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Evaluation of the Cause and Consequences of Defects in Cast Metal-Ceramic Composite Foams

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Abstract

In this research, the quality of manufactured cast metal-ceramic foams (manufactured using blowing gas) was tested. The causes responsible for defect formation in the composite foams and their consequences were analyzed using the FMEA (Failure Mode and Effects Analysis) method, which is a useful tool for minimizing losses caused by low product quality. This method involves analytically determining correlations between the cause and consequences of potential product defects, and it takes into account the criticality factor (risk). The FMEA analysis showed that pore breaks were the most "critical defect" (with the highest number of effects on the product, the Risk Priority Number, affecting the quality of the composite foam). The second most critical defect was discontinuities in the foam frame structure. Destruction or damage to the foam structure (although very rare) deprived the composite foam of its primary function, which is to reinforce the product. The third most critical defect was non-uniform foam pore size.

Keywords: Foams, Composites, Casting, Defects, Failure mode and effects analysis

1. Introduction

Duarte and Ferreira [1] and Ashby et al. [2] presented an overview of manufacturing techniques and industrial applications of metal and composite foams. Marx, Jacob et al. presented the ballistic properties of composite-metal foams using finite element analysis [3]. Selected properties of foams are described in [4, 5]. Orbulov in particular assessed the effect of heat treatment and found the relationship between the fracture force values of the foam, its strength and the values of energy absorbed by the skeletal structures. Also their alleged use as protective covers of engine units was presented in the work by Bejger [6]. The non-flammable, recyclable and lightweight open-cell and closed-cell metal foams have been used as functional and structural engineering applications [7–9]. The closed-cell metal foams, in particular the aluminum alloy (Al-alloy) foams, have been used in structural engineering applications (e.g., automotive, aerospace, sea and land transport, industrial equipment and building construction) that require lightweight structures with high strength-to-weight and stiffness-to-weight ratios, high impact energy absorbing capacity and/or with an good damping of noise and vibration [4, 5]. They can be produced in different ways, e.g. by casting, and, appropriately transformed, modified, divided or combined [10, 11], e.g. into panels. All of these foams, in particular the closed-cell aluminum foams, are usually applied as core and/or as filler of sandwich panels [6] and thin-walled structures [7]. Zhou J. et. al [12] investigated the effect of heat treatment on foams and others [13-17] identified different properties of these lightweight materials.

Generally, the foamed materials market is said to be growing mainly due to the increased demand for metal foams [18-22]. Germany is the largest consumer of metal foams in Europe, using 35% of the elements made from foamed metals worldwide [23-25]. It is important that the produced foams are of good quality.

The product was analyzed after the technological process, in accordance with the standards PN-EN ISO 9000:2001 (*Quality Management Systems. Principles and terminology*) and PN-EN ISO 9001:2001 (*Quality Management Systems. Requirements*) [26, 27]. During the research, the quality of the manufactured cast metal-ceramic foams (manufactured using blowing gas) was tested. The customer's request (order), in which they specify their requirements for the composite foam, is the main factor that determines the procedure used to manufacture the product. This factor affects the course of further actions. To introduce conceptual changes prior to the construction or application, it is necessary to obtain information about strong and weak points of the technological process and product. FMEA [27, 28] is recommended when introducing new materials and/or new or modified technologies. FMEA aims to consistently eliminate product defects by identifying their causes and using appropriate methods to prevent them. In the FMEA method, once the object of analysis has been determined, it is necessary to analyses the defect, reasons, and criticality of defects for the product and determine the objective of the analysis. The purpose of the analysis in this article is to produce good-quality metal-ceramic foams. Quality assessment was carried out using data collected with basic quality management tools, i.e. process diagrams, control sheets, and cards and questionnaires [27, 29-31].

The causes of product defects were identified in Refs. [25, 29-31], where control charts and process diagrams were used. Quantitative analysis was subsequently carried out, i.e. the probability of the occurrence of every cause was assigned based on stages of technological process.

2. Materials

The foam was produced by the authors according to a patented method (Patent No. 211439 "Method of producing structural elements from foamed metals" [24]) of blowing gas into a composite bath. Foam manufacturing technologies are described in detail in [29]. This method, i.e. foaming in a liquid state, is technologically simple and inexpensive, but it requires a lot of experience and precise control of the process parameters to ensure structural repeatability of the product. The initial procedure involved the preparation of a metal bath (alloy aluminium) in a furnace-crucible and addition of 15 mas.% of SiC reinforcement with granulation of about 20 μm. This bath was mechanically mixed at 720°C, which allowed it to obtain a stable composite with a uniformly distributed reinforcement phase (suspension composites) [25]. The production of the composite foam and the produced foam are shown in Figures 1 and 2.

