PERIODICA POLYTECHNICA SER. MECH. ENG. VOL. 44, NO. 1, PP. 139–147 (2000)

TUNING MACHINE COMPONENTS BY MEANS OF Al FOAM

Peter ŠOLEK* and Pavel ÉLESZTŐS**

* Department of Applied Mechanics
Faculty of Mechanical Engineering
Slovak University of Technology
Nám. Slobody 17, 812 31 Bratislava, Slovak Republic
**Department of Applied Mechanics
Slovak University of Technology
Faculty of Mechanical Engineering
Nám. Slobody 17, 812 31 Bratislava, Slovak Republic
also at
Department of Engineering Mechanics
Budapest University of Technology and Economics
H–1521 Budapest, Hungary

Received: October 15, 1999

Abstract

Contribution refers to the possibility of tuning the machine components by means of Al foam. Closed cells Al foams with isotropic properties and with various densities are used in the computational model. Targetting the tuning is an attempt for requirement change values of the stresses, deformations, eigenfrequencies, etc. Increment of the weight in relation to required values of the tuned parameters is the most followed parameter.

Keywords: tuning, metallic foam, closed cell.

1. Introduction

Structural efficiency and cost requirements are the reasons for the new interest in cellular metals. Metallic foams have the potential for use in weight-efficient composite structures for a variety of engineering applications, such as lightweight cores for panels, shell, tubes and components designed for absorbing impact energy.

There have been extensive investigations of open cell solids, particularly polymers and natural materials such as trabecular bone. For these materials [1–2], there are validated scaling relations between density, cell morphology and cell wall properties. For closed cell systems, these relations have not been fully assessed yet. Past studies have shown that metallic foams with a low relative density ($\rho/\rho_s < 0.15$) exhibit particularly poor properties compared to idealized models [3,5]. Closed cell foams deform through two basic mechanisms: bending of cell edges and inplane axial stretching of cell faces. In the cell faces the corrugations and curved cell walls can be created. In the idealized foam structure influence of the corrugations and curved cell walls on stiffness and strength is researched. Idealized structure in the two dimensional analysis [6] is a hexagonal honeycomb. In the three dimensional analysis tetrakaidecahedral cells are used to the model of the idealized foam structure. Tetrakaidecahedral cell is composed from four hexagonal and three square faces and the reduced cell is composed from four half-hexagonal faces, two half-square faces and two quarter-square faces.

The influence of edge curvature and corrugations on the properties of a hexagonal honeycomb [7] and the tetrakaidecahedral foam is quite similar. In each case, the axial stiffness and the flexural rigidity of the curved or corrugated structural members are reduced.

2. Properties of Al Foam [8]

Modulus E is best measured dynamically or by loading the foam into the plastic range, then unloading and determining E from unloading slope. Young's modulus, the shear modulus G and Poisson's ratio ν scale with density as

$$E = \alpha_2 E_s \left(\frac{\rho}{\rho_s}\right)^n, \qquad G = \frac{3}{8}\alpha_2 G_s \left(\frac{\rho}{\rho_s}\right)^n,$$

where n has values between 1.8 and 2.2;
α_2 between 0.1 and 4 – they depend on the structure of the foam.
As rule of thumb $n = 2$.

For design purposes, it is helpful to know that the tensile modulus E of foam is not the same as that in compression – tensile modulus is greater, typically by 10%. Anisotropy of cell shape can lead to significant (30%) differences between moduli in different directions.

Closed cell foams show somewhat more complicated behaviour which can cause the stress to rise with increasing strain because the cell faces carry membrane (tensile) stresses. The plateau continues up to the densification strain ε_D, beyond which the structure compacts and the step stress rises steeply. The plateau stress σ_{pl}, and the densification strain scale with density as

$$\sigma_{pl} = (0.25 - 0.35)\sigma_{y,s} \left(\frac{\rho}{\rho_s}\right)^m, \qquad \varepsilon_D = \left(1 - \alpha \frac{\rho}{\rho_s}\right).$$

For currently available foams m is between 1.5 and 2.0,
α is between 1.4 and 2.0.
As rule of thumb $m = 1.6$,
$\alpha = 1.5$

These properties are important in energy absorbing applications, to which metal foams lend themselves well.

The tensile stress-strain behaviour of metal foams differs from that in compression. The slope of the stress-strain curve before general yield is less than E, implying considerable micro-plasticity even at very small strains. Beyond yield strength σ_y metal foams harden up to the ultimate tensile strength σ_{ts} beyond which they fail at a tensile ductility ε_t.

