Microstructural Characterization of Metal Foams: An Examination of the Applicability of the Theoretical Models for Modeling Foams

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Abstract

Establishing the geometry of foam cells is useful in developing microstructure-based acoustic and structural models. Since experimental data on the geometry of the foam cells are limited, most modeling efforts use the three-dimensional, space-filling Kelvin tetrakaidecahedron. The validity of this assumption is investigated in the present paper. Several FeCrAlY foams with relative densities varying between 3 and 15% and cells per mm (c.p.mm.) varying between 0.2 and 3.9 c.p.mm. were microstructurally evaluated. The number of edges per face for each foam specimen was counted by approximating the cell faces by regular polygons, where the number of cell faces measured varied between 207 and 745. The present observations revealed that 50 to 57% of the cell faces were pentagonal while 24 to 28% were quadrilateral and 15 to 22% were hexagonal. The present measurements are shown to be in excellent agreement with literature data. It is demonstrated that the Kelvin model, as well as other proposed theoretical models, cannot accurately describe the FeCrAlY foam cell structure. Instead, it is suggested that the ideal foam cell geometry consists of 11 faces with 3 quadrilateral, 6 pentagonal faces and 2 hexagonal faces consistent with the 3-6-2 cell.

1.0 Introduction

Aircraft engine noise is a major environmental concern especially in regions surrounding an airport during takeoff and landing (Ref. 1). Significant progress has been made since the advent of the first commercial jet engine-powered airplanes with current ultrahigh bypass engines being much quieter than the first generation engines. For example, the effective perceived noise level in decibels (EPNdB) relative to the International Civil Aviation Organization's (ICAO) Chapter 3 certification standards decreased from about +5 EPNdB for aircraft engines developed in the 1960s to –5 EPNdB for modern engines (Refs. 2 and 3). Despite this large improvement in engine design, there is still a great desire among policy makers and designers to reduce noise much below current levels. For example, the National Aeronautics and Space Administration (NASA) has set ambitious goals to further reduce aircraft noise by –52 db with respect to the newly adapted ICAO's Chapter 4 certification standards by the year 2020 under its Subsonic Fixed Wing (SFW) project (Ref. 4). It is expected that these noise reduction goals will be achieved through a combination of design changes and development of suitable materials (Refs. 3 and 4).

Polymeric foams have been historically used for sound absorption in several applications (Ref. 5). More recently, metal foams are being investigated for their flow resistance (Refs. 6 and 7) and sound absorption properties (Refs. 8, 9, and 10). Metal foams have been proposed for use in jet engines as acoustic treatment over rotors (Ref. 11), fan blades (Ref. 12) and other applications (Ref. 13). The acoustic and other properties of foams are dependent on their relative density, ρ^*/ρ_s, where ρ^* and ρ_s are the densities of the foam and the solid material, respectively, and microstructure (Ref. 5). Simple formulae exist for correlating relative density and some elements of the microstructure, such as, ligament length and thickness (Refs. 5 to 10). However, due to difficulties in controlling process variables, the microstructures of the foams and their properties can vary by large amounts. Although commercially manufactured foams are specified by pores per inch (p.p.i.) and their relative densities, it is noted that the reported values of p.p.i. are not necessarily identical from one manufacturer to another (Ref. 14). For

example, some vendors specify the p.p.i. of their products with that of the precursor polyurethane foam rather than the finished product without accounting for metal shrinkage during the manufacturing process.

In the case of metal foams used as acoustic liners in aircraft engines, it is important to qualitatively and quantitatively understand the role their microstructures play in affecting their acoustic and mechanical properties. Since the complex three-dimensional microstructures of the foams help to dissipate the sound energy, it is evident that a quantitative analysis of the foam microstructures would enable important correlations to be determined between the microstructural features and the gas pressure flow resistance as well as the sound absorption coefficients. These correlations are essential for developing microstructure-based models for designing acoustic liners for aircraft engines. Particularly, establishing the three-dimensional topology of the cell microstructures of foams is important effectively to model fluid flow through them and to understand their mechanical properties. Among the several possible idealized topological representations of the foam microstructures (Ref. 5), the three-dimensional, space-filling Kelvin tetrakaidecahedron (Refs. 5, 15, and 16) is often favored for modeling the foam cellular network. This cell has 14 faces consisting of 6 squares and 8 hexagonal faces. In other words, about 43% of the faces are squares, 0% faces are pentagonal and 57% of the faces are hexagonal. It is worth noting that other topological models have been proposed, where pentagonal faces are incorporated in the cell geometry (Refs. 17 and 18). In reality, cells deviate from these ideal conditions, where they may be distorted and their sizes and shapes non-uniform. Therefore, the objectives of this paper are to statistically evaluate the geometrical features of the foam cells in order to identify the ideal polyhedral topography to use in acoustic and structural models.

