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Effect of Heating Conditions on the Structural Uniformity and Collapse Stress Variability of Aluminium Foam

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In this paper, the possibility to create uniform porous structure for non-symmetric precursor heating was investigated together with changes in collapse stress and their reproducibility. The statistic relative standard deviation (RSD) of pore size was used to determine the structural uniformity. It was shown that proper adjustment of the foaming parameters leads to formation of the uniform foam structure. The compression testing showed that standard deviation of collapse stress was higher for uniform structure than those obtained for non-uniform structure.

Utjecaj uvjeta grijanja na strukturnu jednolikost i lomno naprezanje aluminijske pjene

Izvornoznanstveni članak

U ovome radu istražena je mogućnost stvaranja jednolike porozne strukture nesimetričnim zagrijavanjem prekursora, te su isto tako istražene promjene lomnog naprezanja i njihova ponovljivost. Statistička relativna standardna devijacija (RSD) veličine pora koristila se za određivanje strukturne jednolikosti. Pokazano je da pravilan odabir parametara upjenjavanja dovodi do nastajanja jednolike strukture. Tlačna proba je pokazala da je vrijednost standardne devijacije lomnog naprezanja veća za jednoličnu strukturu od onih ostvarenih za nejednoliku strukturu.

1. Introduction

Aluminium foam manufactured through the foaming of precursors containing blowing agent is created by nucleation and growth of gas pores in heated precursors, which are placed into a mold of predefined shape [1-3]. In laboratory conditions, the effect of material consolidation and composition, precursors arrangement, pre-treatment of powders, ambient atmosphere, external pressure and foaming rate on the porous structure has been studied [4-22].

However, foamable precursor is usually a profile with a given cross-section (e.g. 15 x 4 mm) and therefore, more than one precursor piece is used for the production of larger aluminium foam parts. Since they fill approximately 30 % of the mold prior to foaming and the contact surface between individual precursors and the mold is different, it is impossible to assure their uniform heating. In was shown, that the non-symmetric heating of the precursors during foaming in case of single [18] or multiple [4] precursors leads to formation of the non-uniform porous structure due to various heating rates or loss of heat transfer through developing foam.

The aim of our study was to investigate the possibility for structural modification by changing the foaming temperature and foaming time; i.e. if this simple change of manufacturing parameters can lead to elimination of non-uniform structure formation. The reproducibility of the manufacturing process, changes in porosity, collapse stress and their variation was studied.

2. Experimental

Foamable precursors of a chemical composition Al + 10 wt.% Si + 0.8 wt.% TiH_2 with a cross-section of 15 x 4 mm were supplied by an Austrian company Alulight® GmbH. Cubic samples (a = 50 mm) were manufactured using non-symmetric initial locations of the precursors in the mold, as shown in Figure 1. The mold was inserted into a furnace preheated to various temperatures of 700 °C, 735 °C and 770 °C and held until it was entirely filled with the developed foam, which was indicated by a thermocouple attached to the upper mold wall. After this, a defined time interval of 15, 30 and 45 seconds was counted, before the mold was removed from the furnace. Ten experiments were conducted for each foaming parameters.

Symbols/Oznake

RSD	- Relative Standard Deviation - Standardne relativne devijacije

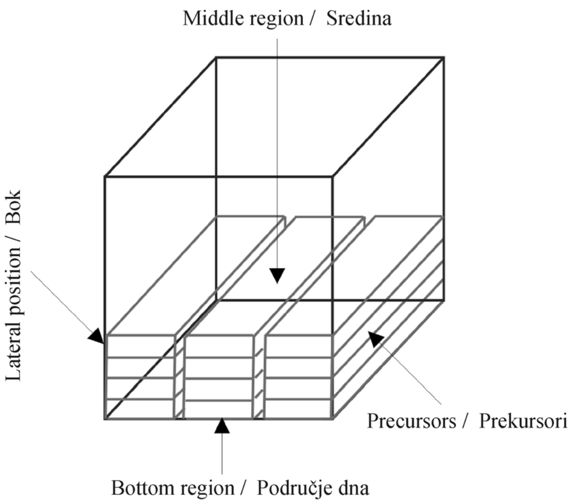

Figure 1. Non-symmetric precursor distribution in cubic mold (a = 50 mm)

