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APPLICATION OF FMEA IN THE QUALITY ESTIMATION OF METAL MATRIX COMPOSITE CASTINGS PRODUCED BY SQUEEZE INFILTRATION

Metal matrix composites (MMCs) are still scarcely described due to various combinations of used materials and a wide array of technologies. Applying the Failure Mode and Effect Analysis (FMEA) method to describe the quality of metal composite castings may contribute to eliminating specific (characteristic only to these materials) defects. This part of the analysis determines the criticality numbers, meaning the frequency of a given failure, detectability level and significance of a given failure to the group of specific composite casting failures. It contributes to establishing the priority number (P), which is a measure used to assess risk, a notion essential in discussing quality in a composite casting.

Keywords: quality, casting, metal matrix composites, MMC, Failure Modes and Effects Analysis, FMEA, material defects, failures

1. Introduction

Quality of castings is affected, among other things, by factors related to order-specific requirements [1,2], along with strictly technological issues, such as designing a casting technology, casting materials, metal melting, filling the mould with metal, solidification, crystallisation, cooling and removing the casting from its mould. Failures in castings, also in MMCs made by infiltration of porous preforms, are created throughout the entire production process [3]. Defect of a similar character may occur on various stages, result from different factors, or even stem from dissimilar mechanisms. It is possible to quote the example of cracks in reinforcement elements, which may be created during production, solidification, cooling or even removing from the mould.

The course of producing castings from conventional materials has been well researched [4,5]. In cases of MMCs made by infiltration of porous preforms, the presence of permanent reinforcement, usually taking up from several to nearly 30% of the casting volume, significantly modifies the course of the discussed process. To examine the quality of MMCs made by infiltration of porous performs, FMEA analysis should be conducted. It would not be possible to identify and describe several basic failures specific for castings made of such composites without assuming such an approach.

2. Methodology

Composite materials analysed in the paper were produced by pressure infiltration of porous short or long carbon, boron, steel, aluminosilicate fibres perform under 15-30 MPa extend pressure using liquid aluminium and Wood's alloys (technology introduced in [1-3].)

The quality of the product, namely a metal ceramic casting, after the completion of the technological process was analysed in accordance with quality standards [6,7]. The factors determining the manner of creating the product (composite castings) are the demands (orders) of the recipients, specifying needs concerning the casting. Said agents influence the course of further actions. Gaining information on strong and weak points of the technological process as well as the product itself is crucial as it makes it possible to introduce conceptual changes before commencing structural work. One of many applications of a Failure Mode and Effect Analysis [8,9] is the instance of introducing new materials as well as new or modified technologies. The goal of FMEA is to consistently eliminate failures of production by identifying the reasons for their presence and applying measures accurately preventing them. In the case of FMEA, after specifying the object of research, the analysis concerning reasons of failure and their criticism for the following stages must be conducted:
- determining the goal of the analysis – the objective in the present analysis is to produce a good quality composite casting,
- gathering data and screening failures.

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This paper is based on a classification of defects in the structure of infiltrated metal composite castings [11-13], creating an entire group in the classification of casing defects (Fig. 1). It bears the name of structure defects, just as suggested in [1,13]. Other groups (shape defects and raw surface defects) included in the classification correspond with groups differentiated in the casting failure classification for conventional materials. This group (structure defects) consists of 5 subgroups encompassing both structure defects in castings made of conventional materials, corresponding to those for infiltrated composite castings, and failures specific for such castings. Only those defects will be submitted to the FMEA method analysis.
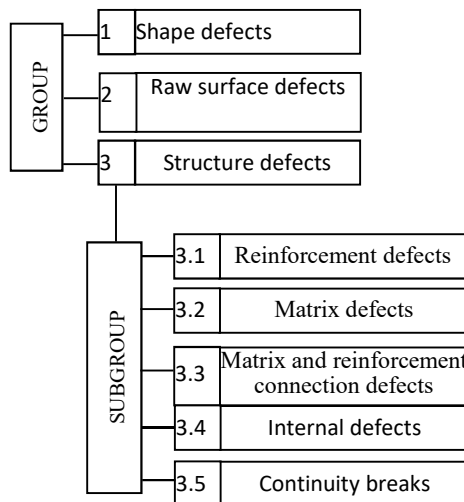