The damping capacity of a metal foam is typically 5 to 10 times greater than that of the metal from which it is made. This increase may be useful, although the loss factor is still much lower than that associated with polymer foams. Metal foams have some capacity as acoustic absorbers, although polymer foams and glass wool are generally better.

As in other materials, cyclic loading causes fatigue damage in metal foams. High-cycle fatigue tests allow a fatigue limit $\Delta\sigma_e$ ($\Delta\sigma_e$ is cyclic stress-range in which the material will just survive 10^7 cycles).

The toughness of metal foams can be measured by standard techniques. As rule of thumb, the initiation toughness J_{Ic} scales with density as

$$J_{Ic} = \beta\sigma_{y,s} l \left(\frac{\rho}{\rho_s}\right)^p,$$

where l is the cell size with $p = 1.3$ to 1.5 and $\beta = 0.1$ to 0.4.

The melting point, specific heat and expansion coefficient of metal foams are the same as those of the metal from which they are made. The thermal conductivity λ scales with density approximately as

$$\lambda = \lambda_s \left(\frac{\rho}{\rho_s}\right)^q$$

with $q = 1.65$ to 1.8.

The only electrical property of interest is the resistivity R. It scales with relative density approximately as

$$R = R_s \left(\frac{\rho}{\rho_s}\right)^{-r}$$

with $r = 1.6$ to 1.85.

3. Analysis

Model of the front subframe with boundary conditions and the loading is shown in *Fig. 1*. The width of the front subframe is 800 mm and its length is 1000 mm. The dimensions of the cross profile are 60 by 60 mm with the thickness of 1.8 mm. The resulting value of the loading is 9600 N. Boundary conditions simulate fixing at the ends and the supporting at the center of the subframe. Von Mises stresses are evaluated in the computation. Space elements are used for modeling Al foam. For computations program Ansys is used.

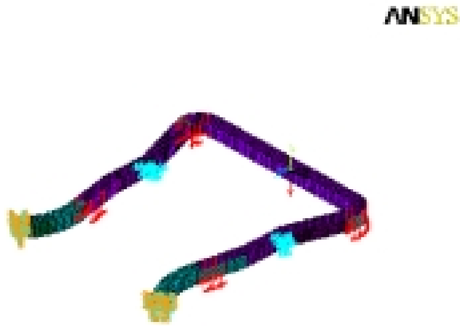

Fig. 1. Model of the front subframe with loading and the boundary conditions

3.1. Computation Stresses, Masses and Deformations ahead of Optimization

Young's modulus and density of the various Al foams used in the computations:

	Foam 1	Foam 2	Foam 3
E [GPa]	4.2	6.6	9.3
$\rho = g \cdot \mathrm{cm}^{-3}$	0.5	0.65	0.8

Von Mises stresses in the front subframe, without the Al foam and with Al foam with various densities are shown in *Table 1*. Evaluated parameters in *Table 1* are the masses, deformations and stiffness.

Table 1. Comparison of the evaluated parameters from the computations

	The front subframe without foam	The front subframe with foam 1	The front subframe with foam 2	The front subframe with foam 3
Mass of the foam [kg]		1.60437	2.08568	2.56699
Resulting mass [kg]	10.0768	11.681	12.162	12.644
Max. deformations [mm]	1.928	1.204	1.129	1.062
Max. stresses [MPa]	390	200	182	167
Stiffness [$\mathrm{N} \cdot \mathrm{mm}^{-1}$]	4979	7973	8503	9039

Mass of the foam, resulting mass, maximum deformations and maximum stresses are obtained from the computations. Stiffness is defined as ratio of the loading force and maximum deformation.

Comparison of the deformations, masses, stresses and the stiffness for the front subframe without Al foam and with Al foams of various densities is given in *Table 2*.

Table 2. Comparison of the evaluated parameters in percentages

	The front subframe with foam 1	The front subframe with foam 2	The front subframe with foam 3
Mass of the foam [%]	–	+30	+60
Resulting mass [%]	+16	+20.8	+25.6
Max. deformations [%]	−38	−42	−45.5
Max. stresses [%]	−48.7	−53.3	−57.17
Stiffness [%]	+60.1	+70.7	+81.52

Maximum stress in the front subframe without Al foam is 390 MPa and this value is in the place of the supporting subframe. The value of the stress is too high, however, decrease of stresses is increasing the thickness of subframe produced by hydroforming. Disadvantage of this approach is high resulting mass of the subframe (in this case, resulting mass is 16.79 kg and maximum stress is 208 MPa). Increase of the resulting mass in percentages is 66.6%. The other weight effective approach of decreasing the maximum stresses is foaming of the front subframe with Al foam in the surroundings of places with maximum stresses.