Slika 1. Nesimetričan raspored prekursora u kalupu

Pore structures were revealed by cutting the solidified samples (cross-section was performed vertically in the middle of the cube; orientation of plane is perpendicular to main precursor axis) with an electro-discharge machine, painting, polishing and scanning them. This procedure assures good contrast between pore walls on the cutting edge and pores themselves. Data processing tool Image J was used to determine pore size in binarized images. Variability in pore size distribution in cross-section were then statistically evaluated using Matlab® to obtain number of pores, mean size, median, standard deviation and relative standard deviation (RSD (%)). Relative standard deviation is a ratio of standard deviation to mean value in percentage. The standard deviation is not suitable to detect the variability of pore size because the mean values of pore size are dependent on foaming conditions. The RSD was used to quantify the uniformity of the foam structure. The lower the RSD values, the lower the data dispersion and increased uniformity of the porous structure. The porosity of foam was calculated as a ratio of the sample volume to sample mass.

To consider the effect of structural uniformity on collapse stress and its dispersion, the uniaxial compression tests were performed on a 10-ton Zwick device with a preloading of 2 N and strain rate of 0.033 s^{-1}. The samples were loaded only in gravity (foaming) direction to eliminate collapse stress dispersion if loading direction is not considered during the testing [4]. The collapse stress, σ_c, was defined as the first peak stress on the stress-strain curve according to [23].

3. Results and Discussion

Figure 2 shows changes in porous structure affected by foaming temperature and foaming time. The area of small pores in the middle-top region (dashed borders) was observed for lower temperatures and with short foaming times as a result of delayed pore nucleation and their expansion in middle area [4]. A region characteristic by large pores was formed on the sides of intensive heating - bottom and lateral positions due to higher heating rate and more enhanced foaming.

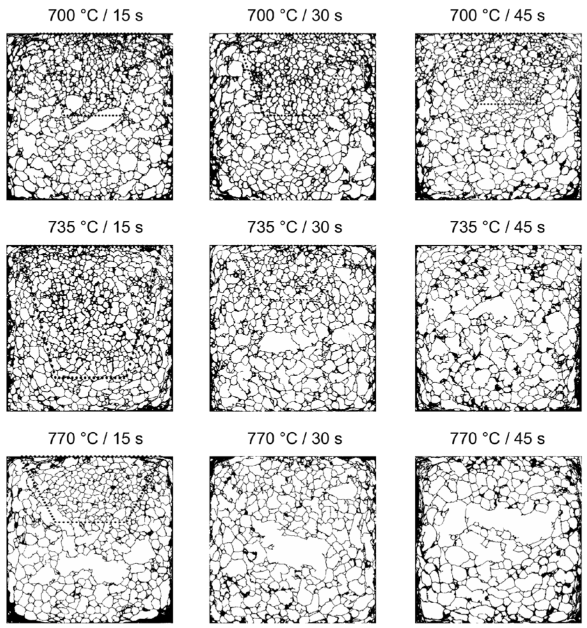

Figure 2. Effect of the foaming temperature and foaming time on the foam structure