2.0   Experimental Procedures

Several FeCrAlY foam panels approximately 210×210 mm^2 in cross-sectional area and varying in thicknesses between 3.2 and 25.4 mm were procured from PORVAIR Fuel Cells Technology, Inc., Hendersonville, North Carolina. The foam panels were manufactured by a proprietary process from precursor polyurethane foams dipped in metal powder slurries followed by sintering of the powder and burning off the polymer foams. The nominal c.p.mm. varied between 0.2 (5 p.p.i.) and 3.9 (100 p.p.i.), whereas $\rho*/\rho_S$ varied between 3 and 15%. Square specimens ~25.4×25.4 mm in cross-sectional dimensions or
50 mm in diameter were wire electro-discharge machined from these panels for metallographic analyses. On close examination, it was observed that the microstructures of these foams are extremely complicated and difficult to characterize. The foam microstructures consisted of interconnected cells randomly stacked in a three-dimensional array with the cell boundaries moving in and out of the field of view. Quantitative metallographic measurements were conducted on 6 to 7 randomly selected areas for each foam specimen and a large number of faces were measured to ensure that the measurements were representative and to minimize measurement errors. A specialized digital optical microscope with a large depth of focus was used in making these in-situ measurements. The number of edges per face was measured by assuming that the faces could be approximated by regular polygons with the number of cell faces measured varying between 207 for foams 0.2 c.p.mm. to 745 for 3.9 c.p.mm. This assumption was not always valid since some faces were either circular or elliptical rather than polygonal and the edges were often curved. In some instances, the edges of a face curved out of the plane of view. In addition, two adjacent edges did not meet always at a relatively sharp point but had a significant curvature, while adjacent faces met at triple surfaces rather than triple points in many instances. These issues complicated the measurements and they are likely to add to the errors in measurements. Nevertheless, by measuring a large number of faces, it was felt that the errors in measurement would be minimized.

3.0   Results and Discussion

Figures 1(a) shows an optical macrograph of a FeCrAlY foam specimen with a nominal cell density of 0.2 c.p.mm. (5 p.p.i.) and $\rho^*/\rho_S = 3.3\%$; Figure 1(b) shows the corresponding polygonal represent-ations of the faces. Since portions of the inner layer were covered by ligaments of the top layer, the outline of these cells were demarcated as carefully as possible. The numbers identify the faces for tracking purposes. The complex nature of the foam microstructures is self evident in these figures. The volume fractions of the open cells decreased while that of the closed cells increased with increasing relative density. Since it was often difficult to clearly discern the boundaries of closed faces, only the shapes of the open faces were demarcated in these measurements in order to minimize errors in measurement. The cells were generally equiaxed irrespective of c.p.mm. and relative density.
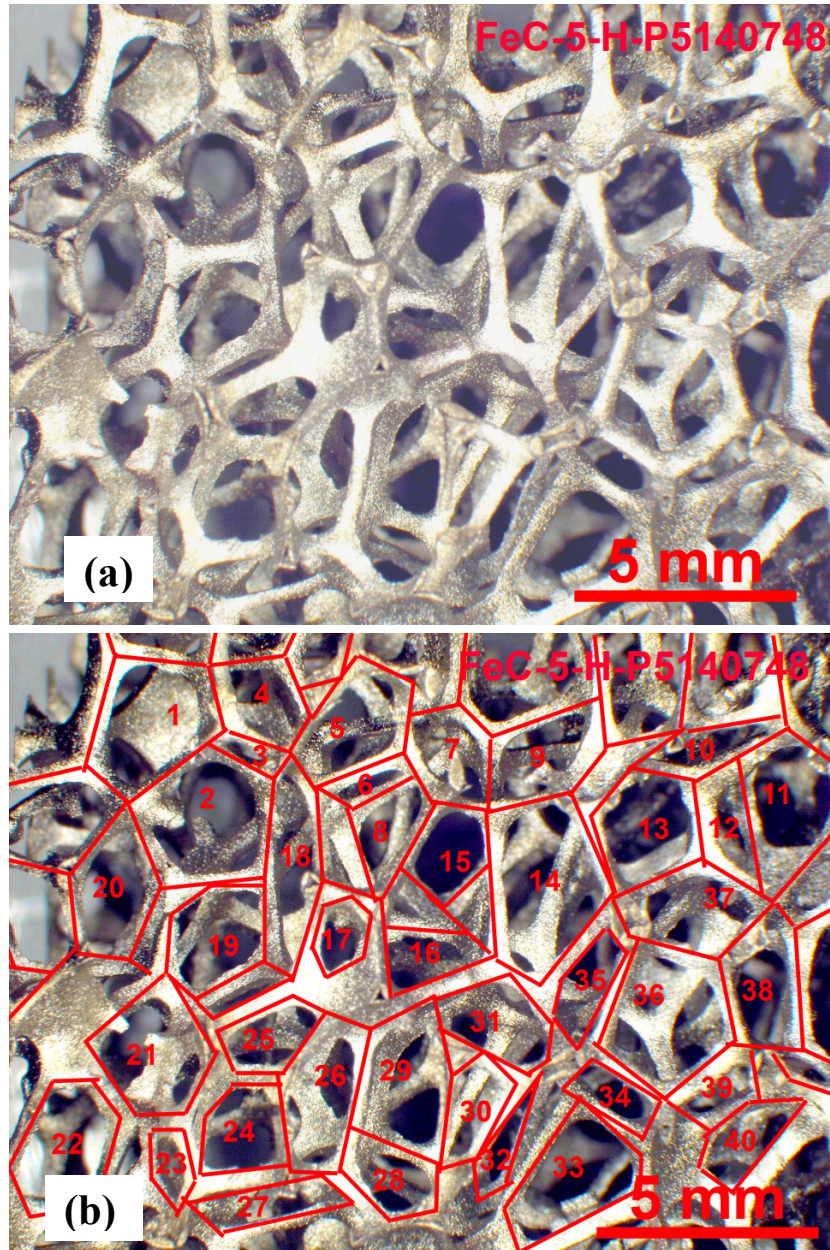