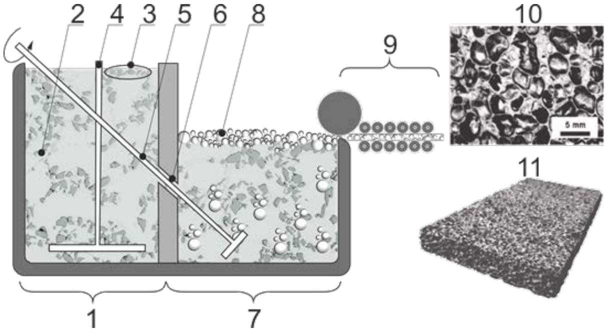

Fig. 1. Diagram of the manufacturing method of metal-ceramic foam by blowing gas: 1 – furnace-crucible, 2 – metal bath, 3 – SiC reinforcing compounds, 4 – agitator, 5 – lance with gas distribution rotor, 6 – culvert, 7 – foaming tank, 8 – metal-ceramic foam, 9 – receiving the foam by a conveyor belt, 10 – foam microstructure, 11 – finished product [25]

Fig. 2. Manufactured cast composite foam – macro view

3. Characterization methods

This analysis is intended to assess the risk factors. Each defect was assessed as an integer in the range (1-10) by three criteria:

- Defect frequency (risk of the defect) – a number (R)
- Detection level, which describes the probability that a given defect will not be detected by the manufacturer and will be delivered to the customer – number (*W*)
- Defect significance, i.e. how important a given defect is for the customer – number (*Z*).

Guidelines for estimating the indicators *R*, *W*, *Z* are given in Tables 1–3 [29]. Tables 1-3 are the author's own work and include only the requirements presented in [26, 27, 28]. Given the complexity of cast metal-ceramic foam defects, a proprietary description of one criterion was introduced (defect detection probability after introducing specific tests to detect defects in cast metal-ceramic composite foams [29]; Table 2). The priority number was calculated by estimating the criticality number, *P* (*Risk Priority Number*), whose value for the tested products was determined according to the formula:

$$P = R \cdot Z \cdot W \qquad (1)$$

The priority number *P* can take a value from 1 to 1000; the greater the value, the greater the risk associated with the defect. Most often, a certain level of criticality is determined, e.g., $P > 100$, above which all defects are analyzed. According to the principle [27], when the criticality level of a defect is significantly higher than 1000, a move to the next stage is required, i.e. preventative actions, such as changing/modifying the technological process or the product itself.

Table 1.
Summary of defect occurrence frequency in metal-ceramic foam castings

Occurrence	Process/product characteristics	R
Unlikely	Defect is unlikely to occur. Technological process is fully mastered and controlled	1
Rarely	There are relatively few defects. Controlled process	2–3
Moderate	Defects occur sporadically	4–6
Often	The defect occurs frequently and cyclically	7–8
Very often	The defect is almost inevitable	9–10

Table 2.
Summary of defect detection levels in metal-ceramic foam castings

Detection of defects	Process/product characteristics	W
Very high	There is a very high probability that a defect will be detected. Validation occurs through suitable material tests carried out after the technological process, primarily by macroscopic examination.	1–2
High	There is a low probability that the defect will not be detected before the process is completed. One defect is obvious, but several defects may not be detected. Validation occurs through suitable material tests, carried out after the technological process.	3–4
Moderate	There is a moderate probability that a defect will not be detected before the process is completed. Validation occurs through suitable material tests carried out after the technological process.	5–6
Low	There is a high probability that the defect will not be detected, even when using appropriate material tests, which include both 2D and 3D structure analysis.	7–8
Very low	There is a very high probability that a defect will not be detected, even when using appropriate material tests.	9–10

Table 3.
Summary of defect consequences (for the customer) in metal-ceramic foam castings

Consequences of defect	Process/product characteristics	Z
Very low	Minimal consequences; a product defect will not affect its use	1
Low	Minimal consequences that create minor difficulties. Moderate deterioration in product properties may be observed	2–3
Moderate	Defect creates limited dissatisfaction and few difficulties. Product does not satisfy needs or poses an inconvenience. User sees the product’s shortcomings. Product may, however, be authorized for use	4–6
Large	Customer dissatisfaction arises. The product cannot be used, and the defect results in a product that does not comply with requirements	7–8
Very large	Defect significance is very high, the defect disqualifies the product, endangers the safety of the user, or violates laws concerning threats to health or life	9–10

To assess the foam structure and identify defects macroscopic examinations, optical microscopy, stereoscopic microscopy, scanning electron microscopy, computed tomography and stereological methods based on image analysis were used (see paper [29, 31]). The characteristics of the observed defects of composite foams [29] are presented in Table 4.