From the comparison of the computed values in *Table 2*, the resulting mass of the subframe increases with raising the foam density. Resulting mass of the front subframe with Al foam increases against the front subframe without Al foam from 16% to 25.6% depending on the Al foam density. Maximum stresses decrease from 48.7% to 57.7% and maximum deformations go back from 38% to 45.5%. Stiffness of the front subframe increases from 60.1% to 81.52% with increasing density of Al foam.

3.2. Computation of Stresses, Masses and Deformations after Optimization

Quantity of the Al foam in the foamy subframe was estimated in relation to the size of the maximum stresses. Minimization of Al foam quantity (increment of the resulting mass) at the subframe in relation to the required values of the tuned parameters is our aim in the next step. Required values of the tuned parameters (stresses, deformations, stiffness, eigenfrequencies, etc.) are constraints in the formulations of the optimization problem. Computed values of the tuned parameters are summarized in *Table 3*.

Table 3. Computed values of the tuned parameters

	The front subframe without foam	The front subframe with foam 1 after optimization	The front subframe with foam 2 after optimization	The front subframe with foam 3 after optimization
Mass of the foam [kg]		1.42611	1.85394	2.28177
Resulting mass [kg]	10.0768	11.503	11.931	12.359
Max. deformations [m]	0.001928	0.001234	0.001158	0.00109
Max. stresses [MPa]	390	203	185	170
Stiffness [$N \cdot mm^{-1}$]	4979	7779	8290	8807

Comparison of the tuned parameters of front subframe after optimization in percentages is given in *Table 4*.

The resulting mass increases from 14.25% to 22.8%. Maximum stresses decrease from 47.9% to 56.4% and the maximum deformations decrease from 36.5 to 44%. Stiffness increases from 52.5% to 47.6%.

Von Mises stresses of the front subframe without foam are shown in *Fig. 2* and the front subframe with foam 1 can be seen in the *Fig. 3*.

3.3. Computation of the Eigenfrequencies

Eigenfrequencies are very important parameters in the process of tuning machine parts. Foaming with Al foam of the subframe is one of the very effective approaches to obtain the requested eigenfrequencies and the weight effective parts.

Computed eigenfrequencies of the front subframe are contained in *Table 5*.

Comparison of the eigenfrequencies of the front subframe in percentages can be seen in *Table 6*.

All computed eigenfrequencies of the subframe foamed with Al foam are increasing in relation to eigenfrequencies of the subframe without Al foam. The most expressive increases are in the second eigenfrequency from 27.3% to 31.4%. Increases in the first and second eigenfrequencies are less expressive and the least expressive increases are found in the fourth and fifth eigenfrequencies.

Table 4. Comparison of the tuned parameters in percentages

	The front subframe with foam 1 after optimization	The front subframe with foam 2 after optimization	The front subframe with foam 3 after optimization
Mass of the foam [%]	–	+30.5	+61
Resulting mass [%]	+14.25	+18.5	+22.8
Max. deformations [%]	−36.5	−40.5	−44
Max. stresses [%]	−47.9	−52.6	−56.4
Stiffness [$N \cdot mm^{-1}$]	+56.2	+66.5	+76.8

Table 5. Computed eigenfrequencies of the front subframe

Numbers of eigen-frequen-cies	Eigenfrequen-cies of the front subframe without foam [Hz]	Eigenfrequen-cies of the front subframe with foam 1 [Hz]	Eigenfrequen-cies of the front subframe with foam 2 [Hz]	Eigenfrequen-cies of the front subframe with foam 3 [Hz]
1	119.47	136.13	138.92	141.71
2	185.8	236.31	240.21	243.92
3	229.96	248.69	253.1	257.41
4	307.76	319.06	320.38	321.56
5	399.02	435.31	434.66	433.95

Table 6. Comparison of the eigenfrequencies in percentages

Numbers of eigenvalues	Eigenfrequencies of the front subframe with foam 1 [%]	Eigenfrequencies of the front subframe with foam 2 [%]	Eigenfrequencies of the front subframe with foam 3 [%]
1	+14	+16.34	+18.7
2	+27.3	+29.4	+31.4
3	+8.18	+10.1	+11.9
4	+3.68	+4.1	+4.49
5	+9.1	+8.93	+8.75

