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Experimental research regarding rigidity improvement of hollow machine tools structures using aluminum foam

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Abstract

The paper studies a method for improving the static rigidity of hollow critical mechanical structures, without greatly affect its weight. There are many applications for this type of structural parts, where mass is critical and are needed increased rigidity properties. The results are obtained by using alternative technologies and composite materials such as filling the interior hollow spaces with metallic expanded aluminum foam. The study is experimentally implemented to a large HSC (High Speed Cutting) CNC machine tool structural moving part. The benefits obtained by reducing its weight and increasing rigidity properties are: better dynamic performance [1], energy efficiency, mechanical parts less expensive for drive systems [2].

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Keywords: CNC machine tool structural parts; alternative technology; aluminum foam.

1. Introduction

Metallic foam US patent dates since Jan. 20 1948 but no commercial application was registered, until recently, because it was extremely dangerous, very expensive and difficult to find couples of metals with the right characteristics [3].

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Worldwide a number of companies have developed recently their own type of Al-Foam based materials, resulting brands like Schunk, Alulight Alporas, Duocel, Alcan etc, products with different properties and domains of application [4].

It is concluded that the quality of foams has improved in the past years but the costs are still very much the same. This is why applications in which metal foams have more than one function are more likely to be economically viable [5]. The examples presented include electromagnetic shielding, carrier plates for mirrors, cooking equipment, architectural panels, and blast protection [3].

2. Aluminum foam general properties

Metal Aluminum foam is a cellular structure consisting of a solid metal, containing a large volume of gas-filled pores (70 % -vol. and relative density \( \rho_r \) less than 0.3) [6]. Aluminum foam typically retains some physical properties of their base material. Aluminum foam shows its advantages primarily in combination with existing constructions. [6]

The pores can form an interconnected network (open-cell foam) or they can be sealed (closed-cell foam) [5].

The open cell materials (Fig. 1.a.) can be formed by Al, Zn, Cu, Ni, steel, bronze and consist essentially of a three-dimensional network of small beams and then the principal mechanism of deformation inside the material is the bending of the edges of cell. [7]

In materials with closed cells (Fig. 1.b.) the base metal can be Al, Zn, Pb, Mg, Sn, Au, brass or steel. The cells are separated by walls that stiffen the structure strongly with the onset of membrane stress and a greater constraint degree within the structure. [3]

![Aluminum foam](image1)

Fig. 1. (a) Aluminum foam open-cell structure; (b) Aluminum foam closed-cell structure. [2]

Aluminum foam is not only particularly light, but also stiff and energy absorbing. Like solid Aluminum it’s also persistent against acid rain, saltwater, fire, fluid and numerous other substances. Through molding capabilities it is also possible to produce complex 3D-shapes. Thereby there are no design limitations [8].

![Diagram](image2)

Fig. 2. The multi-functional application of Al-Foam. [3]
The combination of top attributes such as high stiffness, low weight and high energy absorption enables Al-foam to qualify for specific requirements within the automotive, aviation, railway, engine building and industry. Al-foam is also qualifying for other high potential applications. It is more likely to be competitive in two or more properties, resulting ideal multifunctional applications (Fig. 2.).

3. Experimental

The goal is to obtain an improved HSC CNC machine tool structural moving part using aluminum metal foam for enhanced structural applications. This optimizes mechanical properties and structural function for minimum weight, where polymeric foams are insufficiently rigid and ceramics are too brittle.

3.1. The method used for obtaining the Al-foam filled structure

The method used is by obtaining Al-foam from extruded rods slabs made by Powder Metallurgy. This process can uses pure Aluminum powder type AISI7, AISI10, AISI12 or series Al-Cu, Al-Mn, Al-Zn with a granulation of 100 μm. The foaming agent is a compound powder type TiH₂, ZrH₂ or HfH₂ [9].

First step is mixing the foaming agent powder to obtain a uniform distribution in the base metal powder (Fig. 3.a). After that a powder cold compaction method is used. The extrusion of the pre-compacted billet obtains a precursor material whose density is near of the base metal. The indirect extrusion force depends of the geometric dimension of the part, the resistance to deformation of the material and friction [10], in order to break the oxide layer covering aluminum particles (Fig. 3.b).