Fig. 1. Structure of classification of defects in metal matrix infiltrated composite castings (based on authors' work)

Determining reasons and consequences of failures. Establishing the causes of failures in the analysed product was discussed in the works of [1,8,14-15], using e.g. the Pareto and Ishikawa analysis. The next step regarded a quantitative analysis, namely determining the possibility of each failure. This undertaking aims at assessing risk factors. Each defect is given a whole number between 1 and 10 based on three criteria: frequency of occurrence R (Table 1), level of detectability W, describing the likelihood of a given failure being overlooked by the producer and presenting itself to the customer (Table 2), and severity of the defect Z from the standpoint of product recipient (Table 3).

TABLE 1

Frequency of failure for composite castings [9]

Frequency	Characteristics of the process/product	R
Unlikely	A failure is highly unlikely. The technological process is perfected and fully controlled.	1
Remote	Relatively low level of failures. Controlled process.	2-3
Occasional	Failures happen from time to time.	4-6
Reasonably possible	Failures occur often, in a regular manner.	7-8
Frequent	It is almost impossible to avoid failures.	9-10

TABLE 2

Failure detection levels for composite castings [9]

Detectability	Characteristics of the process/product	W
Certain	It is highly unlikely that the failure will not be detected. Verification using proper material examination after the technological process.	1-2
High	Low possibility of not detecting the fault before process completion. The failure is evident, a few may remain undetected. Verification using proper material examination after the technological process.	3-4
Moderate	Moderate likelihood of not detecting product fault before process completion. Verification using proper material examination after the technological process.	5-6
Low	High possibility of not detecting the failure, even if proper material examination applies.	7-8
Very low	Extremely high likelihood of the fault remaining undetected, even if proper material examination applies.	9-10

TABLE 3

Consequences (severity) of failures in composite castings (ramifications for customers) [9]

Consequences	Characteristics of the process/product	Z
Not relevant	Minimal effect, failure will not affect application.	1
Minor	Minimal effect causing slight inconvenience. Moderate deterioration of product properties may be noticed.	2-3
Moderate	Failure leads to slight dissatisfaction and inconvenience. Product does not satisfy needs or is a source of annoyance. Users notice flaws of the product. However, it may be authorised.	4-6
Critical	Customer dissatisfaction is stronger. Product may not be used. Failure leads to producing a casting not fitting the requirements.	7-8
Catastrophic	The ramification of the failure is grave, the casting is disqualified, threatens the safety of users or violates the law.	9-10

On the basis of estimated criticality numbers, a Risk Priority Number P has been calculated per the formula [8]:

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

The values assigned to P fall between 1 and 1000 [8]. The higher the value of the priority number (P), the greater the risk related to a given failure. In most cases, a specific critical level is assumed, namely the value of the priority number P, e.g. $P > 100$; all failures with a higher value will be analysed. As a rule, if the defect critical level is significantly higher than 1, it is recommended to go to the next level of action, namely apply preventive measures such as changing or rationalising the technical process.

3. FMEA analysis

By virtue of structural specificity of composites, continuity breaks, internal defects as well as failures characteristic to infiltrated composites could be included in one subdivided group. However, preparing this classification would require a detailed analysis of the production process applied to metal composite castings with infiltrated reinforcements, which would be oriented towards determining the possibility of failures on individual stages of said process. The suggested group bears the name: *structural defects*. This is the reason why the paper discusses only this group, namely the structural defects of composite metal with infiltrated reinforcements, combined into one group of casting defects according to [1]. Other groups of failures (shape and raw surface) included in the classification correspond with those enlisted in the classification of defects for conventional material castings. The *structural defects* group is made of 5 subgroups dealing with both structural failures of castings made of conventional materials, applicable also to structural failures of infiltrated materials castings, and defects specific to composite castings. Five subgroups, namely reinforcement failures, matrix defects, matrix and reinforcement connection defects, internal defects and continuity breaks, classify failures discussed in Tables 4-8. The priority number and 3 critical failures were determined on the basis of calculated criticality numbers.

