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Improvement of the foaming process for 4045 and 6061 aluminium foams by using the Taguchi methodology

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Abstract Taguchi methodology has been applied to the production process of aluminium foams to investigate the variability detected in several properties (including bulk density, outward appearance and density homogeneity along foaming direction), for foaming tests carried out under identical conditions. The analysis of the process has been performed separately for two different alloys, the 4045 and 6061. The results have allowed finding the main factors that influence those properties. In addition, it has been possible to establish those foaming conditions able to minimize the variability in density, to improve the outward appearance and to obtain a higher homogeneity in density, all at the same time. Different final factors have been found for the two alloys; such differences have been explained in terms of the different viscosity of the aluminium melts as well as the different content of foaming agent.

Introduction

Aluminium foams are unconventional materials, which have been deeply investigated in the last 10 years. It is possible to obtain metal foams by several techniques, reaching open cell or closed cell metal foams according to the production route [1]. One of the most investigated and with most possibilities of industrialization is the Powder Metallurgical (PM) route [2, 3]. This is because PM closed-cell metal foams can be produced with relatively low cost and the final foam part can be fabricated with the final shape required for the specific application (3D foaming) [4, 5].

The PM route is a batch process in which a precursor material (fabricated from sintered powders of an aluminium alloy mixed with a foaming agent) is introduced into a mould, which is heated at temperatures above the melting point of the aluminium alloy to promote foaming. Once the foam fills the mould and starts to overflow, it is extracted and quickly cooled to avoid collapse. Finally, the foam part is extracted from the mould.

This apparent simply method is influenced by a high number of factors (mould and precursor geometry, foaming temperature, number of precursors, etc.) which can affect the foaming stage, resulting in samples with different bulk density or density distribution along foaming direction and/or external defects among other remarkable differences in the cellular structure. Even if a special care is taken in the production, sensible differences in these and other properties can be found for foaming trials performed under identical conditions.

Although the quality of the materials produced within this technique has been greatly improved in the last years, there are still aspects in which more development is necessary; a more homogeneous internal cell architecture is required, a higher homogeneity in density seems to be necessary and a better outward appearance is demanded [6, 7]. These topics are mainly associated to the *foaming stage* of the PM route which has been investigated by several techniques such as laser or mechanical expandometers [8], computed

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tomography using synchrotron radiation [9], neutron radioscopy [10] and ultra small-angle neutron scattering [11].

The difficulties associated to the metal foam production involve the stochastic nature of the process where drainage and pore coarsening are the most studied phenomena [12–14]. In addition, some interesting studies regarding the cooling conditions [15], changes in porosity of foamed aluminium during the solidification [16] and the control of foaming characteristics during production of foams [17] have been carried out.

All these previous studies are focused on the physical–chemical mechanisms of foaming. This paper takes a different point of view using for the first time a specific design of experiments technique (Taguchi method) to systematically analyse the foaming stage of the PM route and the factors involved in this process. As far as we know, this approach has not been previously applied in the field of metal foams processing.

Taguchi method can be of great help to improve the quality of processes in which the performance depends on many factors [18–20]. It can be used to obtain the best parameters for the improvement of a given process with the least number of experiments. It also allows the design of robust methods, processes or systems, i.e., insensitive to external factors and operators.

This article presents the application of the Taguchi method to the foaming stage of the PM route for the production of aluminium foams. The main aim of the paper is to reach quantitative data about the influence of the different foaming factors on the foam quality.

Materials

Two different alloys 4045 -AlSi10- and 6061 -AlSi0·6Mg1- have been employed. They differed in the foaming agent content: a 0.8% and a 0.4% in weight of TiH_2 was added to the AlSi10 and AlSi0·6Mg1 alloys, respectively. Foam precursors were produced by the Alulight Company (Austria). Powders of the different alloying elements were homogeneously mixed with titanium hydride. Subsequently, this powder was directly extruded in rectangular rods of dimensions $5 \times 20 \times 500$ mm^3 by the Conform method, which could be cut at the desired length according to the mould geometry.

Experimental

The Taguchi method

The Taguchi method is a Powerful statistical technique compute the relative influence of many factors on a given process, so the optimum conditions can be achieved with the least number of trials [21–23]. One more advantage of this method is the robustness the process achieves after the study; it gets almost insensitive to external factors and daily environmental variations.

Taguchi methodology was followed in order to analyse the different properties of aluminium foams produced under similar conditions. The general steps for implementing this kind of experimental design are:

Step-1: To define clearly the problem to be solved.
Step-2: To select the measurable variables that will be the quality characteristics to be improved.
Step-3: To identify all the control and noise factors that may influence on the output variables previously selected.
Step-4: To choose the levels of the factors to be tested.
Step-5: According to the previous analysis, to select the adequate inner and outer orthogonal arrays.
Step-6: To perform the experiments.
Step-7: To carry out a statistical analysis of the data and the signal to noise (*S*/*N*) ratio analysis to determine the best combination of factor levels.
Step-8: To conduct a confirmatory experiment.

It is important to remark that these steps will be developed in this paper as sub-sections inside the ‘‘Experimental’’, ‘‘Analysis and results’’ ‘‘Discussion’’ and ‘‘Conclusions’’ sections. Additionally, before following all these steps it is necessary to deeply *describe the process* and determine the *status quo* to later quantify the improvement achieved with the applied Taguchi method.

