Encapsulation of power electronics components for operation in harsh environments

MARIUSZ STOSUR, KACPER SOWA, WOJCIECH PIASECKI,
ROBERT PŁATEK, PRZEMYSŁAW BALCEREK

ABB Sp. z o.o., Corporate Research Center
Starowiślna 13A, 31-038 Kraków, Poland
e-mail: mariusz.stosur@pl.abb.com

Abstract: This paper reports on analyses and testing of sensitive power electronics components encapsulation concept, enabling operation in harsh, especially high pressure environments. The paper describes development of the concept of epoxy modules that can be used for protecting of the power electronics components against harsh environmental conditions. It covers modeling of the protective capsules using a simple analytical approach and Finite Element Method (FEM) models and validation of the developed models with the high pressure tests on samples fabricated. The analyses covered two types of the epoxy modules: of sphere- and elongated- shape, both with electrical penetrators that enable electrical connection of the encapsulated components with external power sources as well as other power modules and components. The tests were conducted in a pressure chamber, with a maximum applied pressure of 310 bars, for which online strain measurements have been conducted. The experimental results were compared with the simulation results obtained with analytical and FEM models, providing validation of the models employed. The experimental part of this work was conducted in collaboration with Polish Naval Academy in Gdynia.

Key words: passive components, encapsulation, epoxy, high pressure, measurements, harsh environments

1. Introduction

1.1. Background

Power electronic devices, such as frequency converters, often require adaptation for harsh environments, in which operation of the converters would either not be feasible or its reliability would become significantly compromised [1]. The approach that is presently being used for protecting the power electronics devices from external conditions is typically based on the concept where a complete device is located within an application-specific protective enclosure. In the case of design for operation under high pressure conditions a pressure vessel housing the entire unit, equipped with insulated electrical connectors, is the most straightforward approach

[2]. As the power converter power ratings and thus dimensions increase, the pressure vessel dedicated for encapsulation of the entire converter becomes heavy and unwieldy [1]. Moreover, high pressure requirements result in substantial wall thickness of the vessel. In this case the heat conduction from the power electronics components to the outside environment also becomes problematic [3]. Therefore, the industry is looking for alternative solutions enabling power electronics converters to operate under harsh environment conditions [4].

The approach presented in this paper is based on a concept of modularization of the converter that enables encapsulation of converter components instead of modularization of the entire device. As the modules requiring protection are of significantly smaller size as compared against the complete converter, the vessels used for encapsulation of the modules can be manufactured in a simple and standardized way using state-of-the-art manufacturing technologies such as reactive molding of an epoxy-based material. This enables the electrical connectors to be directly embedded into the already insulating vessel's walls, which reduces complexity of the overall capsule design.

The work presented in this paper reports on simulations and testing of the epoxy vessels equipped with electrical contacts [5-7]. The investigated vessels can thus be used for encapsulation of power electronics components to enable their operation in harsh environment [8, 9]. As far as the thermal conditions inside the vessels are maintained unchanged as compared to the regular conditions, the proposed solution can be used without requiring significant design changes to the design of present power electronics (PE) components.

1.2. Modularization of power electronics components for operation in harsh environment

The following essential power electronics components are considered as requiring protection by appropriate encapsulation by appropriate epoxy vessels maintaining atmospheric pressure inside:
 – power semiconductors, such as IGBTs, thyristors and diodes,
 – capacitors,
 – control units and gate drivers.

As indicated above the control units and gate drivers can also be proposed to be assembled in one-bar pressure vessels as separate units with manageable size and weight. Appropriate optical fiber links between gate drivers and power units, as used for signal transmission across a high voltage (HV) barrier, can be as well as electrical penetrators and can be embedded in the epoxy walls of the vessels at the manufacturing stage of the vessels.

In the following sections we present analytical calculations and FEM models for the epoxy capsules of elongated shape with electrical connectors embedded in the vessel's wall [1, 10].

2. Test object

2.1. Capsule description

The aim of this section is to present FEM models and analytical calculation for the epoxy elongated capsules with penetrators for low voltage (LV) electronics inserts.