TABLE 4

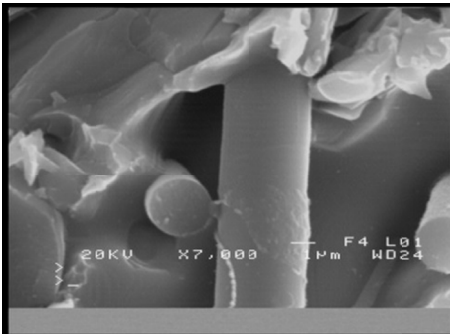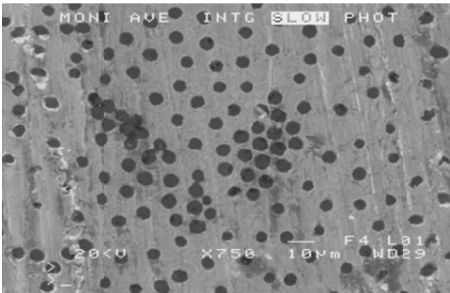FMEA for the *reinforcement defects* subgroup (based on authors' work)

Defect	Defect significance for customer (consequences, results) (Z)	Frequency (R)	Detectability (W) for conventional material castings [1,13] and composite castings using proper research methods

Inhomogeneity of shape and dimensions of the reinforcement elements	Minimal effect causing slight inconvenience. Moderate deterioration of product properties may be noticed. $Z = 2$
	
	Defect description: Varied length, width, shape and shape of fibres
		Failures occur often, in a regular manner.
		
		$R = 7$
			Low possibility of not detecting the fault before process completion. The failure is evident, a few may remain undetected. Verification using proper material examination after the technological process.
			• Microscopic examination:
			  – light,
			  – electron, scanning
			• Microtomography.
			• Computer image analysis.
			$W = 3$

Material:AlSi11/ aluminosilicate, SEM   **Risk Priority Number P = 42**

| Inhomogeneity of distribution of the reinforcement elements | Minimal effect causing slight inconvenience. Moderate deterioration of product properties may be noticed. $Z = 2$

Defect description: Inhomogeneous density of fibres in various areas of the reinforcement | Failures happen from time to time.

$R = 4$ | Low possibility of not detecting the fault before process completion. The failure is evident, a few may remain undetected. Verification using proper material examination after the technological process.
• Microscopic examination:
  – light,
  – electron, scanning.
• Microtomography.
• Computer image analysis.
$W = 4$ |

Material:AlSi11/C, SEM   **Risk Priority Number P = 32**
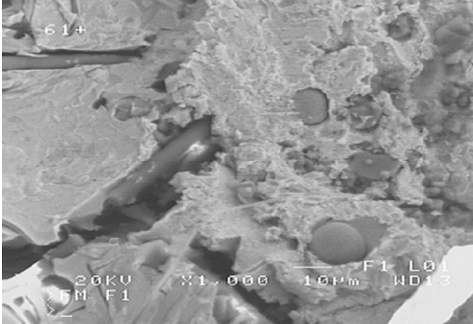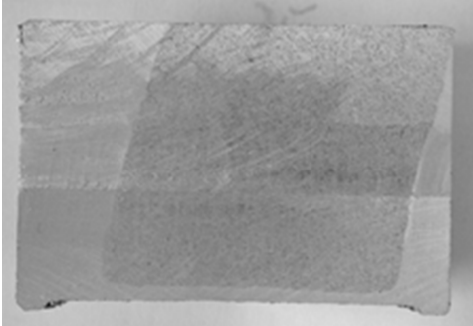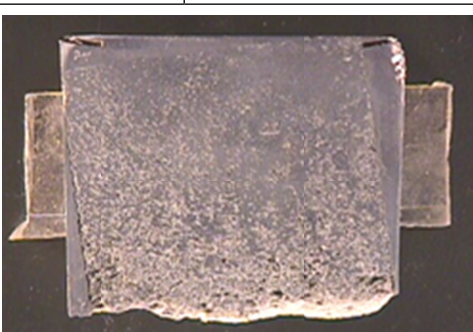
TABLE 4. Continued