Slika 2. Utjecaj temperature i vremena upjenjavanja na strukturu pjene

As shown in Table 1 and Figure 3, RSD increases with an increase of foaming temperature and foaming time. The lowest values of the RSD were obtained for temperature 700 °C and the highest for 770 °C, but, the minimum of the RSD was at 735 °C and 15 seconds. This implies that the medium among chosen foaming parameters assure sufficient heating conditions for all precursors in the mould, in spite of their non-uniform heating. The reason is similar heating rates and foaming onsets which assure that all the precursors expand to almost identical porosities and result formation of relatively uniform porous structure. At 770 °C, the heat transfer is sufficiently enhanced, the heating rate is significantly higher in the bottom and lateral precursors due to the large surface contact with the mold (see. Figure 1). These factors lead to the formation of large irregular pores (Figure 2) due to pore coalescence and tearing of the pore walls during intensive expansion and cooling. the case of higher porosity, a fraction of aluminium melt was impressed by expanded gases and flew out of the mold during foaming through mold leakages. Maximal porosity was attained when all TiH_2 was decomposed. The longer the foaming time, the more material was withdrawn from the mould. It should be mentioned that porosity maximum of approximately 87 % exists independently of the foaming temperature, but the time at which this maximum was achieved decreases with a drop

Table 1. Statistics of the pore size in cross-section (A (mm^2)) as a function of the foaming temperature and foaming time

Tablica 1. Statistička analiza veličine poprečnog presjeka ćelija (A(mm^2)) u funkciji temperature i vremena upjenjavanja

Foaming conditions / Uvijeti upjenjavanja	700 °C / 15 s	700 °C / 30 s	700 °C / 45 s	735 °C / 15 s	735 °C / 30 s	735 °C / 45 s	770 °C / 15 s	770 °C / 30 s	770 °C / 45 s
Number of pores /Broj pora	712	688	664	810	560	435	537	444	398
Mean	2.506	2.412	2.801	2.141	3.391	4.47	3.655	4.281	4.867
Median	1.133	1.219	1.37	1.333	1.551	1.566	1.79	1.908	1.525
STD	4.529	3.42	4.309	2.368	5.504	8.569	8.333	10.882	13.905
RSD (%)	180.74	141.76	153.84	110.61	162.32	191.71	228.03	254.22	285.66
Min	0.126	0.127	0.127	0.127	0.127	0.127	0.128	0.128	0.127
Max	67.173	35.622	43.247	18.094	60.125	99.905	145.69	207.11	232.21

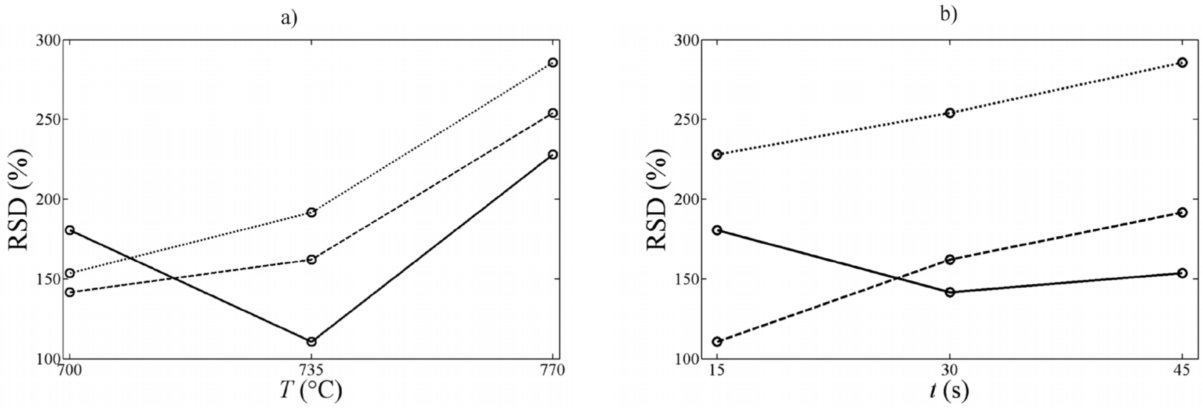

Figure 3. Relative standard deviation of pores size as a function of (a) foaming temperature (15 s (▬▬), 30 s (▬ ▬), 45 s (•••)); and (b) foaming time (700 °C (▬▬), 735 °C (▬ ▬), 770 °C (•••))

Slika 3. Relativna standardna devijacija veličine ćelija u funkciji (a) temperature upjenjavanja (15 s (▬▬), 30 s (▬ ▬), 45 s (•••)); i vremena upjenjavanja (700 °C (▬▬), 735 °C (▬ ▬), 770 °C (•••))