Description of the foaming process

To prepare the foams, pieces of the originally 500 mm length precursors are cut an introduced into a stainless steel mould. In this work prismatic moulds with a thickness of 1.5 mm have been selected. The foam density is controlled by the weight of precursor material introduced into the mould; it is necessary to take into account the metal lost during foaming due to the overflow of molten aluminium when the mould is filled.

The mould is covered internally with a water-based semi-colloidal graphite releasing coating for each foaming. The releasing product used has been a Foseco Company’s product commercialized with the name Dycote E11. It was usually mixed with water in a proportion from 1:2 to 1:10. This releasing agent was used to obtain an easy releasing of the foamed part from the mould, a better outward appearance and also to improve the heat transfer.

Once the mould is coated and a certain number of pieces of precursor have been introduced, the mould is screwed down and introduced into the furnace. The mould showed an elongated shape with wide/length in proportions 1:2 aprox. For this reason, foaming can be carried out in both horizontal or in vertical position as appreciated in Fig. 1. As a general rule, the shape of the precursor/s should be similar to that of the mould.

The temperature of the furnace has been usually set between 675 °C and 775 °C, according to the melting point of the alloy to be foamed. The air circulation furnace was modified by inserting a small window allowing to monitor the foaming progress by visual inspection. This way, the operator can see how the foamed part becomes darker compared to the upper part of the mould which looks brighter and redder. Five to ten seconds after the whole mould gets dark, molten aluminium starts to overflow. For this reason, an overflowing drilled hole can be used—or not—in the top part of the mould (Fig. 1a, b) to allow a controlled overflowing only trough this hole. The mould can be extracted from the furnace when it gets dark or when the overflowing starts.

Finally, the mould is cooled with compressed air, which can be mixed with water, by using a spraying gun. Once cooled, the foam is extracted from the mould with a rubber hammer to avoid damage of the foam surface.

Previous situation (status quo)

The foaming procedure described before has been obtained in our laboratory by trial-error method, having tuned it during approximately one year. Nevertheless, in spite of our efforts, some inaccuracies were observed. For instance, in some cases the fabricated foams did not have the expected density, showing differences up to 15% from the required density. In addition, a 20% of low density foams (lower than 0.45 g/cm^3) presented collapsed zones; and many of them did not present good enough surface quality. In some cases, several trials were necessary to obtain acceptable foams when foaming conditions were changed. All these facts lead us to apply the Taguchi methodology to the foaming stage of the aluminium foaming PM route to improve its robustness and to obtain foams with better quality.

The section ''*Assignment of level for the control and noise factors* (Step-3)'', will explain additional results for the *status quo* of the foaming process. They are not shown within this section because it is necessary to further understand the problems to be solved and the way they are evaluated as well as to clearly define the quality characteristics to be improved.

Definition of the problem to be solved and variables to be improved (Step-1 and Step-2)

The first problem to be solved is to reduce the variability of the bulk density of the foam parts fabricated under the same conditions. Desired density was fixed to 0.55 g/cm^3. Additionally, other two important variables were introduced in the Taguchi test: the homogeneity in density and the outward appearance of the foam produced. The homogeneity in density was defined quantitatively as density gradient from the bottom part to the upper part of the foam (∇_{1-3}), cutting the foam in three sections according to the foaming direction. The outward appearance of the foam produced, was evaluated under four different criteria—i.e. surface roughness, presence of slightly collapsed zones, union of the different precursor pieces and presence of several phases. All these four criteria for the outward appearance were numerically defined with values from zero (very bad) to four (very good). Typical defects of the outward skin are illustrated in Fig. 2. Figure 2a shows an outer skin presenting several phases and a certain degree of surface roughness. Figure 2b, shows non-well joined precursors in the final foam and a collapsed zone.

Three different variables or quality characteristics to be improved have been included in this experimental design and (Table 1). All of them were considered of the same importance for the final evaluation.

Finally, it is important to remark that Taguchi methodology has been applied to both alloys separately, i.e. two different studies have been performed, one for each alloy.

Identification of control and noise factors (Step-3)

According to Taguchi method, it is necessary to create a discussion group to share the ideas and choose the most descriptive steps and variables of the foaming process. It is frequently carried out by means of a brainstorming

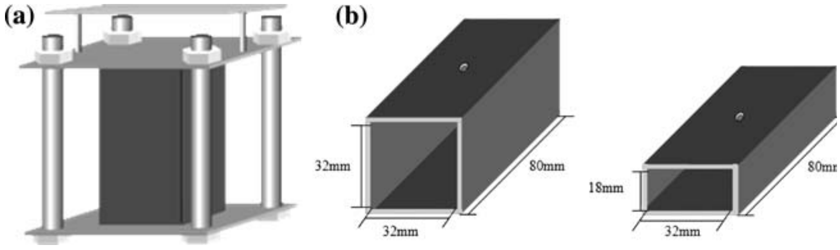

Fig. 1 (**a**) Schematic drawing for the vertical foaming configuration without any overflowing hole. (**b**) Schematic drawing of the two mould geometries for the horizontal foaming position with a top overflowing hole