Epoxy modules subjected to analysis and testing presented in this paper, were fabricated of pre-mixed epoxy system CW 229/HW 229 [13]. The fabricated epoxy capsules used for the entire tests are shown in Fig. 1.

Fig. 1. Epoxy elongated module for PE packaging – capsule profile

2.2. Calculation of wall thickness based on crash pressure

The wall thickness of the capsule was determined based on analytical formulas for the crash pressure defined as the pressure at which the mechanical crash is expected to occur due to mechanical strain tensions in the capsule subjected to external pressure.
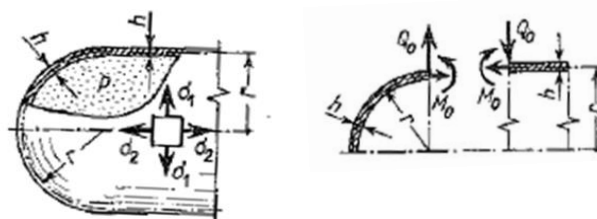

Fig. 2. Mechanical vessel (cylindrical shape with spherical bottom) including bending: *h* is the thickness, *r* is the radius, *p* is the pressure [11]

The crash pressure was assumed as the main failure criterion for the epoxy modules investigated in this paper. For calculation of the crash pressure, standard formulas were employed, as known for a cylindrical shape with a spherical bottom (see Fig. 2).

The crash pressure *p* was calculated according to the formula:

$$\sigma_{max} = 1.032 \frac{p \cdot r}{h} \Rightarrow p = \frac{\sigma_{max} \cdot h}{1.032 \cdot r}, \tag{1}$$

where: σ_{max} is the maximum stress, *p* is the pressure, *r* is the radius, σ_{max} is the maximum stress.

For the capsules investigated in this work, the radius *r* of the capsule was assumed as 0.058 m. For testing, a maximum pressure *p* of 350 bar (35 MPa) was selected. For these values, according to (1), the thickness *h* of the epoxy module of the elongated shape was calculated as:

$$h = \frac{1.032 \cdot p \cdot h}{\sigma_{max}} = \frac{1.032 \cdot 35 \cdot 0.0058}{130} = 0.01611 \text{ m} .$$

The wall thickness h of the epoxy module, calculated for a maximum pressure p of 350 bar, is thus equal to 16.1 mm (0.01611 m). This value was further selected to be confirmed with high pressure testing.

