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The Design of a Cast Suspension Element, Determined by the Pressure Wave

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Abstract

Based on the example of the development process of the cast suspension of a special-purpose vehicle the application of the integrated engineering design methodology (ICME – Integrated Computational Materials Engineering) and the development of construction has been presented. Identification of the operating and critical loads, which are guidelines for carrying out the structure strength shaping process, material and technological conversion, are due to the needs and requirements of the suspension system and the purpose and objectives of the special mobile platform.

The developed cast suspension element construction includes the use of high-strength AlZnMgCu aluminum alloy. The properties of the used alloy and designed shape allows for the transfer of assumed operating loads in normal exploitation conditions and in the dynamic, critical loads to the susceptibility to damage in the assumed casting areas.

For the proposed design, conducted numerical analyzes includes the impact of the shock wave pulse on the occurrence of the destructive stress fields. Based on their distribution, the areas of possible decomposition of the structure of the design element were estimated. The results allowed to devise an element with predicted destructions that allow to absorb a significant part of the impact energy of the shock wave front, which is also the buffer zone for the propagation of destruction for the critical kinematic nodes of the system.

Keywords: Multi-purpose cast, Optimal design, Mechanical properties, AlZnMgCu alloy, IDE explosion protection

1. Introduction

Standard practice in a modern design approach for shaping of casting design assumes the widespread use of computer simulations, not only in the analysis of individual parts but also in the simulation of coupling phenomena occurring in the design of complete assemblies. The integrated design process, which consider material science, technology and manufacturing aspects, allows for a complete validation of the accepted design assumptions and a holistic evaluation of cooperation of the components under assumed operating conditions.

The system of integrated design must be initiated by the process of identifying the requirements and utility of the structure. These guidelines are the key to the rapid introduction of the finished product to the market. The basic research in the filed of material science, selection of suitable manufacturing technology and postprocessing methods must be subordinated to the main criteria and taken into account at each stage of the design process.

A measurable effect of this approach is the optimization of the shape, weight or rigidity of the structure associated with the use of modern, engineering materials, while taking into account both, the aspect of ecology and the economics of the manufacturing process [1-3].

The AlZnMgCu alloy has been used in the design process of the suspension construction, based on design guidelines and literature data. The use of AlZnMgCu alloys in the process of casting responsible structures remains in the process of testing and trials [4]. The 7052 alloy is used in the plastic forming process and has strength near 500 MPa and 20% of elongation. Beside that the alloy is not normally used in casting process it has a great potential for applications for cast, high-strength structural components.

Due to the specific of thermophysical properties the analyzed AlZnMgCu alloy, is characterized by a large solidification range of near 150°C, e.g. from the MAGMASoft material database $T_{liq} = 630^{\circ}\text{C}$, $T_{sol} = 470^{\circ}\text{C}$. For an example AlZnMgCu cast alloy with Zn = 5.8, Mg = 1.9 Cu = 1.6, the ATD derivative curve is shown in Figure 1.

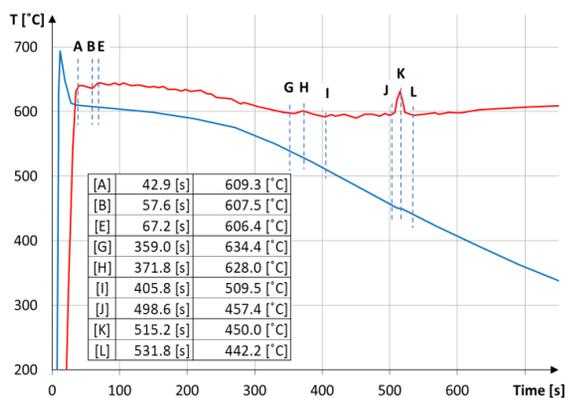


Fig. 1. The ATD derivative curve for AlZnMgCu cast alloy with Zn = 5.8, Mg = 1.9 Cu = 1.6 [wt %] ($T_{liq} = 609^{\circ}\text{C}$, $T_{sol} = 442^{\circ}\text{C}$)

It is important to optimize the three key elements, Zn, Mg and Cu, having effect on the strength and ductility of the alloy. At the same time, the elimination at the casting stage of one of the reinforcement mechanisms, such as cold working during plastic processing, necessitates such control of the alloy structure, the development of the appropriate chemical composition and the manufacturing technology so that the solidification process and subsequent heat treatment determines the desired strength properties. As a result of the work carried out, material and structural conversion of the suspension element is to be achieved, resulting in the casting process from an aluminum alloy, which in its structure will allow to achieve the required tensile strength and plasticity.