Table 4.
Structure defect classification of cast metal-ceramic composite foams

No	Defect	Description
1.	Non-uniform pore distribution in the foam	Uneven reciprocal placement, density, or dispersion of pores throughout the foam or within the examined area
2.	Uneven pore proportion in foams	Uneven number or percentage of pores in a given area or in the entire foam volume. This can also be considered as the porosity of the foam (i.e. share of pores per unit volume). The correct way to identify this defect is to compare the structure of 2- 3 products from a batch.
3.	Non-uniform foam pore shape	Different pore shapes in the foam are referred to as: circular, elongated, and protruded
4.	Non-uniform foam pore size	Uneven pore size in a given area of the foam or in the entire volume of foam
5.	Non-uniform pore surface structure	Different pore surfaces, dendrites, uneven pore surface dimensions, e.g. thickening, incorrect chemical composition of pore surface resulting in separation, inclusions, or contamination in the form of foreign matter
6.	Pore breaks	Narrow zigzag or straight gap passing through or fragmenting the pore canopy, damage to pores in the form of fragmentary tearing of the pore basin surface
7.	Non-uniform distribution of the reinforcement phase in the foam	Uneven distribution, dispersion, or clusters of the reinforcement phase in a given area of the foam or throughout the entire foam under examination
8.	Uneven proportion of reinforcement phase in foams	Unequal amounts of reinforcement phase in a given area of foam or in the entire volume of foam. Unequal share of reinforcement phase per unit volume of foam. The correct way to identify this defect is to compare the structure of 2–3 products (samples) from the same batch.
9.	Discontinuity of the frame foam structure (e.g., cracks)	Gaps in continuity of the matrix material and/or reinforcement in the foam frame area
10.	Damage or crushing of the frame surface borders	Noticeable discontinuities due to crushing or edge tearing in the frame surface (uneven, undulating cross-sectional thickness in 2D images) where successive blisters join, or at the frame-blister wall
11.	Delamination of foam frame structure edges and surfaces	Gaps in frame continuity at the edge of a blister, characterized by “collars”, double or triple films, multiple walls, layering
12.	Brittle phase at the edge (border) of the frame structure – pore	Continuous or discontinuous brittle phases at the blister-frame border

4. Results and discussion

The determination of the priority number using the FMEA method for metal-ceramic foam casting was presented in Table 5.

Critical number estimation was used to calculate the priority number, and 3 critical defects were identified (P > 100). This method is a tool for ongoing improvement that pre-vents the occurrence of manufacturing/handling errors in processes/products. Undoubtedly, the advantages of the FMEA method include the systematization of improvement measures, combining classic techniques and quality management tools, and driving people to examine a problem from different perspectives. In line with FMEA, the greater the value of the priority number (P), the greater the risk associated with a defect.

Various defects may adversely affect the operation of the entire system, therefore the evaluation of their impact on the product is important.. Composite foam casting, which produces a non-uniform pore size, cannot be used. Products with this defect may have reduced properties, e.g., compressive strength [2, 32-33].

Table 5.
Criticality numbers, i.e. frequency of defect occurrence, detection level, and defect significance for cast metal-ceramic foams. Defined priority number. FMEA method

Defect	Defect significance to the customer (consequences, effects) (*Z*)	Occurrence rate I	Detection level upon foam collection (*W*)
1. Non-uniform foam pore shape	Defect creates limited dissatisfaction and causes few difficulties. Product does not satisfy needs or is a source of inconvenience. User sees the product's shortcomings. Product may, however, be authorized for use. Z = 6	Defects occur sporadically R = 4	There is a low probability of not detecting the defect before the process is completed. The defect is obvious, and several defects may be undetected. Validation through suitable material tests, carried out after the technological process. W = 3
Priority number P = 72			
2. Non-uniform pore distribution in the foam	Defect creates limited dissatisfaction and causes few difficulties. Product does not satisfy needs or is a source of inconvenience. User sees the product's shortcomings. Product may, however, be authorized for use. Z = 4	Defects occur sporadically R = 4	There is a low probability of not detecting the defect before the process is completed. The defect is obvious, and several defects may be undetected. Validation through suitable material tests, carried out after the technological process. W = 4
Priority number P = 64			
3. Non-uniform pore surface structure	Minimal consequences that create minor difficulties. Moderate deterioration in product properties may be observed. Z = 3	There are relatively few defects. Controlled process. R = 2	There is a moderate probability that the defect will not be detected before the process is completed. Validation through suitable material tests, carried out after the technological process. W = 5
Priority number P = 30			
4. Non-uniform foam pore size	Customer dissatisfaction arises. Product cannot be used. Product defect results in a product that does not comply with requirements. Z = 8	Defects occur sporadically R = 4	There is a low probability of not detecting the defect before the process is completed. The defect is obvious, and several defects may be undetected. Validation through suitable material tests, carried out after the technological process. W = 3
Priority number P = 96			
5. Uneven pore proportion in foam	Customer dissatisfaction arises. Product cannot be used. Product defect results in a product that does not comply with requirements. Z = 7	There are relatively few defects. Controlled process. R = 3	There is a low probability of not detecting the defect before the process is completed. The defect is obvious, and several defects may be undetected. Validation through suitable material tests, carried out after the technological process. W = 4
Priority number P = 84			
6. Pore breaks	Defect significance is very high, the defect disqualifies the product, endangers the safety of the user, or violates laws concerning the threat to health or life. Z = 9	Defects occur sporadically R = 5	There is a moderate probability that a defect will not be detected before the process is completed. Validation through suitable material tests, carried out after the technological process. W = 6
Priority number P = 270			
7. Non-uniform distribution of the reinforcement phase in the foam	Customer dissatisfaction arises. Product cannot be used. Defect results in a product that does not comply with requirements. Z = 7	There are relatively few defects. Controlled process. R = 2	There is a moderate probability that a defect will be undetected before the process is completed. Validation through suitable material tests, carried out after the technological process. W = 6
Priority number P = 84			
8. Uneven proportion of the reinforcement phase	Customer dissatisfaction arises. Product cannot be used. Defect results in a product that does not comply with requirements. Z = 7	There are relatively few defects. Controlled	There is a moderate probability that a defect will be undetected before the process is completed. Validation through suitable material tests, carried out after the technological process.