3. FEM model of test object

Numerical analysis on the failure criteria of the capsule loaded with high hydrostatic pressure (330-370 bar) have been performed using an ANSYS commercial Finite Element Analysis (FEA) code [1, 10]. The capsule was assumed to be made of the CW 229/HW 229 epoxy resin system filled with a mineral fiber-like phase.
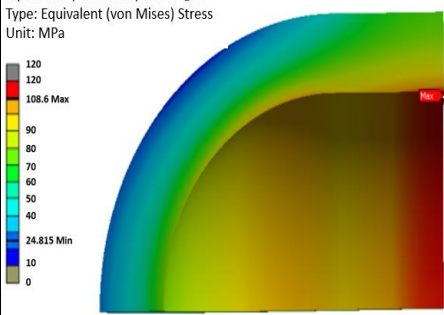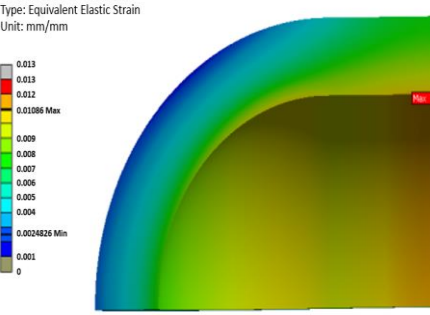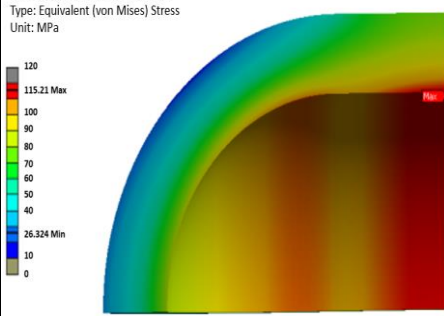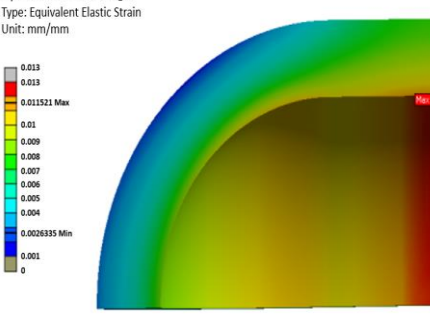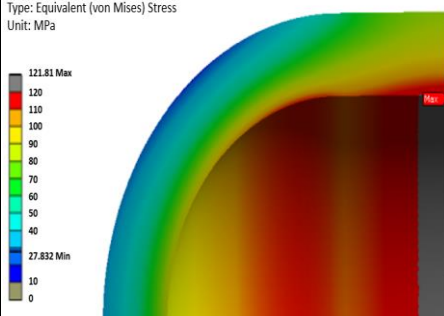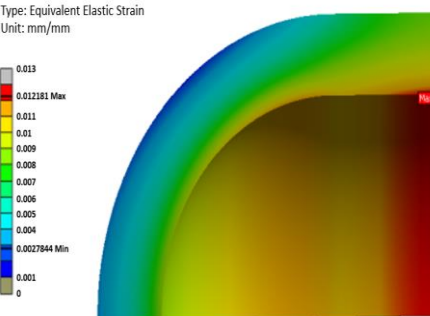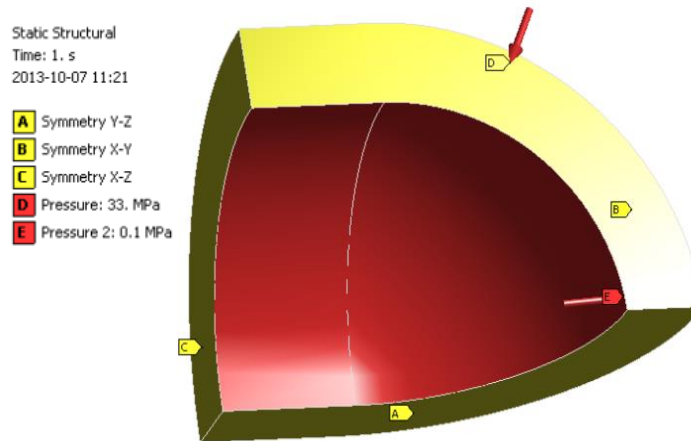

Fig. 3. FEA model for analyses

Elastic properties of the epoxy were assumed for static structural analysis only, since the real non-linear as well as time-dependent behavior of the plastic is not known for the moment.

However, basing the analyses on the elastic properties was good enough for the preliminary evaluation of the capsule, to evaluate its resistance to the external high pressure conditions. The internal pressure was assumed as 1 bar. The ANSYS model used for the analyses is presented in Fig. 3.

Only 1/8th of the model was used for the analysis since the model is symmetrical in all three major symmetry planes. Hexa-dominant quadratic mesh was used for discretization of the model. Distribution of the mesh is presented in Fig. 4. The hexa-dominant mesh consists of both hexahedral and pyramid-like elements with mid-side nodes included.