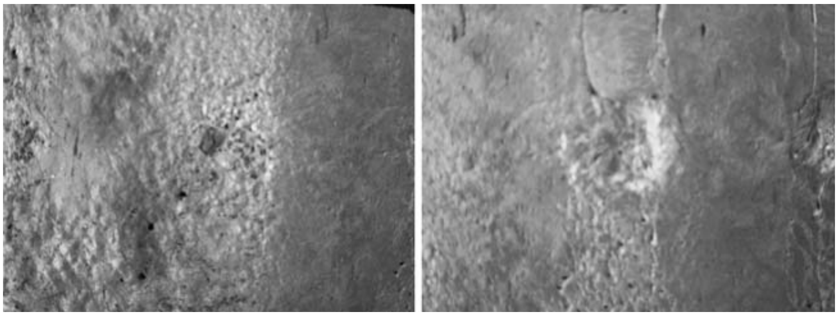

Fig. 2 Typical defects in the aluminium foam outward skin

Table 1 Quality characteristics to be improved

Final density of 0.55 g/cm^3 with minimum variability
Minimum density gradient from bottom to top
Maximum surface quality

procedure and subsequently all steps and possible influences are discussed and some of them are disregarded.

Foaming process was divided into 8 steps as depicted in the flowchart of Fig. 3.

Once the steps in the process have been established, the different factors that could affect each step have been identified. Then, some of them have been selected as *control factors* which are *those that can be controlled during the experimentation*. Some examples would be the foaming temperature, the weight loss assumed or the horizontal/vertical foaming position. Due to the high number of control factors, the Taguchi design was simplified by fixing some of the factors at a fixed value denoted by ''* *'' in Table 2.

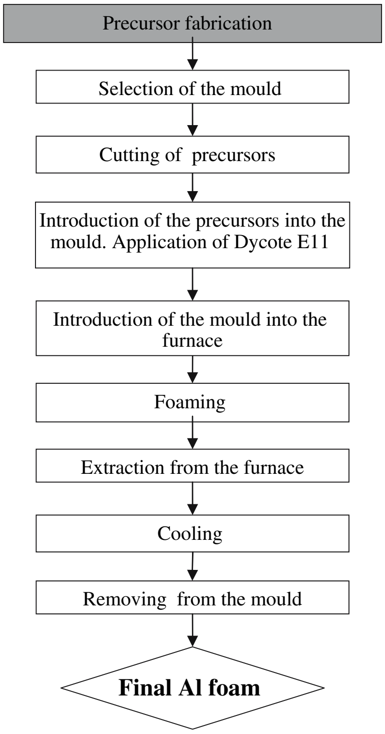

Fig. 3 Schematic flowchart of the foaming process (influence of the first grey box is not considered in this Taguchi experiment). The precursors were supplied by Alulight

Two classes of *noise factors* have also been identified. First class includes those noise factors that *cannot be controlled*, for instance; unintentional shaking of the mould before introducing the foam in the furnace or human errors. Second class correspond to factors that, although they *could be controlled*, usually they are not, because such control would make very difficult (*impractical*) the foaming process. Examples are strength of the screwing; the time elapsed between successive foaming tryals, etc. The main objective of this classification is to obtain a process, which gives results independent of the previous noise factors.

The variability introduced by the noise factors can be simulated by considering two noise levels. This allows studying the signal-to-noise (*S*/*N*) ratio, which in turn permits the reduction of the variability of the results.

Assignment of levels for the control and noise factors (Step-4)

Once control and noise factors are classified, it is necessary to make some preliminary tests to choose the adequate levels. The purpose was to obtain foams with density 0.55 g/cm^3 assuming a weight loss of 15% and trying to reach a high homogeneity in density along the foaming direction as well as good external appearance. Foaming temperatures for these experiments were 700 °C for 4045 alloy and 750 °C for 6061 alloy (the melting points for 4045 and 6061 are, respectively 599 and 652 °C).

Figure 4 presents the densities and the outward appearance scores for the three foams fabricated from each alloy. The differences in density obtained as well as the different outer skin quality could be clearly appreciated. Additionally, the average density gradient obtained was 0.15(g/cm^3)/cm for 6061 alloy and 0.42(g/cm^3)/cm for 4045 alloy.

Table 2 Factors involved in each foaming step

Steps of the process	Control factors	Noise factors
Selection of the mould	*Base material (stainless steel)*	New/old mould
	Thickness of the mould (1.5 mm)	Plain/twisted metal lids
	Mould geometry (MG)	
	Number of overflowing holes (NH)	
Precursors are cut	Precursor geometry (PG)	
	Number of pieces (NP)	
	% of Loss weight assumed (LW)	
Introducing precursor into the mould and application of Dycote E11	*Kind of releasing product (Dycote E11)*	Quantity of Dycote applied
	% dycote/water (D/W)	Hard/soft screwing of the mould
	Contact with the mould wall (CW)	
Introducing the mould into the furnace	Vertical/horizontal (H/V)	Possible unintentional shaking of the mould
Foaming	Furnace temperature (FT)	Elapsed time between successive foaming
Extraction from the furnace	Moment of moulding extraction (ME)	
Cooling	Kind of cooling (KC)	Lifted/laying mould during the cooling
		Cooling gun distance
Removing from the mould		Light or hard hammering

* * Fixed control factors, i.e. only one level will be used

These results made necessary to carry out secondary tests for 4045 alloy assuming a higher weight loss as it is shown in Table 3. For 6061 alloy levels selected were higher and lower than 15%.