Defect	Defect significance to the customer (consequences, effects) (*Z*)	Occurrence rate I	Detection level upon foam collection (*W*)
in foams		process. R = 2	W = 6
Priority number P = 84			
9. Discontinuity of the frame foam structure (e.g., cracks)	Defect significance is very high, the defect disqualifies the product, endangers the safety of the user, or violates the law concerning the threat to health or life. Z = 9	Defects occur sporadically R = 4	There is a moderate probability that the defect will be undetected before the process is completed. Validation through suitable material tests, carried out after the technological process. W = 6
Priority number P = 216			
10. Damage, crushing of the frame surface borders	Minimal consequences that create minor difficulties. Moderate deterioration in product properties may be observed. Z = 3	There are relatively few defects. Controlled process. R = 2	There is a high probability that the defect will be undetected, even when using appropriate material tests. W = 7
Priority number P = 42			
11. Delamination of the foam frame edges and surfaces	Defect creates limited dissatisfaction and causes few difficulties. Product does not satisfy needs or is a source of inconvenience. User sees the product's shortcomings. Product may, however, be authorized for use. Z = 4	There are relatively few defects. Controlled process. R = 3	There is a high probability that a defect will be undetected, even when using appropriate material tests. W = 7
Priority number P = 84			
12. Brittle phase at the edges (border) of the frame structure – pore	Minimal consequences that create minor difficulties. Moderate deterioration in product properties may be observed. Z = 3	There are relatively few defects. Controlled process. R = 2	There is a high probability that a defect will be undetected, even when using appropriate material tests. W = 7
Priority number P = 42			

5. Conclusions

The presented FMEA method allows to precisely define the number of priority - P based on the assumed criteria. This number indicates which of the above-mentioned defects have the greatest impact on the quality of the product. Taking into account the criteria: the frequency of occurrence of a given defect, the significance of the defect for the customer and the risk that a given defect will not be detected, three priority (where P> 100) defects in the structure of composite foams affecting the product quality have been distinguished - Table 5. The analysis (Tab. 5) showed that pore breaks were the most critical defect (with the highest priority number P = 270) affecting the quality of the composite foam. The groups with the greatest influence on this defect were the technological process and human factors, similar to the raw material (components) used to produce the foam. Inconsistent, contaminated composite materials may produce a brittle structure, together with a failure to meet technological conditions. A lack of experience and competence on the part of employees during device operation caused excessive pore growth, which formed pore breaks in the foam and damaged the product. Consequently, this damaged the whole mechanism in which a given element operated or was supposed to operate. High (W = 6) detection levels indicated a medium probability of detecting a defect before the technological process was completed.

The second defect (P = 214) was the discontinuity of the frame foam structure (e.g., cracks). Destruction or damage to the foam structure (although very rarely, R = 4) is a defect that deprives the composite foam of its primary function, which is to reinforce the product. This defect may occur due to a poorly-executed technological process (e.g., excessively fast gas permeability through a liquid composite, or too-slow or fast collection of foam from a conveyor belt) or faulty bonding of components in the composite itself.

The third defect (P = 96) is a non-uniform pore size in the foam. This defect most severely affects the products produced by blowing a composite with liquid gas. This technique requires precise process control and a great deal of experience by the personnel operating the device (very high influence of the "human factor" on the occurrence of this defect).

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