2. Modeling of a pressure shock wave of an explosion

The explosion process is generally understood as the action of the pressure wave and the byproducts generated during the detonation of the solid charge. In the description of the effect of shockwave pressure on structural elements numerical methods are used. The explosion process introduces the interactions between two centers are taken into account: air - described finite elements

in Euler's equations and solid deformable discretized by a Lagrange grid [5,6].

The explosion detonation pressure, described by the Jones-Wilkins-Lee equation (JWL), is the basic parameter for describing the explosion, allowing the value of this pressure to be determined based on the parameters of the explosive [7], [8]:

$$p = A \left(1 - \frac{\omega}{R_1 v}\right) e^{(-R_1 v)} + B \left(1 - \frac{\omega}{R_2 v}\right) e^{(-R_2 v)} + \frac{\omega \rho_0 e}{v} \quad (1)$$

where:

$v = \frac{\rho_0}{\rho}$ - is the relative volume at the selected time of the explosive,

e - internal energy of the charge per unit reference volume [kJ/cm³],

A, B, R_1 , R_2 , ω - characteristic coefficients for an explosive materials (for example trotyl (TNT): A = 524 GPa, B = 4.9 GPa, $R_1 = 4.579$, $R_2 = 0.85$, $\omega = 0.23$) [9].

The equations for the spherical load are used to determine the maximum value of shock pulse pressure applied to the projected casting element during the modeling of Improved Explosive Device (IED) charge explosion [9]. For analyzes of the shock absorber rocker arm, the dependence of the maximum pressure on the front of the wave was taken from the distance reduced from the center of the spherical charge and the pressure impulse value as wave energy. The reduced distance Z is directly proportional to the distance R from the center of charge and inversely proportional to the cube root of the mass of the load ($m = 5$ kg):

$$Z = \frac{R}{\sqrt[3]{m}} \quad (2)$$

For the analyzed IED mass, based on Kinney-Graham's pressure relationship [8]:

$$p(Z) = \frac{0.1 \cdot p_a \cdot 808 \left[1 + \left(\frac{Z}{4.5}\right)^2\right]}{\sqrt{1 + \left(\frac{Z}{0.048}\right)^2} \cdot \sqrt{1 + \left(\frac{Z}{0.32}\right)^2} \cdot \sqrt{1 + \left(\frac{Z}{1.35}\right)^2}} \quad [\text{MPa}] \quad (3)$$

(the preset atmospheric pressure p_a), the maximum wave pressure in the zone of contact with the rocker arm, calculated using the equation (3), is shown in Figure 2.

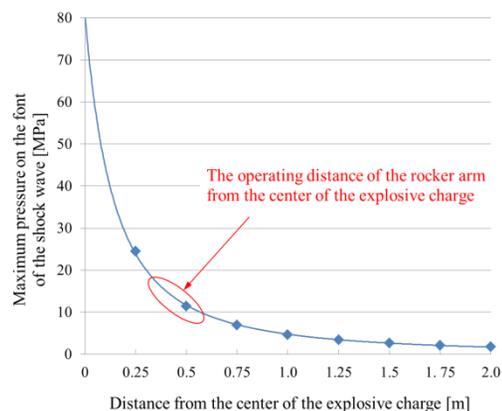


Fig. 2. Maximum shock wave pressure for assumed conditions of the rocker arm ($m = 5$ kg, $R = 0 \div 2$ m) [author]

For numerical analysis, the shock wave pressure value of $p_{\max} = 15$ MPa was assumed, with the area of the analyzed element from the mass center of the assumed explosive charge of about 0.3 m.

Based on the dependency:

$$i_p = \frac{0.067 \cdot \sqrt{1 + \left(\frac{Z}{0.23}\right)^4}}{Z^2 \cdot \sqrt{1 + \left(\frac{Z}{1.55}\right)^3}} \quad [MPa \cdot ms] \quad (4)$$

the impulse value of $i_p = 2,48$ [MPa*ms] was assumed for the assumed time point during the $t = 1.2$ ms explosion.

3. Structure design process

The design process of the castings which are replacing wrought or welded components, allows for much greater flexibility in the choice of structural material as well as in shaping the geometry itself. Particularly important is the aspect of modeling zones with different usable functions.