Foreign matter in the reinforcement	Minimal effect causing slight inconvenience. Moderate deterioration of product properties may be noticed. **$Z = 3$** Defect description: Contamination in the process of reinforcing.	Relatively low level of failures. Controlled process. **$R = 2$**	Moderate likelihood of not detecting product fault before process completion. Verification using proper material examination after the technological process. • Microscopic examination: – light, – electron, scanning. • X-ray microanalysis. **$W = 5$**

Material: alloy Wood / aluminosilicate, SEM   **Risk Priority Number $P = 30$**

Deformation of the reinforcing structure	The ramification of the failure is grave, the casting is disqualified, threatens the safety of users or violates the law. **$Z = 9$** Defect description: Deformed shape of the reinforcement structure	Failures happen from time to time. **$R = 4$**	Low possibility of not detecting the fault before process completion. Verification using proper material examination after the technological process. • Microscopic examination. **$W = 3$**

Material: AlSi11 / aluminosilicate, macroscopic   **Risk Priority Number $P = 108$**

Improper localization of the reinforcing structure	The ramification of the failure is grave, the casting is disqualified, threatens the safety of users or violates the law. **$Z = 9$** Defect description: Relocated reinforcing structure within the casting	Relatively low level of failures. Controlled process. **$R = 2$**	It is highly unlikely that the failure will not be detected. Verification using proper material examination after the technological process. • Microscopic examination. • Radiological defectoscopy. • Ultrasound defectoscopy. **$W = 1$**

Material: alloy Wood / aluminosilicate, macroscopic   **Risk Priority Number $P = 18$**

TABLE 5

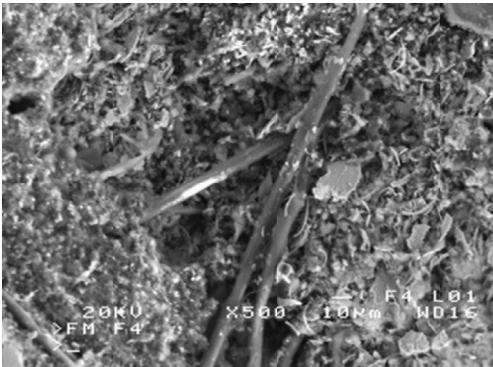FMEA for the *matrix defects* subgroup (based on authors' work)

Defect	Defect significance for customer (consequences, results) (Z)	Frequency (R)	Detectability (W) for conventional material castings [1,13] and composite castings using proper research methods
Improper matrix structure	Failure leads to slight dissatisfaction and inconvenience. Product does not satisfy needs or is a source of annoyance. Users notice flaws of the product. However, it may be authorised. **Z = 4** Defect description: Alien phases, undesired dendritic structure, phases with a fluctuating chemical composition, coarseness	Relatively low level of failures. Controlled process. **R = 2**	It is highly unlikely that the failure will not be detected. Verification using proper material examination after the technological process. • Microscopic examination: – light, – electron, scanning. • Computer image analysis • X-ray microanalysis **W = 1**
Material:AlSi11/ aluminosilicate, SEM **Risk Priority Number P = 8**			

TABLE 6

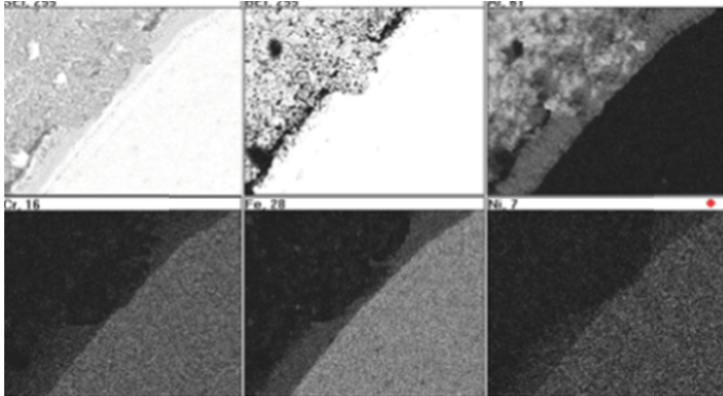FMEA for the *matrix and reinforcement connection defects* subgroup (based on authors' work)

