IRREVERSIBLE THERMAL EXPANSION OF REPLICATED ALUMINIUM FOAM

*Arkady Finkelstein[1], Dmitry Husnullin[1] ***
[1] *Ural Federal University, Institute of New Materials and Technologies*, Yekaterinburg, Russia

Abstract
Irreversible thermal expansion of large items made of the replicated aluminium foam was detected during the extraction of soluble filler from Al-NaCl composite. Sources of the phenomenon were investigated The expansion discovered was caused by incomplete contraction of the porous metal due to the oxidation of its internal porous surface in air and water mediums during thermal cycling. Significant influence of oxide film defects on the expansion process was shown. The information about irreversible thermal expansion dependence on temperature of the extraction process and metal foam pore size was collected. Measurements of expansion dynamics showed its finite character. It was also noted that the expansion is limited by the thermal expansion coefficient of an alloy used. Finally, correction coefficients were obtained that, being applied to nominal sizes of a porous item, compensates the expansion.

Keywords: aluminium, replicated foam, alumina film, micro-cracks, contraction, thermal expansion

1   Introduction

The effect of irreversible three-dimensional expansion of items was detected at the stage of soluble filler extraction during the manufacturing process of commercial replicated aluminum foam at Composite Materials LLC (Kirovgrad, Russia) [1]. Replicated aluminum foam technology involves mechanical treatment to final shape before the filler dissolving from the casting body. This treatment was applied during the process of mold fabrication for expandable polystyrene (EPS) molding with an overall dimension of 850 mm. Control measurement, performed by the customer, showed the overall dimension of 854 mm, not 850 mm, and the product was rejected. It was checked that the dimensional non-compliance was not a mistake at the machining process but the consequence of the filler extraction in accordance with the adopted manufacture technology.

The case of the expansion was not identified by the other researchers of the replicated aluminum foam technology [2, 3, 4, 5] due to insignificant sizes of laboratory specimens (not over 200 mm). In this case extraction of the filler is not a difficult task and may be realized within the mode of water external convection at room temperature. Such extraction process is ineffective if sizes of a casting are large, as mentioned above. Non-soluble aluminum hydroxide is formed in the pores while casting is immersed into water for a long time. The hydroxide blocks the process of the filler extraction. A casting is to be heated up to 200-300°C before immersion into the water in order to form a gap between the metal surface and the filler particles [5].Also formation of the gap is used for acceleration of wax model removing from the ceramic molds in the investment casting process [6].

Dimensional correction of the oversized item by additional machining stage after extraction is not commercially efficient. Much more rational approach is to investigate the phenomenon, obtain the data on relative expansion and take it into account during the machining process in such a way that parts will be irreversibly expended up to the required dimensions after the filler extraction.

It was assumed that the irreversible thermal expansion was conditioned by hindered thermal contraction of casting due the growth of the oxide film as a result of thermal cycling and oxidation during the filler extraction. It is the main hypothesis relative to reason of considered phenomenon.

2   Materials and Methods

Proposed hypothesis was tested on specimens heated in a furnace with air and vacuum medium with further measuring of their elongation. Two sets (each 2 pcs.) of specimens were prepared according to technique of [5, 7]. The specimens are square cross-section bars made of replicated aluminium (**Fig. 1**). 290 mm is a control dimension. The filler fraction of 0.315-0.63 mm was used for specimen preparation. The bar length was determined by the dimensions of an operating chamber of the heating furnace applied. The material of specimens is AlSi7 (A 356) which is usually utilized in industrial production of cast replicated aluminium. Actual alloy chemical composition, measured at Argon-5SF spectrometer (Spectrosoft LLC, Moscow), is given in **Table 1**.
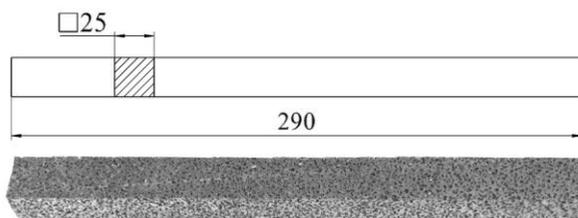

Fig. 1   Specimen

Table 1 Chemical composition of used alloy

Element	Al	Si	Mn	Fe	Cu	Mg
Wt.[%]	Balance	8.1	0.11	1.49	0.3	0.21

To heat specimens in vacuum medium vacuum chamber resistance furnace SNV 1-3-1/15I1 was used, with operating pressure of 0.00665 Pa, produced by Moscow Plant of vacuum electric furnaces. Remaining experiments were conducted in air medium with muffle furnace SNOL made by Nakal LLC (Moscow).