Table 1. Simulation results using ANSYS environment

|	Failure criteria	
	Equivalent stress	**Equivalent strain**
Bending at load pressure 330 bars *Grey region in the legend denotes values above the limit*	Equivalent (von Mises) Stress @ 5 Type: Equivalent (von Mises) Stress Unit: MPa 120 120 108.6 Max 90 80 70 60 50 40 24.815 Min 10 0	Equivalent Elastic Strain @ 5 Type: Equivalent Elastic Strain Unit: mm/mm 0.013 0.013 0.012 0.01086 Max 0.009 0.008 0.007 0.006 0.005 0.004 0.0024826 Min 0.001 0
	108.9 MPa	**1.09%**
Bending at load pressure 350 bar *Grey region in the legend denotes values above the limit*	Equivalent (von Mises) Stress @ 4 Type: Equivalent (von Mises) Stress Unit: MPa 120 115.21 Max 100 90 80 70 60 50 40 26.324 Min 10 0	Equivalent Elastic Strain @ 4 Type: Equivalent Elastic Strain Unit: mm/mm 0.013 0.013 0.011521 Max 0.01 0.009 0.008 0.007 0.006 0.005 0.004 0.0026335 Min 0.001 0
	115.2 MPa	**1.15%**
Bending at load pressure 370 bar *Grey region in the legend denotes values above the limit*	Equivalent (von Mises) Stress @ 3 Type: Equivalent (von Mises) Stress Unit: MPa 121.81 Max 120 110 100 90 80 70 60 50 40 27.832 Min 10 0	Equivalent Elastic Strain @ 3 Type: Equivalent Elastic Strain Unit: mm/mm 0.013 0.012181 Max 0.011 0.01 0.009 0.008 0.007 0.006 0.005 0.004 0.0027844 Min 0.001 0
	121.8 MPa	**1.22%**
Failure Criteria based on technical data sheet provided by the supplier	Tensile strength: …………………80 ÷ 90 MPa Bending strength: ……………...110 ÷ 120 MPa Compressive strength: …………...170 ÷ 190 MPa Elongation at break: ……………..1.3 ÷ 1.5%	
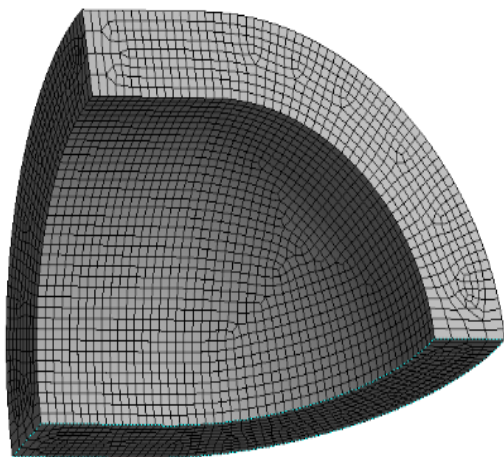
Fig. 4. Hexa-dominant mesh used for the model

As the analysis was performed with assumption of fully elastic behavior of the material model, thus the final results can be treated as an estimation of the failure behavior. For the hydrostatic pressure tests, the geometry of the cylinder with spherical endings having 17 mm wall thickness was selected. Table 1 presents calculated stress and strain, with estimates of the load bending pressure to failure.

Stress evolution under the pressure loading above 330 bar can lead to the failure in bending mode in the range of 335-365 bar (average 350 bar). Taking into consideration the von Mises stress failure criterion in bending (as provided by the resin system supplier), it can be stated that the failure can be potentially initiated just above 330 bars. This is because at this pressure level, the lower limit of admissible equivalent stress (at break) is reached. On the other hand, the strain at the break criterion is reached at 395 bars.

It is emphasized however, that the damage of the capsule was evaluated based on the elastic structural analysis only and a more precise evaluation could be done after a careful estimation of the non-linear (elastic-plastic or even visco-elastic) response of the material [1].

4. Strain measurements under high pressure conditions

4.1. High pressure test set-up

The experimental part of this work was prepared and conducted at Polish Naval Academy in Gdynia. The test set-up used for high pressure testing is presented in Fig. 5. The high-pressure chamber has a cylindrical shape of 190 mm diameter and 260 mm length (which constitutes approximately 9 dm3 volume). The maximum pressure that can be obtained in the chamber is 350 bar (35 MPa). The tests reported in the present work were performed with 310 bar.