Figure 1.—(a) Optical macrograph of a FeCrAlY foam with a nominal pore density of 0.2 c.p.mm. (5 p.p.i) and $\rho^*/\rho_S = 3.3\%$; (b) polygonal representations of the faces forming the cells.

Figures 2(a) to (d) show the frequency histogram and cumulative frequency plots of the number of edges per face for four FeCrAlY foams. An examination of Figures 2(a) to (d) clearly establish that 97% of the faces were either four, n_4, five, n_5, or six, n_6,-sided with over 50% of the faces being five-sided. Less than 1% of the faces were triangular and less than 2% were heptagonal except in the case for foams with 2.4 c.p.mm (60 p.p.i), which had about 4% heptagonal faces. The average values of the number of edges per face, $\bar{n}$, were determined to be 4.9±0.7, 5.0±0.8, 4.9±0.8, and 4.9±0.8 for the FeCrAlY foams with actual values of ρ^*/ρ_S being 3.3% (0.2 c.p.mm.), 9.5% (2.4 c.p.mm.), 10.1% (3.1 c.p.mm.) and 9.3% (3.9 c.p.mm.), respectively. Significantly, these observations were not influenced by either the relative densities of the foams or the lineal cell densities.
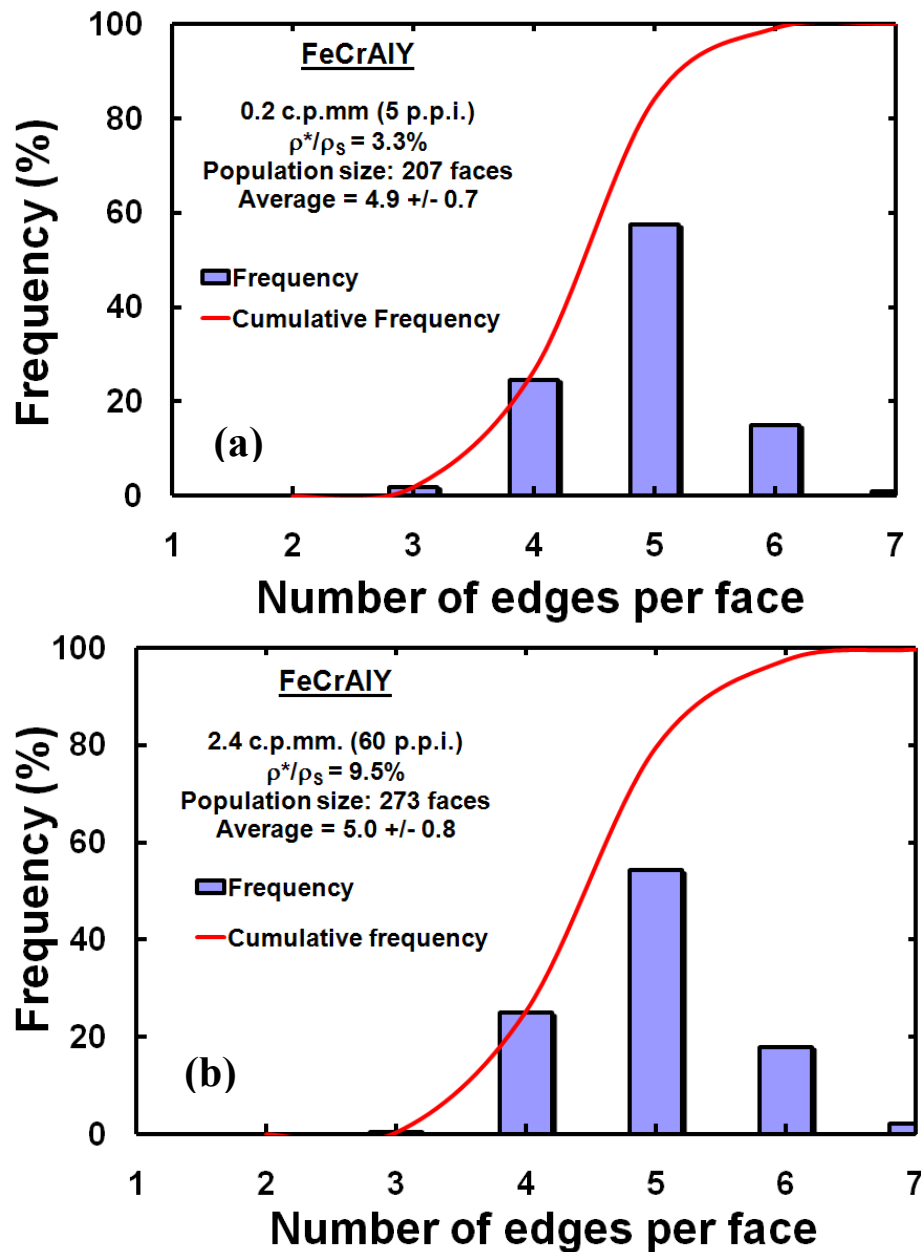