Table 2 shows the effect of the foaming temperature and foaming time on the foam porosity and collapse stress and their variations. It can be seen, that porosity increases with an increase of foaming time and/or foaming temperature, which is obvious [10,13,15]. The reason in this case is, that the amount of precursors in the mold prior to foaming was calculated for foam porosity of 76 % to assure sufficient filling of the mold by foam. In in temperature due to more intensive foaming. When the porosity maximum was reached, the expansion potential of the foaming agent was exhausted and the foam collapsed on cooling due to insufficient gas pressure inside the pores. The variation of the porosity decreases with a drop of the foaming temperature as a result of the increased intensity of the foaming process and more accurate amount of evolved hydrogen for several experiments.

Table 2. Effect of the foaming temperature and foaming time on the foam porosity, collapse stress and their dispersion

Tablica 2. Utjecaj temperature i vremena upjenjavanja na porozitet pjene, lomno naprezanje i njihovo rasipanje

Foaming temperature/ Foaming time Temperatura upjenjavanja / Vrijeme upjenjavanja	Porosity / Poroznost, %	RSD, %	Collapse stress / Prekidno naprezanje, MPa	RSD, %
700 °C / 15 s	77.8 ± 1.30	1.67	8.16 ± 0.95	11.6
700 °C / 30 s	80.3 ± 0.87	1.09	6.95 ± 0.57	8.20
700 °C / 45 s	85.6 ± 0.86	1.01	4.12 ± 0.46	11.1
735 °C / 15 s	83.0 ± 0.61	0.74	5.47 ± 0.46	8.42
735 °C / 30 s	86.4 ± 0.59	0.68	4.14 ± 0.36	8.78
735 °C / 45 s	87.3 ± 0.48	0.56	3.49 ± 0.29	8.45
770 °C / 15 s	84.1 ± 0.24	0.28	4.87 ± 0.13	2.59
770 °C / 30 s	87.1 ± 0.21	0.24	3.59 ± 0.17	4.70
770 °C / 45 s	86.5 ± 0.25	0.29	3.16 ± 0.25	8.02

The collapse stress and its dispersion were affected by manufacturing parameters, mainly because they influenced the final foam porosity. The collapse stress was higher in the case of the lower porosities, which was previously explained by more material acting against the applied load during compression [12,24-27]. The lowest collapse stress RSD of 2.59 % was found for a non-uniform structure with presence of structural defects foamed at 770 °C and 15 s. Collapse stress RSD for uniform structure foamed at 735 °C and 15 s is 8.42 %. This observation suggests that the reproducibility of the collapse stress is significantly affected mainly by the presence of structural defects, because the foam predominantly deforms in those areas [12,25]. The defects include: local porosity maxima, structural inhomogeneities as large pores, pore elasticity, cell wall defects like curvature, corrugations, cracks and holes [28-31]. Since foam manufactured at 770 °C (Figure 2) always contains large irregular pores due to heating conditions applied on foaming, the reproducibility is high. On the other hand, there is no presence of high structural variability within the foam structure in case of uniform structure (735 °C and 15 s), and therefore, RSD of the collapse stress is higher. In the case of the presence of small pore size structures foamed at 700 °C, deformation is even stochastic and RSD is the highest.

4. Conclusion

The effect of foaming conditions on pore size distribution in foam volume, porosity and collapse stress and their dispersion is discussed in this paper. The pore size relative standard deviation (RSD) was used to determine the structural uniformity of the foam by evaluation of the distribution of pore size in volume; the lower the RSD values, the lower the RSD values, the more uniform the pore structure is. It was shown that proper adjustment of the foaming temperature and foaming time result in the creation of the uniform foam structure even, if the foamable precursors are not-symmetrically heated in the mold. The presence of inhomogeneities in foam structure (such as large irregular pore) is responsible for pre-mature yielding and results in good reproducibility of the collapse stress.

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