The test set-up allows to investigate an impact of mechanical stress on the capsule mechanical endurance and tightness aspects for epoxy materials.
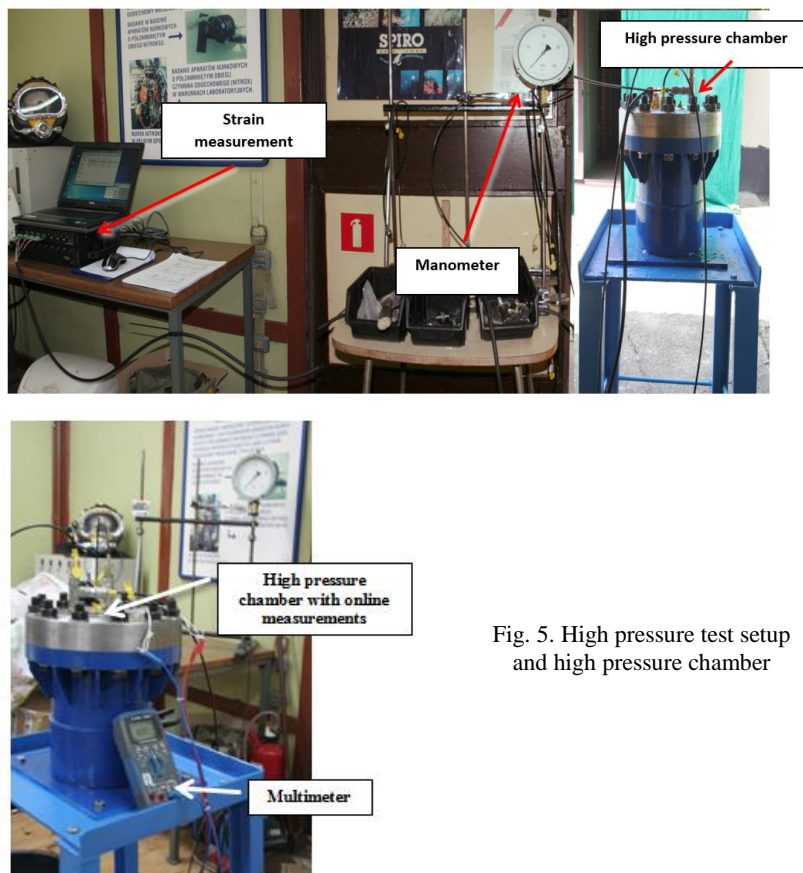
Fig. 5. High pressure test setup
and high pressure chamber

The main testing options of the test set-up used, included long-term tests with an assumed load profile of time varying pressure. As the pressure chamber was equipped with powering cables, on-line measurements of mechanical strains were conducted during the high pressure tests.

The high pressure tests, performed in the test set-up shown in Fig. 5, were conducted according to the test profile, presented in Fig. 6.

4.2. Strain tensors arrangements

The strain gauges were connected to an 8-channel Wheastone Bridge, Strainbook 616 model provided by IOTech Company [12]. It allowed precise measurements of the sensor resistance change during pressure tests, and automatically provided related strain values. Measured values were further recalculated to the stresses, based on the generalized Hook's law according to the following equations:

$$\sigma_1 = \frac{E}{1-v^2}(\varepsilon_1 - v\varepsilon_2)\,, \tag{2}$$

$$\sigma_2 = \frac{E}{1-v^2}(\varepsilon_2 - v\varepsilon_1) , \tag{3}$$

where: E is the module of elasticity, v is the Poisson ratio, ε_1 is the strain in direction 1, ε_2 is the strain in direction 2.

The overall strain tensors arrangement during the measurements is shown in Fig. 5.
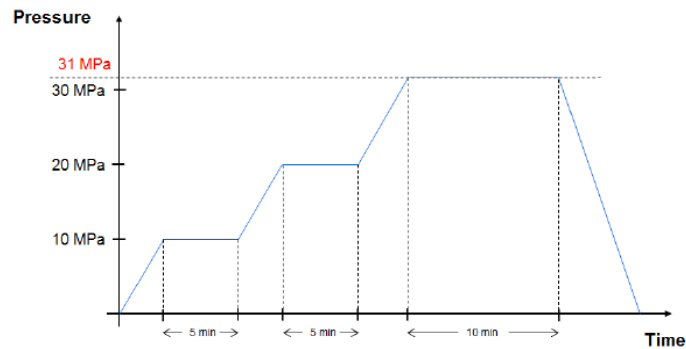