The process obtains non expanded rods; slabs catted to proper dimensions for further insertion in hollow metal structure (Fig. 3.c).

The structure internal surfaces are chemically treated for adherence. After heating up the structure, until melting temperature of the base metal, the foaming agent compound powder starts to produce gas. Foam is created from the rods, and the hollow structure is filed by expansion (Fig. 3.d) [11].

![Diagram of the method used for obtaining Al-foam filled parts](https://via.placeholder.com/150)

**Fig. 3.** Method used for obtaining Al-foam filled parts: (a) mixing the foaming agent powder with the base Al powder; (b) breaking the oxide layer covering aluminum particles by extrusion; (c) insertion of the non-expanded rods in hallow structure; (d) heat treatment for filling the structure by foaming the compacted rods

3.2. Experimental application

The method is used on an experimentally obtained spindle motor carrier of a HSC CNC milling machine tool center (Fig.4.) and consists in an alternative design of a large mass, moving CNC milling machine tool components [11]. The part overall dimensions are L: 680, l: 540, H: 720 mm.

The newly designed structure is improved by applying several technics:
- Laser cut welded relatively thin steel plates for constructing the structural frame;
- Internal shape modification by applying ribs and cut outs for stiffening and reducing weight [12];
- Obtaining a box type shape for increased rigidity;
- Filling the interior space with expanded metallic aluminum foam for rigidity and vibration dampening [13].
For results confirmation the experimental part undergoes several steps:
- The CAD design (Fig. 4. a.);
- FEM analysis for optimization;
- Remodeling the problematic parts for improved performance;
- The actual primary building of the part, consisting from classical welded steel panels;

![Diagram](image)

Fig. 4. (a) The experimentally HSC CNC milling machine tool center spindle motor carrier layout (b) The experimentally HSC CNC milling machine tool center spindle motor carrier made part.

- Annealing heat treatment of the part for reducing internal tensions;
- Chemical treatment of the internal surfaces for adherence with Alu-Flux solutions;
- The insertion of the unexpanded aluminum foam billets in the hollow structure through precut holes (Fig. 5. a);
- The expansion heat treatment of the aluminum foam, resulting the final structure (Fig. 5. b.).

![Images](image)

Fig.5. (a) Precut holes for billets insertion (b) The aluminum foam filled HSC CNC milling machine tool center spindle motor carrier experimental final part.

4. Results

The obtained part is a steel skin composite based on Al-foam core close cell type. The combination of attributes like high stiffness at low weight and energy absorption [3] qualifies for lightweight components with specific high-end requirements and applications, especially in machine tool manufacturing.
The experimentally build part was extensively impact tested with and without aluminium foam filling during other personal studies.

The important results obtained are presented below:
- Material used: AlSiMg;
- Obtained foam density: 375.5 kg/m³;
- Structural and cover steel sheets are made from: SR EN 10025-2:2004;
- Overall thermal properties:
  - Thermal expansion: 25*10⁻⁶ 1/K [3];
  - Thermal conductivity: 10-15 W/Mk [3];
- Mass increase of the part by filling with aluminum foam: 7.15%;
- Reduced stress equivalent from 13,813 MPa (hollow) to 3,275 MPa (alu-foam filled);

5. Conclusions

The new obtained structural part, made by the alternative presented technology, is approx. 50% lighter, comparative to a similar steel welded classic part with the same dynamic behavior. This mass reduction and the dynamic behavior preserved, is the main goal of this paper. The result is an improved structural moving part of a high speed cutting CNC milling machine.

Deformations were kept in acceptance limits, and beater comportment at different chattering frequencies was achieved also.

The method can be applied in other fields of performance engineering such as automotive, bridge constructions, ladders or other applications with good rigidity properties and low mas. It offers interesting solutions if we are able to use some of their other properties simultaneously [6].
- High impact energy absorption;
- Compressive strength;
- Vibration reduction and sound absorption;
- Structural and resonance damping;
- Electromagnetic – shielding and low electric conductivity;
- Low thermal conductivity;
- Flame resistant according to ÖNORM B3800.

References