observed at hollow profiles,
- the natural frequencies differ only slightly from each other,
- as a rule, the natural frequencies are very high.

Variant No. 4 was technologically implemented. This variant represents the best compromise between low mass, low statical deformation, and a high 1st natural bending frequency as well as manufacturing considerations. The calculated values are confirmed by the metrological studies performed on the manufactured cross beam (see Table).

Table 2: Comparison of the cross beam variants for the laser cutting unit

	Profile wall thick-ness	Density	Mass	Entire deformation (Objective: <10 µm)		1st bending frequency in the x direction	
				Sim.	Meas.	Sim.	Meas.
	mm	g/cm³	kg	µm	µm	Hz	Hz
1	4	0.7	96.7	5.4		419	
2	5	0.7	102.8	5.2		432	
3	6	0.7	108.9	5.0		442	
4	4	0.6	93.2	5.5	8.2	411	375
5	4	0.5	89.7	5.8		402	

Modal damping of each frequency could also be found with the natural frequency measurements. The values range from 0.064 % to 0.42 % for the twelve natural frequencies beginning. Damping of the 1st natural bending frequency was 0.12 %. However, a specific assessment of the damping increase when using metal foam is only possible in comparison with an identical design without foam. Similar hollow profiles with a damping of about 0.1% can be taken as reference value.

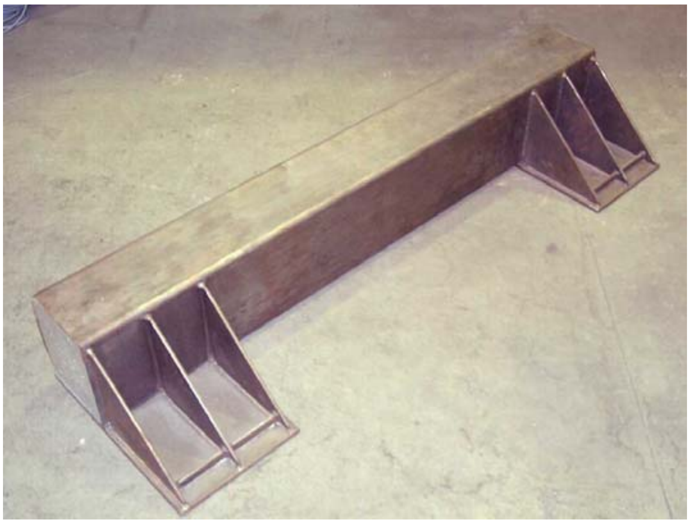

Fig. 2. : Cross beam (foamed out) of the laser cutting unit

c) Frame for a machining centre

The vibration damping characteristics and the good mass to stiffness ratio of the metal foams are the advantages which are particularly useful for machine tool building.

For the machining centre CWK 500D of the Heckert Werkzeugmaschinen GmbH, the frame to mount the main spindle assembly was built of aluminium foam. This measure was designed to achie higher stiffness and essentially better damping of vibrations in comparison with the present design with – whenever possible – the same weight.

The new design was optimised according to its parameters with FEA and compared with the original design model (see Figure 3). In simulation, on the spindle top, the resulting deformations in the X, Y and Z directions with a load of 10 kN were calculated.

Figure 4 illustrates the frame manufactured for the machining centre. Foamed out profiles and aluminium foam sandwiches were used for design.

Simulations with the aluminium foam design gave the following changes in the characteristics in comparison to the original design. Optimisation was focused on reducing deformation:

- Mass : + 4.6 %,
- Deformation in X direction: - 13.9 %,
- Deformation in Y direction: - 25.4 %.

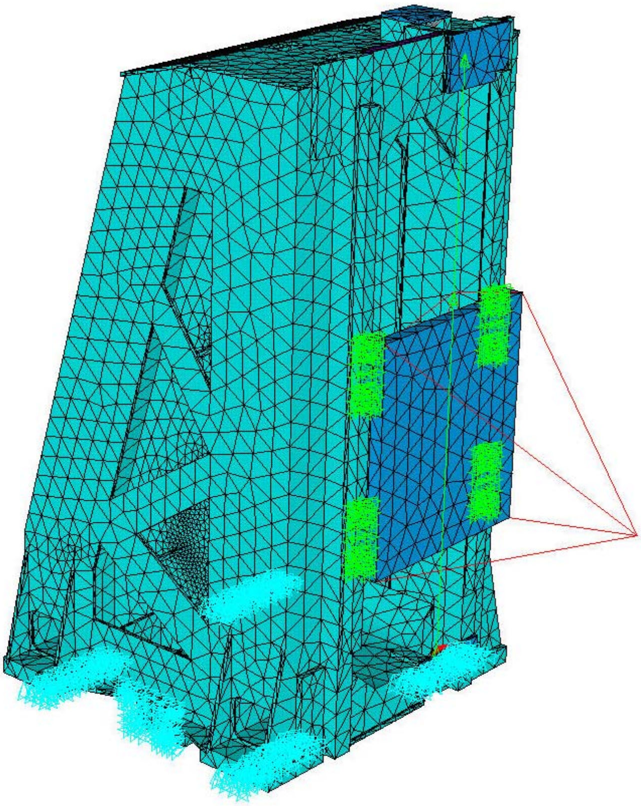

Fig. 3. Frame optimised by FEA

In the next step, the frame optimised by FEA was produced. The aluminium foam sandwiches and the foamed out tube profiles, which were mounted with the other components to build up the frame assembly by the firm Heckert Werkzeugmaschinen GmbH were made at the IWU's metal foam centre.

In order to evidence the characteristics of the aluminium foam design, the original and the new frame assemblies were measured in an unmounted state. The measurements provided the following alterations in comparison with the original frame:

- Deformation in the X direction : - 17.6 %,
- Deformation in the Y direction : - 35.8 %.

The deviations between the simulated and the measured values result from the fact that the deformation values were taken at slightly different recording points. However, the values' mutual proportions are within an acceptable range.

The advantage in damping of the aluminium foam design cannot be simulated, since it is a parameter of the entire system, which, in turn, is composed of many individual components. The metrological evidence was not yet available at publishing date. However, experience has shown that damping capacity of the foamed material is five to eight fold higher (amounts 600 to 900 %) than in the original design.

4. OUTLOOK

Due to its excellent characteristics, closed-porous aluminium foam is expected to be used for applications other than just mechanical engineering. Efforts of numerous carmakers indicate that – in spite of many remaining problems - aluminium foam will find its place even in the car industry and can be an alternative to conventional material solutions. Parts subjected to crash hazard, such as carbody, bumper and side sill may particularly benefit from the use of metal foam. The side sills integrated into the Ferrari-Modena spider convertible series are a metal foam application which has already been realised. Apart from the energy absorbing components, the engineers also contemplated using metal foam in the frame elements in order to obtain additional stiffening [4].

However, the success achieved thus far in metal foam fabrication and application should not make us forget that there is still work to be done to solve the many remaining problems. Thus, investigations are aimed at intentionally influencing and controlling foam homogeneity, which depends on a number of factors. But issues such as cohesion between metal foam and the cover sheet or the surrounding profiles are being researched and discussed.

As described, closed-porous metal foams are only one variant to build at light weight. As a rule, the planned use of the cellular materials should be subjected to a plausibility check. The technological know-how to develop, produce and use cellular materials is offered by the alliance of cellular materials Saxony (the VZWS). The Fraunhofer Institute for Machine Tools and Forming Technology initiated this working group last year.

Fig. 4. Realised welding construction.

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