Fig. 6. "*Test profile*" during the high pressure tests

4.3. Strain tensors arrangement

The analyzed epoxy module was equipped with foil strain gauges having resistance equal to 120 Ω. Location of the strain gauges is presented in Fig. 7. At each location, the strain gauges were positioned in two directions, which was for the purpose to monitor strains in axial and tangential directions. As depicted in Fig. 7, channel 1 (Ch1) and channel 4 (Ch4) are strain gauges in the axial direction, while channel 2 (Ch2) and channel 3 (Ch3) are strain gauges in the tangential direction.
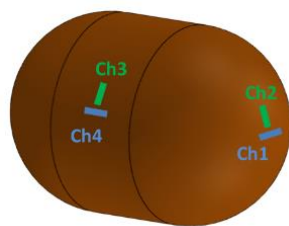

Fig. 7. Position of the strain gauges on the coil during test (left), and coil with attached sensors (right)

The strain gauges were attached to the epoxy capsule by the glue PATTEX Repair Epoxy. The example of the measurement point attached to the epoxy surface is presented in Fig. 8.

4.4. Strain tests preparation

The tests were performed in the following way. Attaching tensors (gluing strain gauges and cable soldering) were mounted one day before the actual high pressure tests. Connecting cables from the strain gauges were connected to the bridge for calibration of the stain measurements.

The epoxy capsule was placed inside the chamber, the top cover of the chamber was fixed with screwing.

Fig. 8. Strain measurements system – examples of the measurement points
on the spherical (left) and cylindrical part (right)

Finally, the high pressure was supplied to the chamber, and the tests were performed according to test profile, as presented in Fig. 6.
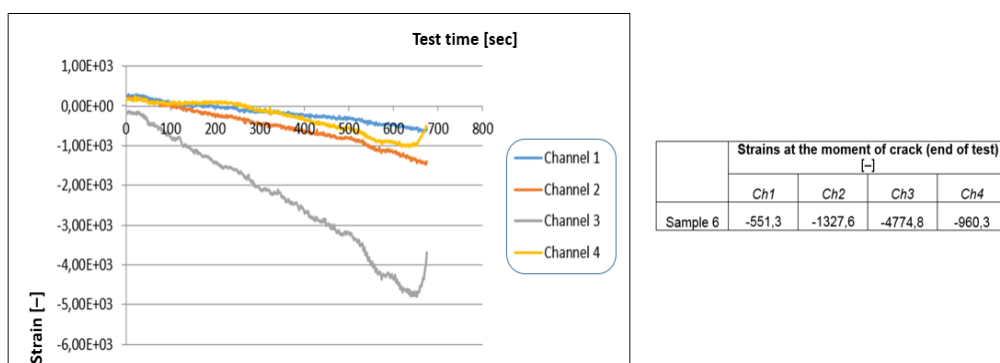

	Strains at the moment of crack (end of test) [–]			
	Ch1	Ch2	Ch3	Ch4
Sample 6	-551,3	-1327,6	-4774,8	-960,3

Fig. 9. Strain readings during pressure test for analysed sample number 6

4.5. Strain measurement results

Fig. 9 shows strain measurement results obtained for the selected epoxy capsule which exemplifies the most important observations.

Strain gauges were applied and calibrated at room temperature (assumed as 0 stress @ 20°C) before the test. It means that the calibration was done before the samples were inserted to the chamber, and before screwing of the cover. Thus, some strains are observed at the beginning of the strain chart (see Fig. 9). The strain gauges were glued by using PATTEX Repair Epoxy. Visually, one can observe in Fig. 8 that the strain gauges are over-molded by the glue. The glue is visible between some strain gauges and samples a glue was visible which may have an impact on the final values of the strains, depending on the thickness of that layer. Representative strains diagrams are presented in Fig. 9. The most critical part of the tested capsule is a cylindrical part as shown in Fig. 7. The measured stresses for this part are depicted in Fig. 9 (Ch3 and Ch4).