The final levels chosen for control factors are presented in Table 3. As it can be observed three control factors were fixed to only 1 level because a stainless steel mould with 1.5 mm thickness and Dycote E11 as releasing agent are the most frequently used.

Some additional comments are required to further understand the levels and factors exhibited in Table 3.

- Mould geometry and precursor geometry were selected because of the possible influence of the aspect ratio of the precursor compared to the mould where it is foamed (Fig. 1). Actually, when only a precursor is used, the precursor geometry is similar to that of the mould. For this reason, precursor geometry was large/short (see explanation of this term just below Table 3).
- The minimum number of pieces of precursor compatible to both types of precursor geometries were three, the maximum number of pieces compatible to the geometry and to the fixed density were four.
- Different values for weight loss were set for the two alloys, according to previous results. In a same way, furnace temperature levels were chosen taking into account the two melting points reported before. Values for the furnace temperature were values over the melting point of the alloy.
- The contact of the precursors with the mould was considered important to obtain good outward appearance and for this reason it was introduced in the design.

The two noise levels are collected in Table 4. The first one corresponds to a combination of factor levels in which the foaming is performed under better conditions. In level 2 noise effects are provoked to obtain the required information in the study of the *S*/*N* ratio.

Selection of the orthogonal array (Step-5)

Fourteen control factors, 11 of them at two levels containing 11 degrees of freedom give as result 2^{11} different

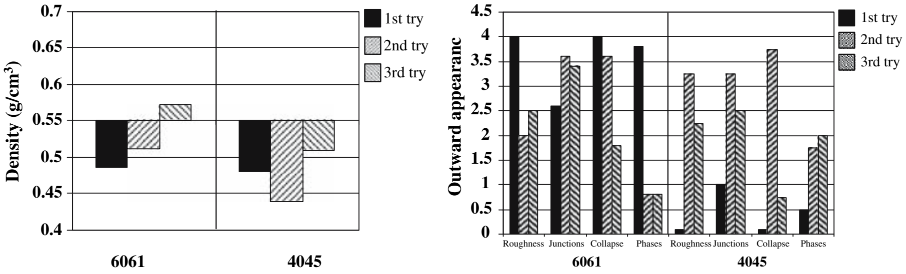

Fig. 4 Density and surface quality scores obtained in the initial tests

Table 3 Control factors and levels chosen

Control factors	Level 1	Level 2
Fixed factors		
Base material (stainless steel)	Stainless steel	
Thickness of the mould (1.5 mm)	1.5 mm	
Kind of releasing product (Dycote E11)	Dycote E11	
Two-level factors		
Mould geometry (MG)	Squared prismatic based	Rectangular prismatic based
Number of overflowing holes (NH)	0	1
Precursor geometry (PG)[a]	Long	Short
Number of pieces of precursor (NP)	3	4
% of weight loss assumed (LW)	10% for 6061 22% for 4045	17% for 6061 30% for 4045
Dycote/water (D/W)	1:5	1:8
Contact with the mould (CM)	Maximum	Random
Vertical/horizontal (H/V)	Vertical	Horizontal
Furnace temperature (FT)	+100 °C	+120 °C
Moment of moulding extraction (ME)	Overflowing	Black mould
Kind of cooling (KC)	Compressed air	Water spraying

* * Fixed control factors, i.e. only one level was used

[a] Term ‘‘*long*’’ indicates it is longer than 2/3 of the total length of the mould, meanwhile the precursor is ‘‘*short*’’ means it is smaller than 2/3 of the mould total length

Table 4 Noise levels

Noise factors	Level 1 (optimum)	Level 2
Internal surface of the mould	Used mould	Unused mould
Mould screwing	Tighten	Not tighten
Quantity of Dycote applied	normal	More than usual
Possible un-deliberated shaking of the mould	No	Slight
Elapsed time between foaming tests	15 min	20 min
Laying of the mould during the cooling	Lifted	Layed
Cooling gun distance	Near	Far
Removing from the mould	Light hammering	Hard hammering

possible experiments. It is possible to choose a representative simplified collection of experiments. An orthogonal array named $L_{12}(2^{11})$ was selected, reducing the 2^{11} possible tests to only 12. This array is presented in Table 5 where horizontal lines contain the conditions in which the 12 experiments were performed. In the table the levels for each factor (level 1 or 2 according to Table 3) are given. As an example, for the experiment 1(first horizontal line) all the control factor took the level 1. Additionally, the Taguchi method is designed to obtain a more robust process by analysing the signal to noise ratio (*S/N* analysis), in order to do that 12 + 12 experiments are necessary: 12 according to the L_{12} array with the ‘‘good’’ noise and 12 more with the same array but with ‘‘bad’’ noise were carried out. This way the L_{12} array is named the inner array meanwhile the noise factors are included as an outer array, which duplicates the number of experiments. A total of 24 foaming tests for each alloy, i.e. 48 for the two alloys, were carried out.