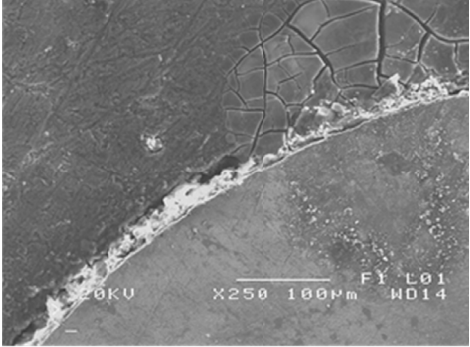| Defect	Defect significance for customer (consequences, results) (Z)	Frequency (R)	Detectability (W) for conventional material castings [1,13] and composite castings using proper research methods
Lack of the transition zone or its discontinuity on the matrix – reinforcement boundary	Failure leads to slight dissatisfaction and inconvenience. Product does not satisfy needs or is a source of annoyance. Users notice flaws of the product. However, it may be authorised. **Z = 4** Defect description: Visible lack of a longitudinal transition zone different in colour and chemical composition form the reinforcement and matrix	Relatively low level of failures. Controlled process. **R = 2**	High possibility of not detecting the failure, even if proper material examination applies. • Microscopic examination: – light, – electron, scanning. • X-ray microanalysis **W = 7**
Material: Al/steel, SEM **Risk Priority Number P = 56**			

TABLE 6. Continued

Brittle phases on the matrix – reinforcement boundary	Failure leads to slight dissatisfaction and inconvenience. Product does not satisfy needs or is a source of annoyance. Users notice flaws of the product. However, it may be authorised. **Z = 4** Defect description: Continuous or discontinuous brittle phases on the matrix-reinforcement boundary	Relatively low level of failures. Controlled process. **R = 2**	High possibility of not detecting the failure, even if proper material examination applies. • Microscopic examination: – light, – electron, scanning. • X-ray microanalysis **W = 7**

Material: Al/steel, SEM   **Risk Priority Number P = 56**

TABLE 7

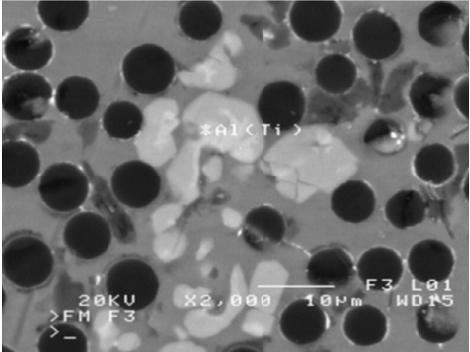FMEA for the *internal defects* subgroup (based on authors' work)

Defect	Defect significance for customer (consequences, results) (Z)	Frequency (R)	Detectability (W) for conventional material castings [1,13] and composite castings using proper research methods
Inclusions	Minimal effect causing slight inconvenience. Moderate deterioration of product properties may be noticed. **Z = 2** Defect description: Inclusions with a chemical composition and structure different from the chemical composition and structure of the matrix or reinforcements	Failures happen from time to time. **R = 5**	High possibility of not detecting the failure, even if proper material examination applies. • Microscopic examination: – light, – electron, scanning. • Ultrasound and radiological defectoscopy. **W = 8**