A modern approach to structural design involves a two-step process of using topological optimization

- the Soft Kill Option, in which the initial set of solutions describing the shape of an element is arbitrary, bounded by boundary conditions, structural dimensions and functional properties of the structure.
- in the next stage, the method of design optimization for the designing of construction nodes, called Computer Aided Optimization.

The use of numerical methods in design process with shape optimization methods, allows the removal of excess material from construction areas with stress values below the assumed safety level, while maintaining the required performance characteristics of the structure [3].

In the case of the suspension and rocker arm design for a special-purpose vehicle, the design process assumed a change in manufacturing technology, replacing the welded steel structure with cast aluminum AlZnMgCu alloy with increased strength properties. The main assumptions of construction and operation included the following aspects:

- suspension safe operation under normal operating conditions,
- maximum resistance for the Improved Explosive Device (IED) explosive load and maximum dissipation of the pressure shock wave,
- destruction of an element as a result of the IED charge in the assumed construction areas, thereby limiting the impact of the forces acting on the suspension kinematic nodes,

Due to the specific use of the vehicle, it was possible to model movement at low cruising speeds and for such assumptions a numerical simulation of the kinematics of the system was carried out during the passage of the experimental track. Identification of the component loads of the suspension elements allowed to determine the maximum values of the forces acting on the vehicle wheel during normal suspension operation. In further numerical analyzes of the load of the new rocker structure, the maximum values of the force components were assigned to the rocker switch

knob. Five variants of active forces were adopted, corresponding to the actual conditions of extortion while traveling on uneven terrain [3].

As a result of the development work of the cast structure, the 3D model of the lower and upper swing arm has been developed at the subsequent stages of shaping the element's topology, assuming the two-dimensional cross-section of the arms of the main structure. Numerical analyzes carried out at subsequent stages of the optimization of the shape of the element allowed to redefine the structure for which the strain of the material at the assumed loads allows for safe use of the suspension. The proposed construction concept is shown in Figure 3.

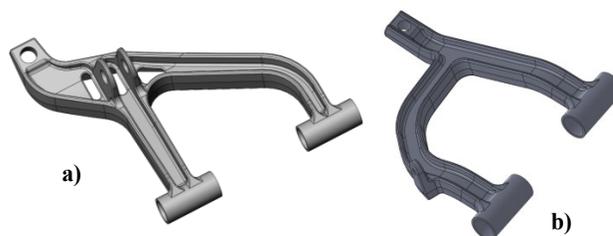


Fig. 3. The prototype design of the swing arms as the element of suspension of the transport platform

At a further stage, the process of shaping the bottom swing arm will be discussed. This is the most significant element of the force imposed by the shock wave pulse as a result of explosion of an explosive charge of IED (of mass up to 5 kg).

Due to the assumptions regarding resistance to shock wave pressure and the initiation of element destruction, the assumed areas, the formation of specially shaped cavities located in the lower part of the casting was used in modeling the final shape of the detail. The primary task of these areas, initially designated as destructive initiation zones, was to take as much energy from the shockwave pressure as possible, preventing the explosion pressure from transferring the rocker arm mounts to the vehicle frame. The final design of the lower rocker arm with marked zones is shown in Figure 4. This suspension element absorbs the biggest load during the explosion.

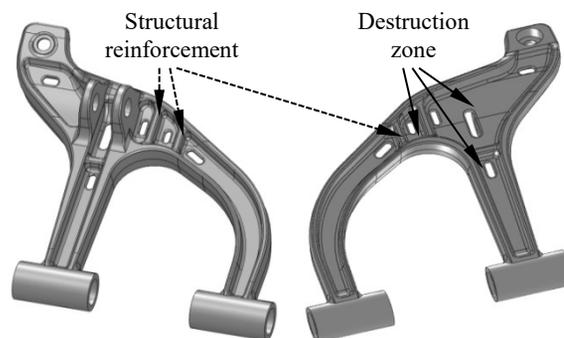


Fig. 4. The final shape of the prototype structure of the bottom swing casting together with the assumed destruction zone

4. Research methodology

AlZnMgCu alloy was selected for the special suspension design of the vehicle, the average chemical composition of which is shown in Table 1.

Table 1.