Figure 2.—Frequency histograms and cumulative frequencies showing the distributions of the number of edges per face for FeCrAlY foams with different values of cells per mm and relative densities.
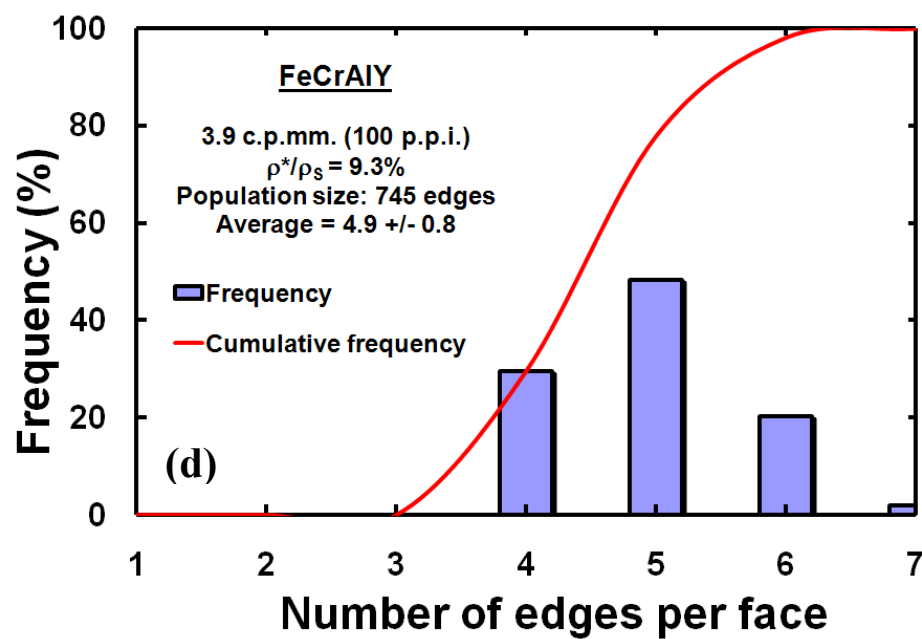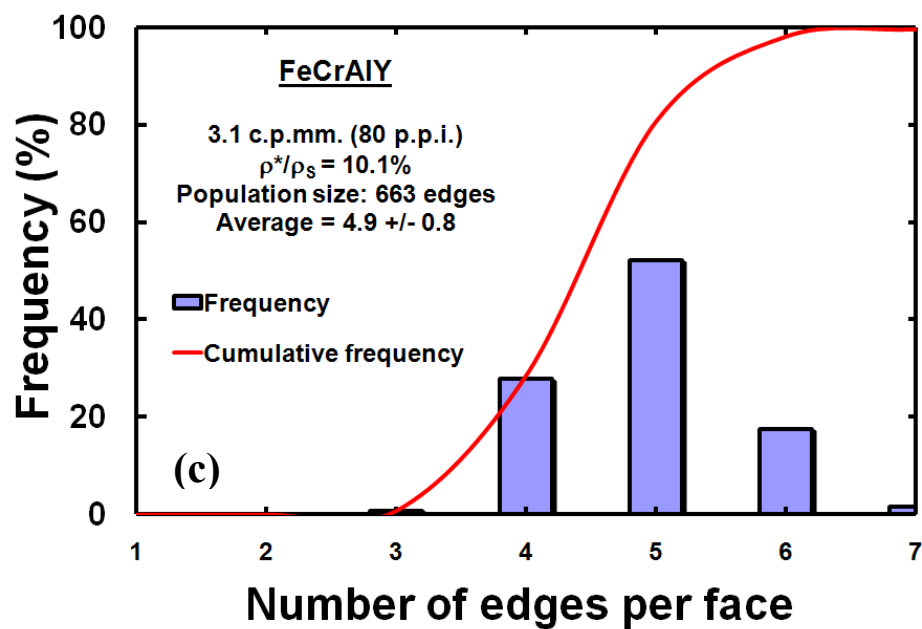
Figure 2.—Concluded.

Figure 3 compares the present results with similar measurements on soap bubbles (Refs. 19 to 21) and polyurethane foams (Ref. 22). These literature data include measurements conducted on both surface and internal cells using different measurement techniques. Table 1 provides details of the percentages of four, five, and six-sided faces observed on the FeCrAlY foams and reported in the literature (Refs. 19 to 22), which were the predominant faces observed in these foams. Significantly, in all cases, more than 50% of the cell faces had a pentagonal geometry irrespective of the foam material and measuring technique used. The present results fall within the range of other observations reported in the literature. Other observations on plant cells (Ref. 17) and metal grains (Ref. 23)' have also reported a predominance of pentagonal faces in nature.