Analysis and results

Analysis of the experimental data (Step-6)

Once all foams were produced, the bulk density was measured. Subsequently, their outward appearance was evaluated according to previously explained characteristics by five different ‘‘internal referees’’ and then scores were averaged. Finally, foams were cut into three pieces along their foaming direction and they were weighted and measured to obtain their density. The density gradient from the bottom foam (part-1) to the top foam (part-3) was calculated ∇_{1-3}.

For each quality characteristic, two analyses were carried out. The first one, *Analysis of the average quality characteristics*, indicates the most influencing variables in the foams properties. The second is the *analysis of the S/N ratio*, which allows selecting the most appropriate levels to improve the quality characteristics.

Table 5 Control levels used in the 12 experiments as shorten sample of the 2^{11} possible ones

Experiment number	Level number										
	1	2	3	4	5	6	7	8	9	10	11
$L_{12}(2^{11})$											
1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	2	2	2	2	2	2
3	1	1	2	2	2	1	1	1	2	2	2
4	1	2	1	2	2	1	2	2	1	1	2
5	1	2	2	1	2	2	1	2	1	2	1
6	1	2	2	2	1	2	2	1	2	1	1
7	2	1	2	2	1	1	2	2	1	2	1
8	2	1	2	1	2	2	2	1	1	1	2
9	2	1	1	2	2	2	1	2	2	1	1
10	2	2	2	1	1	1	1	2	2	1	2
11	2	2	1	2	1	2	1	1	1	2	2
12	2	2	1	1	2	1	1	2	2	2	1

Taguchi is a partial factorial experiment. Since it is a shorten sample of the full experimentation, a confidence analysis must be performed to set the certainty bonds. In this work, the Analysis of Variance (ANOVA) was used to carry out a confidence analysis of the results [21]. The contribution of each control factor to the three characteristics is determined within the confidence limits when ANOVA is developed. Moreover, not only the variance given by control and noise factors but also, the most robust conditions can be identified by understanding the source and magnitude of such variance. Then, a selection of the control factor levels with a higher *S/N* ratio value has to be made to achieve a more robust performance. When the contribution of a control factor is small, its contribution may be disregarded by a pooling process [21, 23]. More worthy information is thus shown because only important factors are seen apart from insignificant factors.

In our case, all influences initially lower than 3% were disregarded in the *percentage of influence analysis* and in *the S/N ratio analysis*. In Tables 6 and 7, pooled values are shown as a broken line. Although after the pooling, some factors that showed initial influence over 3% presented a value lower than 3%, they were not disregarded. Tables 6 and 7 are presented showing the residual error accumulated after the pooling and the total percentage of contribution of the not disregarded factors.

Analysis of the average quality characteristics

The ANOVA results for the three selected characteristics: influence on density 0.55 g/cm^3, density gradient and outward appearance are shown in Table 6. It is important to consider that the average values presented in the last column are the values giving a statistical weight of 1/3 to the three studied properties, taking into account that *the external appearance* is a four-parameter index with individual weights of 1/12.

The most influential factor for both the 6061 and 4045 alloys is the foaming position with 28% and 36% influence, respectively. This factor deals mainly with a determinant influence for the density gradient in both alloys. The second most important factor—15% and 17%, respectively—is the mould geometry showing again similar influencing percentages for both alloys. The effect of mould geometry seems to affect mainly to those parameters related to the outward appearance, and more specifically to the roughness and the collapsed zones. It is important to remark that only two foaming parameters influence more than 40% on the selected quality characteristics.

On the other hand, the third most influential factor is not the same for both alloys. For 6061 alloy, the precursor geometry, which is closely related to mould geometry, is the third most influential factor, meanwhile for 4045 alloy it is the number of overflowing holes.

The cumulative influential percentage of the other eight non-mentioned foaming parameters is not higher than 45% for both alloys. Additionally, it is also important to consider the low average residual error after the pooling for 6061 alloys, which is fairly higher for 4045 alloy.

Finally, it is important to remark that one of the factors that was expected to have an important influence in the final characteristics of the alloys (the contact of the precursors with the mould), had a negligible influence.

Analysis of the S/N ratio

The main objective of this work was to reduce the variability of the results for experiments performed under the

Table 6 Percentage of influence for control factor on each characteristic as results for the *analysis of average quality*