Material: Al/C, SEM   **Risk Priority Number P = 80**

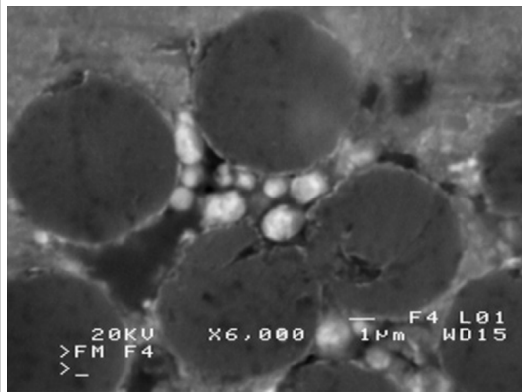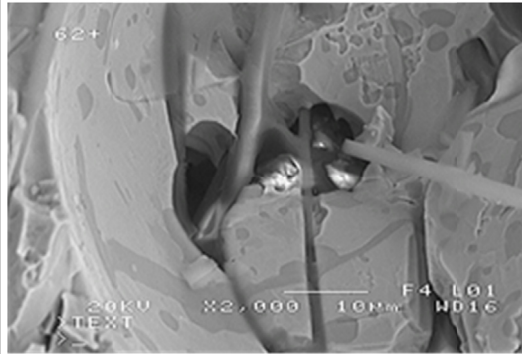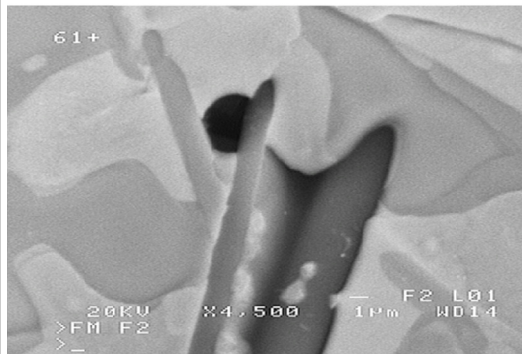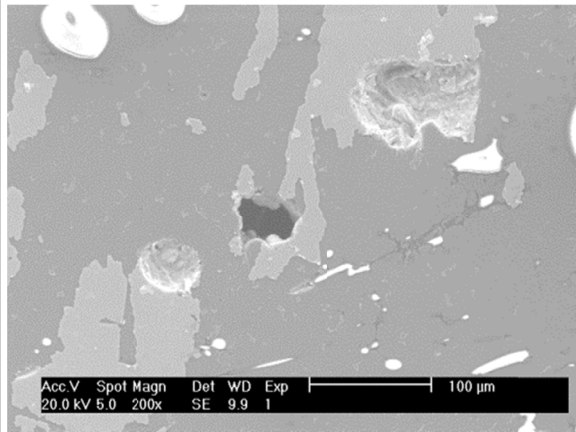| Unfilled reinforcement spaces	Minimal effect causing slight inconvenience. Moderate deterioration of product properties may be noticed. **Z = 3** Defect description: Unfilled spaces in places of connecting reinforcement fibres	Failures happen from time to time. **R = 5**	High possibility of not detecting the failure, even if proper material examination applies. • Gravimetric survey. • Microscopic examination: – light, – electron, scanning. **W = 7**

TABLE 7. Continued

Material: Al/C, SEM　**Risk Priority Number** $P = 105$

Occluded gas bubbles	Minimal effect causing slight inconvenience. Moderate deterioration of product properties may be noticed. $Z = 2$ Defect description: Pores in a spherical shape, found in the entire casting, with greater size in its isolated parts	Failures happen from time to time. $R = 4$	Extremely high likelihood of the fault remaining undetected, even if proper material examination applies. • Macroscopic examination. • Gravimetric survey. • Microscopic examination: – light, – electron, scanning. • Microtomography. • Computer image analysis. • Ultrasound and radiological defectoscopy. $W = 10$

Material: AlSi11/ aluminosilicate, SEM　**Risk Priority Number** $P = 80$

Separated gas bubbles	Failure leads to slight dissatisfaction and inconvenience. Product does not satisfy needs or is a source of annoyance. Users notice flaws of the product. However, it may be authorised. $Z = 4$ Defect description: Gas pores in a regular spherical shape	Failures happen from time to time. $R = 5$	Low possibility of not detecting the fault before process completion. Verification using proper material examination after the technological process. • Macroscopic examination. • Gravimetric survey. • Microscopic examination: – light, – electron, scanning. • Microtomography. • Computer image analysis. • Ultrasound and radiological defectoscopy. $W = 4$

Material: alloy Wood / aluminosilicate, SEM　**Risk Priority Number** $P = 80$

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TABLE 7. Continued

Gas porosities	Failure leads to slight dissatisfaction and inconvenience. Product does not satisfy needs or is a source of annoyance. Users notice flaws of the product. However, it may be authorised.
	Z = 4
	
	Defect description:
	Small "clusters of pore production" in a spherical shape
		Failures happen from time to time.
		