An examination of Figure 3 shows that the Kelvin tetrakaidecahedron model (Ref. 15), which predicts 0% five-sided faces, is inconsistent with the experimental observations. The fact that the Kelvin model fails to be consistent with the experimental results is not surprising. This model is based on a mathematical conjecture that soap bubbles and foam microstructures can be ideally represented by dividing three-dimensional space into cells of equal volume in a manner that follows Plateau's rules for mechanical equilibrium and minimization of the surface area (Ref. 24). It is noted that the Kelvin model requires the arrangement of tetrakaidechedron cells to be topologically ordered and spatially periodic to fill space. Real foams are far from this ideal configuration since factors, such as residual stresses due to processing methods, topological disorder (Ref. 24), unequal cell volumes, aperiodic spatial ordering of the cells (Ref. 19), and thick ligaments and triple points, can influence the cell topology.
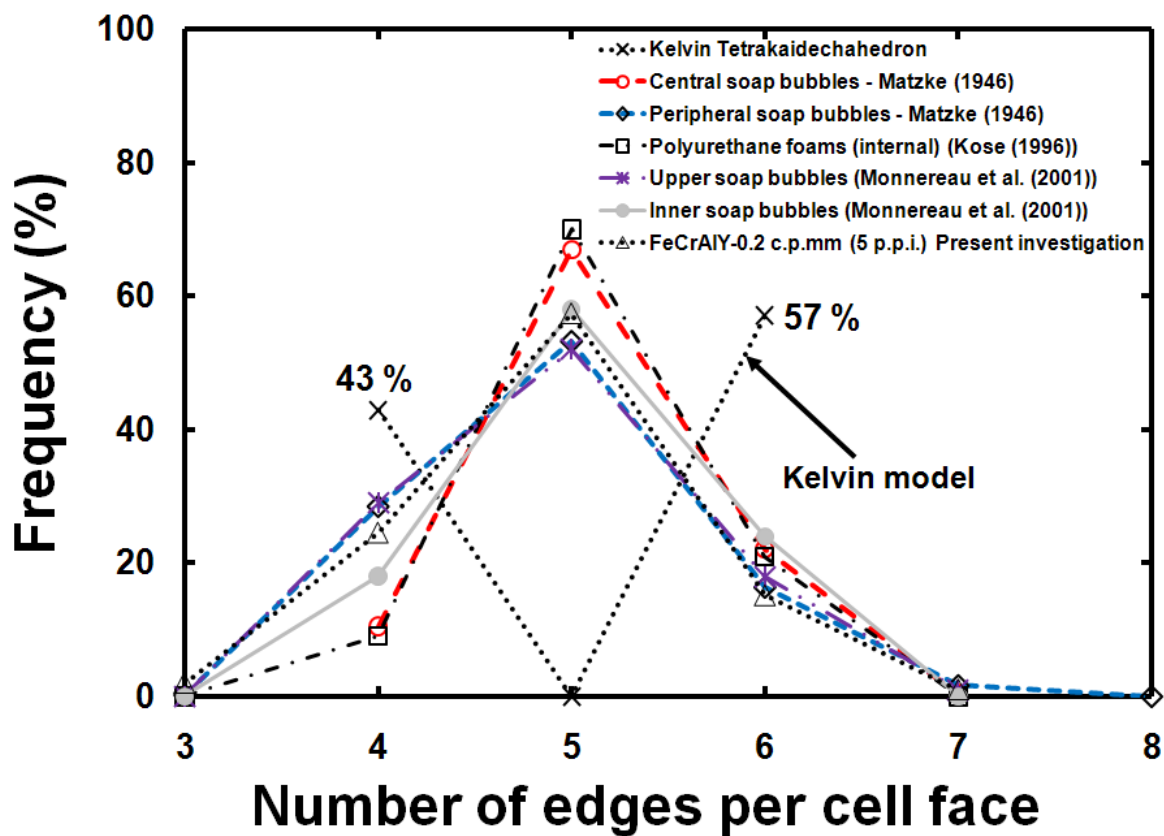

Figure 3.—Comparison of the frequency histograms of the distributions of the number of edges per face for soap bubbles (Refs. 19 and 21), polyurethane foams (Ref. 22) and a FeCrAlY foam with 0.2 c.p.mm. (5 p.p.i.) and ρ^*/ρ_s. The solid squares and associated legends represent the theoretical values for the Kelvin tetrakaidechedron.

TABLE 1.—COMPARISON OF THE PERCENTAGES OF FOUR, FIVE, AND SIX-SIDED
FACES OBSERVED IN FECRALY FOAMS WITH OBSERVATIONS ON SOAP BUBBLES
(REFS. 19 AND 21) AND POLYURETHANE FOAM (REF. 22).