	Density	∇_{1-3}	Roughness	Unions	Collapse	Phases	Average
6061							
Mould geometry (MG)	11.49	4.69	45.60	8.01	43.12	21.12	15.21
Number of overflowing holes (NH)	7.93	–	–	3.31	–	3.03	3.17
Precursor geometry (PG)	6.89	1.94	25.55	33.38	30.76	4.54	10.80
Number of pieces of precursor (NP)	14.58	–	6.08	9.99	1.96	7.34	6.97
% of weight loss assumed (LW)	7.67	5.80	6.08	–	–	7.34	5.61
Dycote/water (D/W)	5.93	9.85	–	–	8.64	–	5.98
Contact with the mould (CM)	6.64	7.39	–	–	–	–	4.68
Vertical/horizontal (H/V)	9.63	58.55	–	13.36	–	52.01	28.17
Furnace temperature (FT)	16.08	–	–	23.04	–	–	7.28
Moment of moulding extraction (ME)	9.33	4.00	–	3.96	–	–	4.78
Kind of cooling (KC)	3.83	–	8.96	–	–	–	2.02
Residual error	0.00	7.78	7.74	4.95	15.53	4.63	5.33
% Real contribution	100.00	92.22	92.26	95.05	84.47	95.37	94.67
4045							
Mould geometry (MG)	20.09	–	35.46	17.94	58.05	12.76	17.05
Number of overflowing holes (NH)	26.10	–	5.50	–	5.46	–	9.61
Precursor geometry (PG)	1.78	–	24.30	–	8.96	–	3.36
Number of pieces of precursor (NP)	–	2.44	11.96	5.18	4.70	42.14	6.15
% of weight loss assumed (LW)	17.89	–	–	3.94	4.70	–	6.68
Dycote/water (D/W)	–	–	–	–	–	3.36	0.28
Contact with the mould (CM)	–	–	–	–	–	–	0.00
Vertical/horizontal (H/V)	3.30	84.65	–	64.92	2.68	8.41	35.65
Furnace temperature (FT)	1.78	–	–	–	–	8.41	1.29
Moment of moulding extraction (ME)	7.86	–	–	–	–	2.08	2.79
Kind of cooling (KC)	–	4.45	0.99	–	–	6.53	2.11
Residual error	21.22	8.46	21.78	8.02	15.45	16.32	15.02
% Real contribution	78.78	91.54	78.22	91.98	84.55	83.68	84.98

same conditions. As explained previously, a statistical analysis of the *S*/*N* is necessary in this situation. Therefore, to carry out the *S*/*N* study it is necessary to convert the set of observations into a single number, trough two steps. First, the Mean Squared Deviation (MSD) for each experiment is calculated according to the final characteristic. As the three studied characteristics presented different objectives, three types of equations were employed for the MSD calculations [21]:

- The objective, a density of 0.55 g/cm^3, is a ‘‘nominal is better’’ objective, so the equation used is:

  $$\mathrm{MSD} = ((Y_1 - Y_0)^2 + (Y_2 - Y_0)^2 + \cdots + (Y_N - Y_0)^2)/N$$

  where Y_0 = 0.55 g/cm^3
- The minimum desired gradient ∇_{1-3}, is a ‘‘minimum is better’’ objective, so in this case the proper equation is:

  $$\mathrm{MSD} = (Y_1^2 + Y_2^2 + \cdots + Y_N^2)/N$$
- The task to try to obtain the better skin is a ‘‘maximum is better’’ task, so the equation for this kind of objective is:

  $$\mathrm{MSD} = (1/Y_1^2 + 1/Y_2^2 + \cdots + 1/Y_N^2)/N$$

For all the previous equations N is the number of repetitions in each of the 12 internal experiments, i.e. $N = 2$ (two levels of noise were selected Y_1 and Y_2).

Secondly, the *S*/*N* ratio is computed from the MSD by the equation:

$$S/N = 10\log_{10}(\mathrm{MSD})$$

It is important to remark that the *S*/*N* ratio is a variance index given by experimentation, which must be maximised in order to find the most robust and optimum combination of the levels of the control factors. Thus the greater this value, the smaller the variance around the required—nominal, minimum, maximum—value.

Table 7 Percentage of influence of selected levels on the process robustness as results for the *S*/*N* analysis

	Optimum level	Density	∇_{1-3}	Roughness	Unions	Collapse	Phases	Average
6061								
Mould geometry (MG)	1	5.27	16.36	37.99	4.99	39.54	18.09	15.59
Number of overflowing holes (NH)	2	22.4	2.63	–	5.71	–	–	8.82
Precursor geometry (PG)	2	3.63	–	28.61	30.79	25.01	5.30	8.69
Number of pieces of precursor (NP)	1	15.13	18.91	8.10	13.38	–	8.75	13.87
% of weight loss assumed (LW)	1	8.04	–	2.58	–	–	4.57	3.28
Dycote/water (D/W)	1	14.91	2.91	–	–	11.28	–	6.88
Contact with the mould (CM)	1	–	–	5.32	–	3.6	–	0.74
Vertical/horizontal (H/V)	1	–	44.38	–	8.23	2.16	51.99	19.99
Furnace temperature (FT)	2	2.94	–	–	21.67	–	–	2.79
Moment of moulding extraction (ME)	1	18.35	–	–	6.40	–	–	6.65
Kind of cooling (KC)	2	4.88	6.24	12.44	–	7.77	–	5.39
Residual error		4.45	8.57	4.96	8.84	10.64	11.30	8.03
% Real contribution		95.55	91.43	95.04	91.16	89.36	88.7	91.97
4045								
Mould geometry (MG)	1	14.09	–	30.61	18.02	53.82	12.61	14.29
Number of overflowing holes (NH)	1	10.64	–	11.17	–	8.02	3.10	5.40
Precursor geometry (PG)	2	26.51	–	28.29	1.68	13.93	3.56	12.79
Number of pieces of precursor (NP)	1	–	–	12.51	8.31	6.34	35.13	5.19
% of weight loss assumed (LW)	1	10.29	–	–	5.52	4.28	–	4.25
Dycote/water (D/W)	2	–	2.57	2.91	–	–	6.55	1.65
Contact with the mould (CM)	1	2.08	–	–	–	–	–	0.69
Vertical/horizontal (H/V)	1	24.91	93.6	2.70	47.21	2.65	4.13	44.23
Furnace temperature (FT)	1	–	–	2.56	0.91	–	13.06	1.38
Moment of moulding extraction (ME)	2	–	–	–	3.46	–	2.13	0.47
Kind of cooling (KC)	1	–	–	–	1.33	–	6.59	0.66
Residual error		11.48	3.83	9.25	13.59	10.96	13.14	10.04
% Real contribution		88.52	96.17	90.75	86.41	89.04	86.86	89.96