The specimens were heated up to 300°C for 30 minutes. Thereafter, they were cooled down to 20°C in the furnace. The vacuum level in the furnace was equal to 0.01 Pa. There were three cycles performed. Experiments in air medium were conducted in the same manner.

The measurement of the specimen control dimension after cooling to room temperature was performed by a digital calliper ShCC-Sh-500 GOST 166-89 by Chelyabinsk Tool Plant, with 0.04 mm error. Taking into account possible misalignment of the specimen between the calliper jaws, the control dimension was measured from two sides. Two obtained values were averaged.

Further, in order to determine "reverse allowance" value the research, simulating the technological process of filler extraction, was conducted. All the filler fractions, involved in production, were utilized in the experiment: 0.16-0.315 mm, 0.315-0.63 mm, 0.63-1.6 mm, 1.6-3 mm. The number of "heating-cooling" cycles and the end of the experiment was determined by the end of considerable growth of the control dimension. The experiments were performed at heating temperatures of 200 and 300°C. Other parameters of the experiment were the same as those for testing of the irreversible thermal expansion hypothesis.

3   Results and Discussion

The results of identification of irreversible thermal expansion reason are given in **Table 2**.
Observing the absence of irreversible thermal expansion of the specimens under heating in vacuum, one can convincingly say about correctness of the proposal made: the explanation of this phenomenon is incomplete thermal contraction of the replicated foam. Being heated to the temperature up to 300°C, a casting will expend according to the thermal expansion coefficient (23.4 $10^{-6}K^{-1}$ in the mentioned temperature range [8]) by 0.7%. This is an ultimate value of irreversible thermal expansion for the mentioned temperature. Compression will take place under air cooling but not to the initial size.

Table 2 Irreversible thermal expansion of replicated aluminium foam after three cycles

Thermal cycling mode	Specimen # 1			Specimen # 2			Average relative expansion, %
	Dimension before extraction, mm	Dimension after extraction, mm	Relative elongation, %	Dimension before extraction, mm	Dimension after extraction, mm	Relative elongation, %	
Vacuum	289.98	289.98	0.00	290.00	290.00	0.00	0.00
Air	289.95	290.55	0.21	289.90	290.50	0.21	0.21

The entire metal foam inner surface is coated by oxide film which is amorphous aluminium oxide within 300°C [9, 10]. In the process of thermal expansion due to deformation cracks will occur [11-15, 20] in the amorphous alumina film (**Fig. 2**). The oxide will be regenerated in the cracks. It will cause the resistance to reverse compression during cooling. The possibility of the oxide formation in the cracks is determined by the open nature of a crack that reaches the metal matrix.
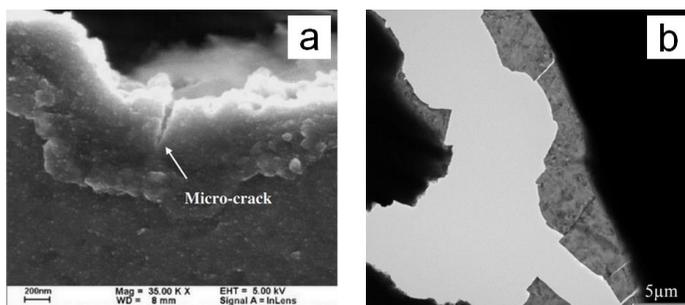

Fig. 2   Cracks in the oxide film: A – [11, 12]; B – [13]