Description	Percentage of polyhedral faces, n_4, n_5, and n_6
Soap bubbles (19)	Peripheral: $n_4 = 29\%$; $n_5 = 53\%$; $n_6 = 16\%$; Central: $n_4 = 11\%$; $n_5 = 67\%$; $n_6 = 22\%$
Soap bubbles (21)	Upper bubbles; $n_4 = 29\%$; $n_5 = 52\%$; $n_6 = 18\%$; Internal bubbles: $n_4 = 18\%$; $n_5 = 58\%$; $n_6 = 24\%$
Polyurethane foam (22)	$n_4 = 9\%$; $n_5 = 70\%$; $n_6 = 21\%$
FeCrAlY foams (Present investigation)	$n_4 = 25\%$; $n_5 = 57\%$; $n_6 = 15\%$ (0.2 c.p.mm.; $\rho^*/\rho_s = 3.3\%$)
	$n_4 = 24\%$; $n_5 = 54\%$; $n_6 = 18\%$ (2.4 c.p.mm.; $\rho^*/\rho_s = 9.5\%$)
	$n_4 = 28\%$; $n_5 = 52\%$; $n_6 = 18\%$ (3.1 c.p.mm.; $\rho^*/\rho_s = 10.1\%$)
	$n_4 = 26\%$; $n_5 = 50\%$; $n_6 = 22\%$ (3.9 c.p.mm.; $\rho^*/\rho_s = 9.3\%$)

Although the excellent agreement between the present results and the Matzke's data (Ref. 19) is encouraging, it is important to note that the present measurements were conducted on cross-sections cut through the three-dimensional FeCrAlY foam cells unlike Matzke's measurements (Ref. 19), which were made on peripheral soap bubbles enclosed by the surface of the container. It is also noted that the present data are in reasonable agreement with the surface and internal cell data obtained on soap bubbles by Monnereau et al. (Ref. 21). Matzke (Ref. 19) studied 400 peripheral soap bubbles and observed that the largest number of them possessed eleven-hedra cells with 3 four-sided, 6 five-sided and 2 six-sided faces (3-6-2)[1] (Fig. 4). However, these soap bubbles only constituted 17% of the total number of bubbles studied since twenty other shapes were observed. In contrast, 97% of the cell faces in the FeCrAlY foams were either four, five or six-sided.

Since quantitative optical metallography gives two-dimensional information, there is no easy and direct way to determine the three-dimensional topographical features of the foam cells. However, the number of faces per cell, F, the number of edges, E, and the number of vertices, V, of the three-dimensional cell can be determined from the Coexeter equations (Refs. 5 and 25)

$$F = \frac{12}{[6 - \bar{n}]} \tag{1a}$$

$$E = \frac{6\bar{n}}{[6 - \bar{n}]} \tag{1b}$$

$$V = \frac{4\bar{n}}{[6 - \bar{n}]} \tag{1c}$$

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[1]This nomenclature of identifying the cells was suggested by Kryanik et al. (Ref. 24).
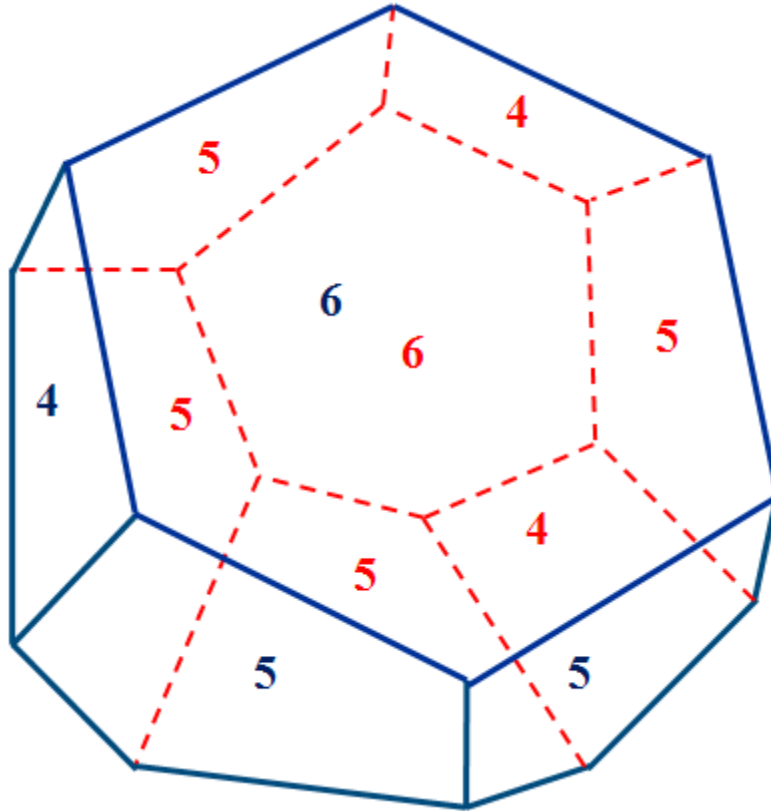
Figure 4.—A 3-6-2 eleven-hydra cell with 3 quadrilateral, 6 pentagonal and 2 hexagonal faces (Ref. 19). The numbers represent the number of edges enclosing the cell face. The blue solid lines representing the forward faces are identified by the blue lettering, while the red broken lines representing the back faces are identified by the red lettering.