The relative significance of the individual factors on the *S*/*N* ratio was quantitatively evaluated by using the analysis of variance—ANOVA. As previously commented, the low contribution of some factors was disagreed by a pooling process (again <3% was applied as criterion).

Table 7 shows the optimum levels for 6061 and 4045 alloys and the influence percentage for the six quality characteristics under study. A high congruence was found for the optimum levels of the six parameters for each alloy. Grey-marked values presented a mismatching with the optimum level given in the table. In these cases, cumulative percentages for the two possible levels—taking into account the statistical weights described previously—were compared, selecting the level with a higher cumulative influence percentage. Only, in case of 6061 alloy, slight similar cumulative values were found in the selection of the optimum level for the loss weight assumed; level-1 was finally selected because the higher influence percentage in density compared to the statistical weighted-percentage reported for roughness + phases. It is important to report that for the *S*/*N* pooling, the residual error was not higher than 10% for the two alloys.

There is a similarity with the results of the analysis of the mean values; the same factors are the most influential in both analysis.

Some other interesting facts can be extracted from Table 7, such as the high influence of mould geometry to avoid roughness or collapsed foams.

On the other hand, it is interesting to observe how the influence percentages for density are completely different in 6061 and 4045 alloys.

Discussion

Comparing the results for both alloys it is possible to observe differences in the final optimum levels obtained by the *S*/*N* ratio analysis. Compared results are shown in

Table 8. A disagreement (showed in grey for the final optimum level), for the ‘‘number of overflowing holes’’, ‘‘% of weight loss assumed’’, ‘‘Dycote/water’’, ‘‘furnace temperature’’ and ‘‘moment for extraction’’ was observed. These results can be understood from the different foaming agent content—0.4% of TiH_2 for 6061 alloy and 0.8% of TiH_2 for 4045 alloy—and the differences in viscosity which present these two alloys melts. The viscosity for AlSi10 for the foaming range 700–720 °C is lower than the value of viscosity for the AlSiMg alloy in the range of temperatures 750–770 °C. This is because the addition of silicon in aluminium produces a decrease in viscosity meanwhile the addition of magnesium in the aluminium enhances it [24]. The combination of more TiH2 and lower viscosity of the AlSi10 Alloy makes it more unstable at foaming temperature and this drives to the need of a lower foaming temperature, assuming a higher weight loss because this melt foam grows more and flows better. In the same way, it is necessary to take it out from the furnace before overflowing starts to prevent the collapse of the foam and it is better to avoid the usage of the overflowing hole to foam this alloy. All the above mentioned factors should influence in the final density as it can be appreciated in Table 6 where the sum of these control factors takes more than 53% of influence for 4045 and 41% for the 6061 alloy.

Figure 5 presents the values taken from last column in Table 7 for 4045 and 6061 alloys, ordered by its percentile contribution, note that this contribution is for the selected level-1 or -2 of each control factor. It can be observed that the first five factors, which sum near 70% for 6061 alloy and near 80% for AlSi10 alloy, are the same for both materials. Nevertheless important differences in percentage of relative contribution can be also appreciated in certain variables, such as the influence of foaming position, or the number of pieces of precursor, which once again indicates important differences for the two alloys.

It is important to take in account that Table 8 shows the final recommended parameters to obtain the best foaming for these two alloys and these parameters will be applied in the next step to make the confirmatory experiments.

Confirmatory experiments

In order to check if the applied Taguchi method was successful, a confirmatory experiment was conducted using the optimum levels predicted by the experimental design. Three foams for each alloy were produced considering the levels recommended in Table 8.

Results for bulk density and outward appearance can be seen in Fig. 6. If these results are compared to those initially obtained (presented in Fig. 4) we can appreciate that foaming process for 4045 alloy has been improved. A better outward appearance is now obtained for 4045 foams because averaged scores changed from 1.75 to 2.9 (65% of improvement). Additionally, results for bulk density are now nearer from the desired density (the average differences to the desired density have pass from 13% to 7%, i.e. aprox.50% of improvement) and all densities are now very similar in the three trials (higher robustness).