		R = 5
			Low possibility of not detecting the fault before process completion. Verification using proper material examination after the technological process.
			• Macroscopic examination.
			• Gravimetric survey.
			• Microscopic examination:
			  – light,
			  – electron, scanning.
			• Microtomography.
			• Computer image analysis.
			• Ultrasound and radiological defectoscopy.
			W = 4

Material: AlSi11/ aluminosilicate, SEM   **Risk Priority Number *P* = 80**

TABLE 8

FMEA for the *continuity defects* subgroup (based on authors' work)

Defect	**Defect significance for customer (consequences, results) (*Z*)**	**Frequency (*R*)**	**Detectability (*W*) for conventional material castings [1,13] and composite castings using proper research methods**

Shrinkage cavities	The ramification of the failure is grave, the casting is disqualified, threatens the safety of users or violates the law.
	Z = 10
	
	Defect description:
	Irregular continuity breaks in the material, cone-shaped cavities with a frequently developed and rough surface
		Relatively low level of failures. Controlled process.
		
		R = 2
			It is highly unlikely that the failure will not be detected. Verification using proper material examination after the technological process.
			• Macroscopic examination.
			• Gravimetric survey.
			• Microscopic examination:
			  – light,
			  – electron, scanning.
			• Microtomography.
			• Computer image analysis.
			• Ultrasound and radiological defectoscopy.
			W = 1

Material: alloy Wood / aluminosilicate, macroscopic
Risk Priority Number *P* = 20
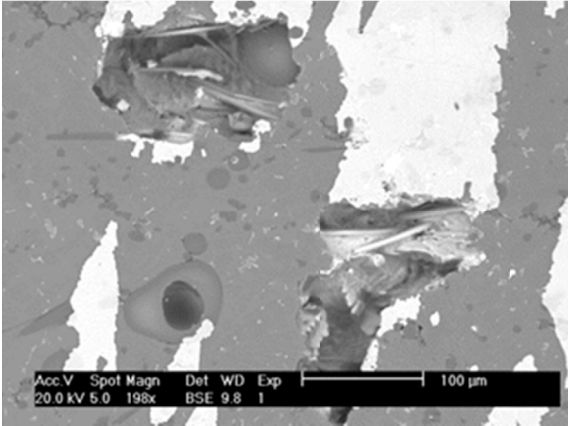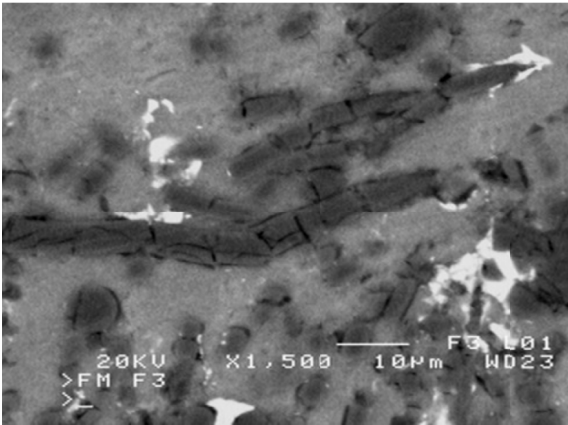
TABLE 8. Continued

Shrinkage Porosities	The ramification of the failure is grave, the casting is disqualified, threatens the safety of users or violates the law. **Z = 10**
	
	Defect description:
	Dense cluster of small porosities with sharp contours and rough walls
		Relatively low level of failures. Controlled process.
		
		R = 2
			Low possibility of not detecting the fault before process completion. The failure is evident, a few may remain undetected. Verification using proper material examination after the technological process.
			• Macroscopic examination.
			• Gravimetric survey.
			• Microscopic examination:
			  – light,
			  – electron, scanning.
			• Microtomography.
			• Computer image analysis.
			• Ultrasound and radiological defectoscopy.
			W = 1

Material: AlSi11/ aluminosilicate, SEM   **Risk Priority Number *P* = 20**

Fractures of reinforcement elements	Failure leads to slight dissatisfaction and inconvenience. Product does not satisfy needs or is a source of annoyance. Users notice flaws of the product. However, it may be authorised. **Z = 4**
	
	Defect description:
	Break, fracture, discontinuity of fibre
		Failures happen from time to time.
		