TABLE 2.—CALCULATED VALUES OF F, E, V, n_4, n_5, and n_6 FOR FECRALY FOAMS

Linear cell density (c.p.mm)	ρ^*/ρ_s	F	E	V	n_4	n_5	n_6
0.2 (5 p.p.i.)	3.3	11.0	26.7	17.8	3	6	2
2.4 (60 p.p.i.)	9.5	11.7	30.0	20.0	3	6 or 7	2
3.1 (80 p.p.i.)	10.1	11.1	26.7	17.8	3	6	2
3.9 (100 p.p.i.)	9.3	11.4	26.7	17.8	3	6	2 or 3

Table 2 shows the calculated values of $\boldsymbol{F}$, $\boldsymbol{E}$, $\boldsymbol{V}$, and the corresponding experimental values of n_4, n_5, and n_6 for the four FeCrAlY foams. Using the measured values of $\bar{n}$, the corresponding values of $\boldsymbol{F}$ calculated from Equation (1a) are 11.0, 11.7, 11.1, and 11.4 for foams with 0.2 (5 p.p.i.), 2.4 (60 p.p.i.), 3.1 (80 p.p.i.), and 3.9 c.p.mm. (100 p.p.i.), respectively. Most of the values of $\boldsymbol{F}$, $\boldsymbol{E}$ and $\boldsymbol{V}$ are 11, 27, and 18, respectively, with average values of $n_4 = 3$, $n_5 = 6$, and $n_6 = 2$. These values are independent of relative density.

Table 3 compares the topological features of the FeCrAlY foams with several simple cell shapes (Ref. 5), where **C** is the number of cells. The topological characteristics of the FeCrAlY foams do not agree with any of these simple geometries. Instead, they appear to be closer to the topological structure of clathrates although more detailed topological modeling needs to be conducted to establish this possibility (Refs. 26 and 27). As noted above, Matzke (Ref. 19) observed that most of the peripheral soap bubbles were eleven-hedra cells with 3 four-sided, 6 five-sided and 2 six-sided faces (3-6-2). Based on the excellent agreement between the present results and Matzke's data on peripheral soap bubbles (Ref. 19) (Fig. 3) taken together with the fact that the total number of faces for the FeCrAlY foams was determined to be 11 (Table 2), it is reasonable to suggest that the 3-6-2 cell is the most representative of the FeCrAlY foam cellular structure.

Table 4 shows the predicted (Refs. 15 to 18) and the experimental (Refs. 19, 21, and 22) percentage distributions of polyhedral faces and the average number of faces per cell. The percentages of n_4, n_5, and n_6 for the relatively complex Weaire and Phelan model (Refs. 16 and 18) correspond to the values reported by Kose (Ref. 22). The present observations are in very good agreement with the experimental observations on the peripheral (Ref. 19) or upper (Ref. 21) soap bubbles for which the average number of faces is about 11. However, the average number of faces varied between 13 and 14 for the internal cells (Refs. 19, 21, and 22). Although it is tempting to conclude from these comparisons that the present observations on the FeCrAlY foam panels were influenced by surface effects much in the same way as the peripheral soap bubbles, it is important to note that the soap bubbles have very low stiffness compared to the FeCrAlY foams and they were formed dynamically. In contrast, the present observations were conducted on sections cut through preformed FeCrAlY panels, which are much stiffer than the soap bubbles. Therefore, it is doubtful that the present results can be attributed to surface effects.

TABLE 3.—COMPARISON OF THE GEOMETRIC PROPERTIES OF FeCrAlY
FOAM CELLS WITH THOSE FOR SIMPLE POLYHEDRAL (REF. 5)

Cell shape	Number of face shapes				F	E	V	C	Remarks
	3	**4**	**5**	**6**					
Tetrahedron	4	-	-	-	4	6	4	1	Regular Platonic solid
Triangular prism	2	3	-	-	5	9	6	1	Packs to fill space
Square prism	-	6	-	-	6	12	8	1	Packs to fill space
Hexagonal prism	-	6	-	2	8	18	12	1	Packs to fill space
Octahedron	8	-	-	-	8	12	6	1	Regular Platonic solid
Rhombic dodecahedron	-	12	-	-	12	24	14	1	Packs to fill space
Pentagonal dodecahedron	-	-	12	-	12	30	20	1	Regular Platonic solid
Tetrakaidecahedron	-	6	-	8	14	36	24	1	Packs to fill space
Icosahedron	20	-	-	-	20	30	12	1	Regular Platonic solid
3-6-2 cell	**-**	**3**	**6**	**2**	**11**	**27**	**18**	**1**	**FeCrAlY foam (present investigation)**

TABLE 4.—COMPARISON OF THE GEOMETRIC PROPERTIES OF THE CELLS PREDICTED BY SEVERAL
THEORETICAL MODELS (REFS. 15 TO 18) AND EXPERIMENTAL DATA (REFS. 19 TO 22)