On the other hand, results do not show a significant increase—less than 5%—for 6061 alloy. The outward appearance has not been improved more than 5% and the density continues being 7% different from the desired value. However, it is important to remark that now the density is nearly the same in all the three foams, i.e. more

Table 8 Optimum combination of levels for both studied alloys

Control factors	Optimum level (AlSi0·6Mg1)	Optimum level (AlSi10)
Fixed factors		
Base material (stainless steel)	Stainless steel	Stainless steel
Thickness of the mould (1.5 mm)	1.5 mm	1.5 mm
Kind of releasing product (Dycote E11)	Dycote E11	Dycote E11
Two-level factors		
Mould geometry (MG)	Squared prismatic based	Squared prismatic based
Number of overflowing holes (NH)	1	0
Precursor geometry (PG)	Short (<2/3)	Short (<2/3)
Number of pieces of precursor (NP)	3	3
% of weight loss assumed (LW)	10%	30%
Dycote/water (D/W)	1:5	1:8
Contact with the mould (CM)	Maximum	Maximum
Vertical/horizontal (H/V)	Vertical	Vertical
Furnace temperature (FT)	+120	+100
Moment of moulding extraction (ME)	Overflowing	Black mould
Kind of cooling (KC)	Water spraying	Water spraying

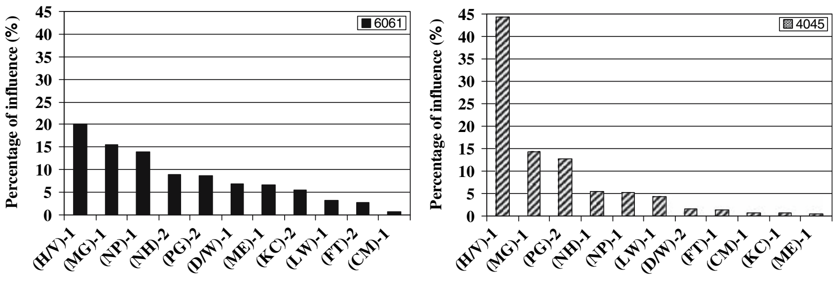

Fig. 5 Relative contributions of control factors for both studied alloys. Influence percentage is presented with the optimum level for each factor (example: (MG)-1 means level one is the optimum level for the mould geometry factor)

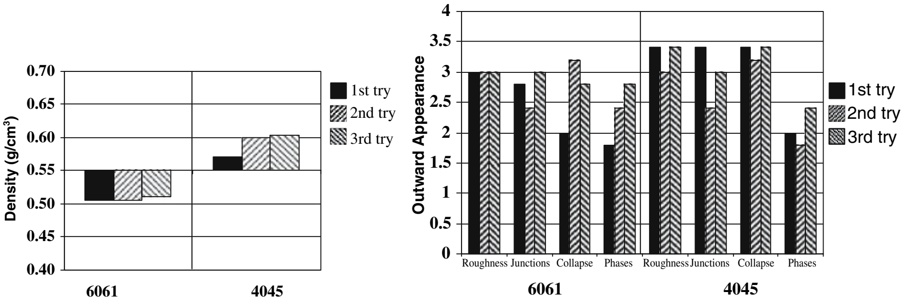

Fig. 6 Density and surface quality scores obtained in the confirmatory experiments

robustness. The most reliable cause for the small improvement in this alloy (regarding density and outward appearance), could be related with the selection of a low percentage of weight loss—only 10%. This low percentage leads to lower density than desired and it is obvious that when density is lower it is more difficult to obtain good outward appearance.

Taking into account previous results, it is probable that selecting a weight loss of 10% for 6061 alloy has been insufficient and a weight loss of 30% for 4045 alloy could be higher than enough.

Finally, after confirmatory experiments, the density gradient of both alloys presented values lower than (0.1 g/cm^3)/cm, a much lower value compared to the initial one. Actually, two density gradients for 4045 alloy were now negative, which means that the density gradient has been really minimized.

Conclusions

The Taguchi methodology has been applied to the foaming process of aluminium foams, separately for 6061 and 4045 alloys. From this study some remarkable results have been obtained:

- The influence for each control factor on the foaming process has been numerically quantified.
- From the *S*/*N* ratio study the optimum combination of levels to obtain a fixed bulk density, lower density gradient and higher quality in the outer skin have been obtained. The combination of a low viscosity and a higher content of titanium hydride for 4045 alloys drives to different foaming requirements that those needed to foam the 6061 alloy, more viscous and with lower TiH_2 content. In consequence the optimum levels related to the viscosity and foaming agent content are different for each alloy.
- Foaming parameters as the weight loss to be assumed previously to foaming are completely different: a value slightly higher than 10% mass loss is required for 6061 meanwhile a mass lower than 30% is necessary for 4045, according to the Taguchi results. This difference between the two alloys is clearly related to the different viscosity and TiH_2 content of the two studied alloys.
- The most contributing factors to obtain a robust foaming process are the foaming position and the mould geometry.
- The confirmatory experiments revealed clear improvements in outward appearance and density gradient, as well as a nearly constant final density. It should be necessary to fine tune the weight loss assumed for the foaming process to obtain the exactly desired bulk density. The analysis could be done by using more than two levels for this critical factor.

From the industrial point of view the need of having a final product with similar characteristics (density, outer skin, etc.) is a key factor to succeed in the progressive commercialisation of aluminium foams as parts of serial products.

Additionally, although specific results are only applicable to our laboratory-scale foam production, the background results of this paper can be taken into account in the large scale aluminium foam production by means of the PM route, where it is obvious that a low tolerance in density as well as other properties is required.

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