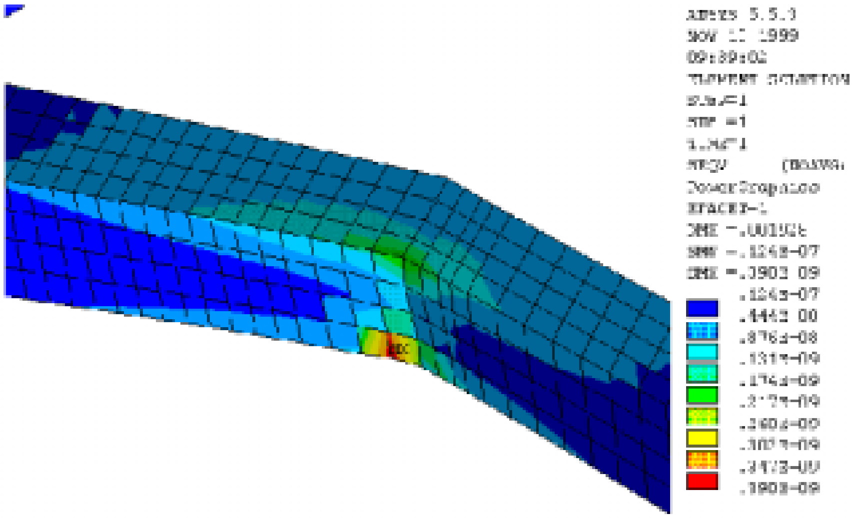

Fig. 2. Von Mises stresses in the front subframe without foam

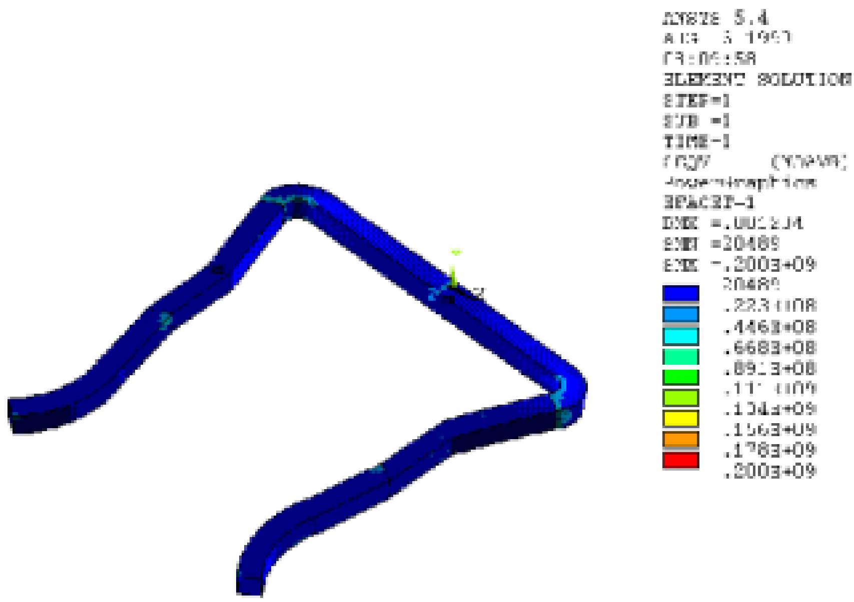

Fig. 3. Von Mises stresses of the front subframe with foam 1

4. Discussion

Tuning the hydroformed machine components by means of Al foam is a very effective approach to obtain weight-effective machine parts. In most cases, it is only one way we can get tuned material inside the hydroformed machine part and obtain the requested shape. Requested shape of the Al foam in the hydroformed machine part is result of optimization mass of the Al foam with regard to the requested values of tuned parameters.

Tuned parameters of the hydroformed machine parts foamed with Al foam are stresses, deformations, stiffness, eigenfrequencies and the mass. All tuned parameters are compared in function of the values of densities Al foam. Mass of a machine part foamed with Al foam increases from 16 to 25.6%, deformations decrease from 38 to 45.5%, stresses decrease from 48.7 to 57.2%, stiffness increases from 60.1 to 81.52%. After optimization of mass of Al foam, resulting mass of foamy machine part decreases from 1.75 to 3% against the value before optimization, deformations increase to 1.5%, stresses decrease to 0.8% and stiffness decreases from 3.9 to 4.72%. Difference betwen values of tuned parameters before and after optimization is not very expressive, because the first estimation of the shape and the mass of Al foam was relative precise. It is not a rule for all cases. As for eigenvalues, expressive increase is in the second eigenfrequency from 27.3 to 31.4%. Tuning eigenfrequencies by means of Al foam is sensitive to the shape and position of Al foam in the hydroformed machine part. These two factors allow tuning the requested eigenfrequencies.

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