To obtain an absolute stress value from the above measurements of strain values, the residual stress (after manufacturing process) was added, which was estimated to be approximately 15÷30 MPa for epoxy resin.

4.6. Verification of FEM models with measurement results

Table 2 presents results of the analytical calculation (as reported in Section 2 above), the simulation results obtained with FEM models (as reported in Section 3 above), and the measurements obtained in a high-pressure chamber. The results are for the epoxy capsule of elongated shape, with a wall thickness of 17 mm.

Table 2. Comparison of crash pressure obtained from calculation, simulation, and high pressure measurements, for tested object of epoxy elongated capsule, with a wall thickness of 17 mm

Crash pressure		
Calculation	**Simulation**	**High Pressure Tests**
350 bar	350 bar	330 bar [*)]

The arrangement of the test set-up was applied, so as to allow for performing the on-line electrical measurements during the high pressure tests (powering cables inside a chamber, see Fig. 5 and Fig. 10).
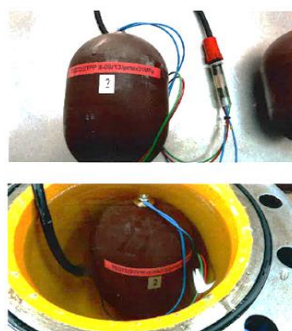

Fig. 10. High pressure test with online measurements – typical photo documentation

During the tests, online temperature was also measured (measurements of a working device under tests). Typical temperature curves for a capacitor and power resistor are shown in Fig. 11.

It can be observed that there is no significant difference in temperature during the high pressure tests. For the components used for testing, the temperature is below the temperature limit under normal device working conditions.

5. Conclusions

The objective of this paper was to demonstrate and test the encapsulation concept for power electronic modules under harsh environment conditions. The concept is based on the epoxy

capsules with electrical connectors embedded in the capsules walls. The paper presents results of the high pressure testing supported with analytical and FEM calculation of the epoxy modules crash pressure. The measurement results provided validation of the FEM models developed. Online temperature measurements of a working device under high pressure tests illustrated feasibility of electrical connectors embedded in the capsules walls.
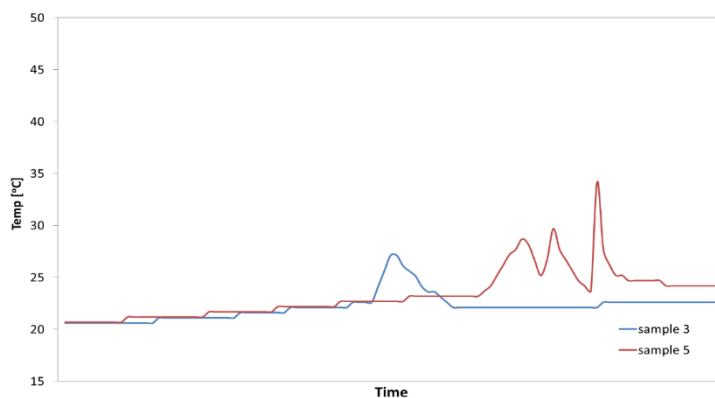

Fig. 11. Temperature characteristic during the high pressure tests – for sample 3 (tantalum capacitor) and sample 5 (power resistor)

During the high pressure tests the strain measurements were performed using a high pressure setup. A maximum pressure of 330 bar (33 MPa) was applied and measured.
Furthermore, it can be noted that:
  – epoxy elongated capsules with electrical contacts, tested under a high pressure of 330 bar, passed the tests with positive results;
  – epoxy elongated capsule with LV electronics insert was tested with positive results;
  – analytical calculation and FEM simulation results were confirmed with real high pressure tests results.

The developed FEM models, verified with high pressure tests for the proposed capsules of elongated shape, can be used for other shapes and sizes of the capsules, for which analytical solution or testing facilities (or both) are not viable.

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