		R = 4
			Moderate likelihood of not detecting product fault before process completion. Verification using proper material examination after the technological process.
			• Microscopic examination:
			  – light,
			  – electron, scanning.
			W = 5

Material: AlSi11/C, SEM   **Risk Priority Number *P* = 80**

Matrix fracture	The ramification of the failure is grave, the casting is disqualified, threatens the safety of users or violates the law. **Z = 9**
	
	Defect description:
	Discontinuity in the matrix material
		Relatively low level of failures. Controlled process.
		
		R = 2
			Moderate likelihood of not detecting product fault before process completion. Verification using proper material examination after the technological process.
			• Microscopic examination:
			  – light,
			  – electron, scanning.
			W = 5

TABLE 8. Continued

Material: AlSi11/ aluminosilicate, SEM   **Risk Priority Number $P = 90$**

| Fractures on the matrix-reinforcement boundary | The ramification of the failure is grave, the casting is disqualified, threatens the safety of users or violates the law. **$Z = 9$** Defect description: Lack of connection between the matrix and reinforcement | Failures happen from time to time. **$R = 4$** | Moderate likelihood of not detecting product fault before process completion. Verification using proper material examination after the technological process. • Microscopic examination: – light, – electron, scanning. **$W = 5$** |

Material: AlSi11/ aluminosilicate, SEM   **Risk Priority Number $P = 180$**

| Hot crack | The ramification of the failure is grave, the casting is disqualified, threatens the safety of users or violates the law. **$Z = 9$** Defect description: Thin, often ramified crack cutting through the product, visible on casting surface as a zig-zag scratch | Relatively low level of failures. Controlled process. **$R = 2$** | Low possibility of not detecting the fault before process completion. The failure is evident, a few may remain undetected. Verification using proper material examination after the technological process. • Macroscopic examination. • Microscopic examination: – light, – electron, scanning. • Ultrasound and radiological defectoscopy. **$W = 3$** |

Material: AlSi9/B, SEM   **Risk Priority Number $P = 54$**

TABLE 8. Continued

Cold crack	The ramification of the failure is grave, the casting is disqualified, threatens the safety of users or violates the law.
	Z = 9
	
	Defect description:
	Thin crack, visible on casting surface as a regular scratch
		Relatively low level of failures. Controlled process.
		
		R = 2
			Low possibility of not detecting the fault before process completion. The failure is evident, a few may remain undetected. Verification using proper material examination after the technological process.
			• Macroscopic examination.
			• Microscopic examination:
			  – light,
			  – electron, scanning.
			• Ultrasound and radiological defectoscopy.
			W = 3

Material: AlSi11/ aluminosilicate, macroscopic   **Risk Priority Number P = 54**

4. Conclusions

An undeniable benefit of the FMEA method lies in the systematic approach to upgrade – oriented activities as it combines classic techniques and quality management tools [16, 17], demands approaching the problem from various perspectives [18, 19]. An elastic attitude is towards the specificity of a company, product/service may be noticed. According to FMEA assumptions, the higher the priority number (P) value, the greater the risk assigned to a given failure. The conducted analysis proves that the most catastrophic failure (the highest value of the priority number $P = 180$) affecting the quality of a composite casting is the failure: fractures on the matrix-reinforcement boundary, belonging to the continuity breaks subgroup. It is most significantly affected by the technological method (28.5%) and, to the same extent, by the material used to create composite castings, then management, the human factor and technological stance (14.2% each). It is fully comprehensible as the composite material may fulfil its function only if the matrix and reinforcement are fully "continuous." Cracks in the casting lead to product damage, consequently, to a failure of an entire mechanism in which a given element operates. The second place belongs to the defect ($P = 108$): deformation of the reinforcing structure. Damaging, fracturing the reinforcing structure (though not frequent $R = 4$) is a defect which deprives the composite of its basic function – strengthening the product. This may be caused by incorrect application of the technological process (e.g. too high pressure during saturation) or faulty materials. Third defect ($P = 105$) is: unfilled reinforcement spaces, also called insufficient saturation of the reinforcing structure with a liquid matrix metal. The factors of the greatest importance here include the technological method (26.6%) and material (same percentage), then the human factor (20%) as well as management and technological stance (13.3%). It is impossible to use a composite casting which is not fully infiltrated as it cannot provide a full-value final product.

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