Description	Percentage of polyhedral faces, n_4, n_5, and n_6	Average number of faces
Kelvin cell (Ref. 15)	$n_4 = 43\%$; $n_5 = 0\%$; $n_6 = 57\%$	14
Williams cell (Ref. 17)	$n_4 = 14\%$; $n_5 = 57\%$; $n_6 = 29\%$	14
Weaire and Phelan model (Refs. 16 and 22)	$n_4 = 0\%$; $n_5 = 89\%$; $n_6 = 11\%$	13.4
Soap bubbles (Ref. 19)	Peripheral: $n_4 = 29\%$; $n_5 = 53\%$; $n_6 = 16\%$ Central: $n_4 = 11\%$; $n_5 = 67\%$; $n_6 = 22\%$	11.0 (peripheral) 13.7 (central)
Soap bubbles (Ref. 21)	Upper bubbles: $n_4 = 29\%$; $n_5 = 52\%$; $n_6 = 18\%$ Internal bubbles: $n_4 = 18\%$; $n_5 = 58\%$; $n_6 = 24\%$	11.1 (upper bubbles) 13.5 (internal bubbles)
Polyurethane foam (Ref. 22)	$n_4 = 9\%$; $n_5 = 70\%$; $n_6 = 21\%$	13.6
FeCrAlY foams (Present investigation)	$n_4 = 24\text{-}27\%$; $n_5 = 55\text{-}60\%$; $n_6 = 14\text{-}18\%$	11.3

A close examination of Table 4 reveals that the present results do not agree with the predictions of the three cell topological models (Refs. 15 to 18). The Kelvin cell (Ref. 15) does not possess any pentagonal faces, whereas the Weaire-Phelan model (Refs. 16, 18, and 22) does not have any quadrilateral faces, with the total number of faces being either 14 or 13.4, respectively. The Williams cell (Ref. 17) with a total of 14 faces possess 14% quadrilateral, 57% pentagonal, and 29% hexagonal faces. However, this model also does not agree with the present observations on the FeCrAlY foams. This difference between the experimental results and the theoretical predictions is to be expected since theoretical efforts mainly consider the surface and volume free energy contributions to the total free energy (Ref. 24). As indicated earlier, other factors can influence the final cell topology of real foams. For example, the effect of residual stresses developed in the foam panels during processing have not included in these theoretical derivations. Qualitatively, one can modify the Gibbs free energy equation as follows:

$$\Delta G = \left(\Delta g_v + \Delta g_e\right)V + \Delta g_s S \tag{2}$$

where, ΔG, Δg_v, Δg_e, and Δg_s are the changes in the total, volume, residual strain and surface Gibbs free energies, respectively, V is the cell volume and S is the surface are of the cell. It is important to note that current theoretical models agree incorrectly assume that $\Delta g_e = 0$ for real foams.

4.0 Summary and Conclusions

A detailed microstructural analysis of several FeCrAlY metal foams with relative densities varying between 3 and 15%, and linear cell densities varying between 0.2 and 3.9 c.p.mm., was conducted to evaluate the topology of the foam cells. The shapes of cell faces were evaluated by approximating the edges by regular polygons. It was observed that between 24 and 28% of the cell faces were quadrilateral, 50 to 57% pentagonal, and 15 to 22% hexagonal in morphology. The present results are in excellent agreement with observations on soap bubbles (Refs. 19 and 21). Based on Matzke's observations (Ref. 19), it is suggested that the FeCrAlY foam cells had a total of 11 faces with 3 quadrilateral, 6 pentagonal, and 2 hexagonal faces. Both sets of results do not agree with the 14-hedra Kelvin tetrakaidecahedron model (Ref. 15), which only has 43 and 57% quadrilateral and hexagonal faces, respectively. Neither do the present results agree with the Williams (Ref. 17) and Weaire-Phelan model (Refs. 16, 18, and 22) models. The present calculations show that the 3-6-2 cell, which probably best describes the FeCrAlY foam cells, has 27 edges and 18 vertices.

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14. ABSTRACT
Establishing the geometry of foam cells is useful in developing microstructure-based acoustic and structural models. Since experimental data on the geometry of the foam cells are limited, most modeling efforts use the three-dimensional, space-filling Kelvin tetrakaidecahedron. The validity of this assumption is investigated in the present paper. Several FeCrAlY foams with relative densities varying between 3 and 15 percent and cells per mm (c.p.mm.) varying between 0.2 and 3.9 c.p.mm. were microstructurally evaluated. The number of edges per face for each foam specimen was counted by approximating the cell faces by regular polygons, where the number of cell faces measured varied between 207 and 745. The present observations revealed that 50 to 57 percent of the cell faces were pentagonal while 24 to 28 percent were quadrilateral and 15 to 22 percent were hexagonal. The present measurements are shown to be in excellent agreement with literature data. It is demonstrated that the Kelvin model, as well as other proposed theoretical models, cannot accurately describe the FeCrAlY foam cell structure. Instead, it is suggested that the ideal foam cell geometry consists of 11 faces with 3 quadrilateral, 6 pentagonal faces and 2 hexagonal faces consistent with the 3-6-2 cell.

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