The experimental dynamics of the irreversible thermal expansion of a "metal-filler" composite during filler extraction imitation process per cycles is presented in **Fig. 3** and **Fig. 4**. As thickness of the oxide film is growing, the crack healing becomes more and more difficult. The shape of produced curves completely corresponds to the power law of oxide films growth [16].
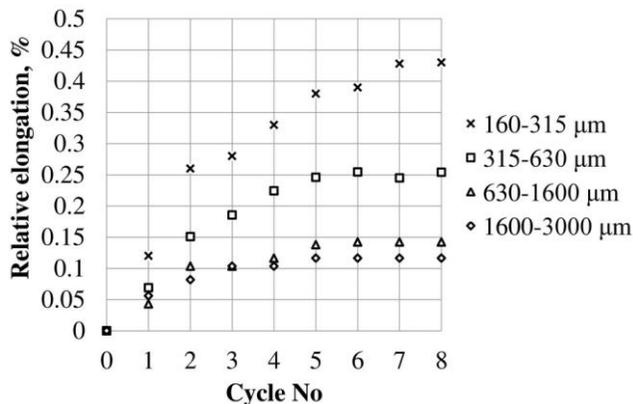
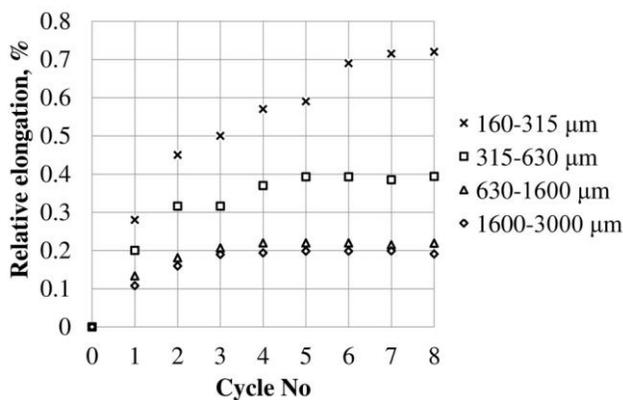**Fig. 3**   Relative elongation of specimens at heating temperature 200°C

Fig. 4   Relative elongation of specimens at heating temperature 300°C

The hindered contraction factor as the relation of specimen elongation to the metal thermal expansion was offered to be used as a criterion of porous metal irreversible thermal expansion (**Table 3**). In the case of hindered contraction metal matrix of the material is in stressed condition after cooling. Further heating will relax the stresses, but the dimensions of an item will not grow up beyond the thermal expansion level of an alloy used, i.e. this level is an asymptote for irreversible thermal expansion.

The hindered contraction factor, as shown in **Table 3**, does not depend on the heating temperature and will be determined by the filler fraction only, i.e. the specific surface of the porous metal the oxide film grows on.

Table 3 Irreversible thermal expansion of replicated aluminium foam after three cycles

Filler fraction, mm	Heating temperature, ºC	Elongation, %	Maximum thermal expansion, %	Hindered contraction factor, %.
0.16-0.315	200	0.41	0.45	91.11
0.16-0.315	300	0.70	0.70	100.00
0.315-0.63	200	0.25	0.45	55.56
0.315-0.63	300	0.39	0.70	55.71
0.63-1.6	200	0.14	0.45	31.11
0.63-1.6	300	0.22	0.70	31.43
1.6-3	200	0.12	0.45	26.67
1.6-3	300	0.21	0.70	30.00

The dependence of relative irreversible elongation on the specific surface of porous structure which is theoretically calculated in [5] is given in **Fig. 5**. The linear dependence of relative elongation on the specific surface is quite evident that may be explained by the uniform distribution of the cracks on the oxide film surface.
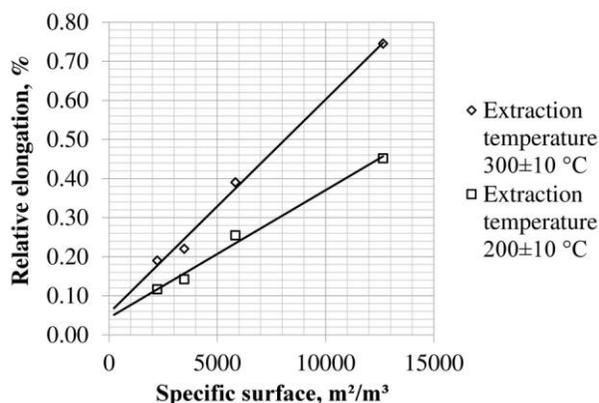
Fig. 5   Dependence of relative elongation on specific surface of replicated aluminium.

Comparison of replicated aluminium thermal cycling results in air medium (**Table 2**) and imitation of the filler extraction process (**Fig. 3**) shows additional effect of water vapour and sodium chloride ions on the oxide film growth. It leads to more intensive crack formation and healing and, consequently, increases the hindered contraction factor that in agreement with known data on aluminium oxidation and corrosion [17-20].

Conclusions

Irreversible thermal expansion of cast replicated aluminium has been found. It is proved that this phenomenon is caused by cracking and healing of oxide films on the "metal-air" interface under cyclic heating. The hindered contraction factor as the relation of the irreversible thermal expansion to the total thermal expansion of an alloy was proposed to be used as a criterion of the phenomenon. It is proved that hindered contraction factor is a function of specific surface only.

The value of "reverse allowance" for controlled irreversible thermal expansion of the items in the process of filler extraction is calculated on the basis of hindered contraction factors in terms of production operations at Composite Materials LLC.

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