The chemical composition of AlZnMgCu alloy, [wt %]

Zn	Mg	Cu	Mn	Zr	Be	Ti	Fe	Si	Al
5.8	1.98	1.53	0.17	0.13	0.14	0.1	0.08	0.06	rest

Casting of the bottom swing construction was made in the sand mold, and its weight of about 8 kg has been reduced by about 28% in relation to the welded steel part (above 11 kg). Because of the need to obtain the desired strength properties of the material, the castings were subjected to a two-stage heat treatment process T6 [10,11]:

1 - Annealing:

- for 8.5 hours at 450°C,
- for 1.5 hours at 500°C
- cooling in water at 80°C

2 - Aging:

- for 30 hours at 120°C

Test specimens were cut from the castings to determine strength properties in a static tensile test, and at the stage of further tests to determine the fatigue strength [4]. The diameter of the sample was $\varnothing = 6\text{ mm}$ and its measuring length 30 mm. Samples were cut from two areas (a and b), in which simulation of the estimated strength of the material carried out in the MAGMASoft program shows large variations in the cast area. The higher strength, approximately 420 MPa, occurs in area a. In area b, in which the riser was positioned, extending the solidification time, the strength dropped to the value below 380 MPa.

Distribution of predicted strength R_m of the swing arm cast after the casting process and heat treatment T6 and cut out areas for strength tests (a and b) are shown in Figure 5.

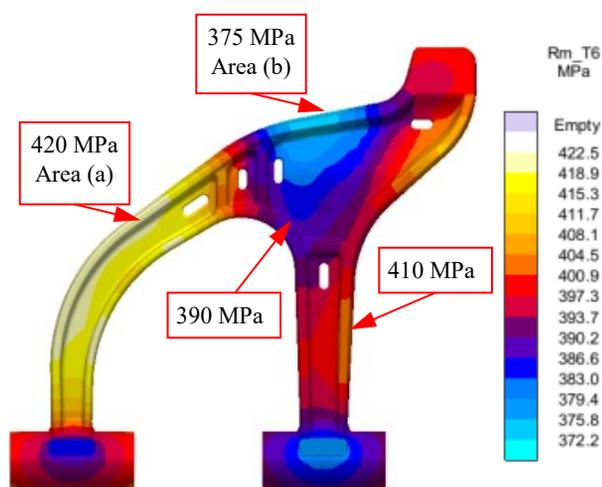


Fig. 5. Predicted strength distribution R_m characteristic areas of the swing arm

The results of the basic strength properties, after the heat treatment according to the proposed scheme, for the samples cut from the swing arm are shown in Table 2.

Table 2.

The results of the strength tests of specimen from the a and b area of the casting

Specimen	Area a)		Area b)	
	R_m [MPa]	A [%]	R_m [MPa]	A [%]
1	397	0,77	397	0,69
2	444	0,74	361	0,60
3	470	1,21	398	0,73
4	467	1,28	399	0,65
5	(a defective specimen)		362	0,59
Average	444	1,00	383	0,65

Numerical analyzes of the loaded casting of the suspension structure were carried out using ANSYS software, using conjugate simulation, defining in the first step the operating pressure due to the explosion of an explosive of not more than 5 kg IED charge.

All variants of the simulations includes only the analysis of the pressure changes in the medium surrounding the rocket casting caused by the explosion of the cargo, excluding the heat phenomena and the impact of the solid products (IED splinters) occurring during the detonation process.

For this purpose, the area of the gaseous medium (air) was modeled (Figure 6), in which the shape of the casting element together with the hydroactive cylinder and the explosion initiation zone. Estimate the spread of the shockwave front using the discretization of the analyzed area in Euler's terms was based on tetrahedral elements.

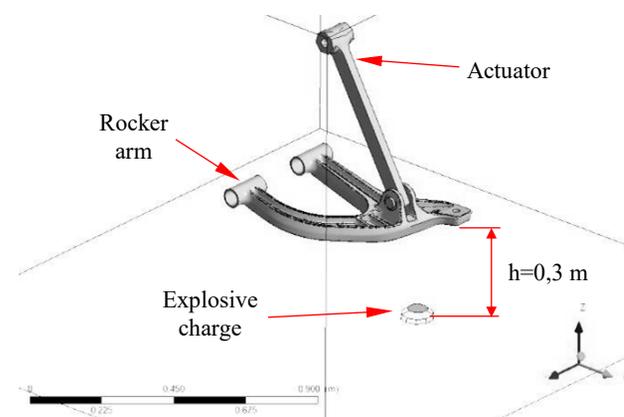


Fig. 6. Model of impact analysis of explosion shock pressure on cast die cast

During the analysis, the flow tracers (corresponding particle velocity on the front of the shockwave) velocity distribution of the analyzed castings. The distribution of the pressure fields, shown in Figure 7, was determined by the shock wave front, assigned to the surface of the pendulum structure analyzed.

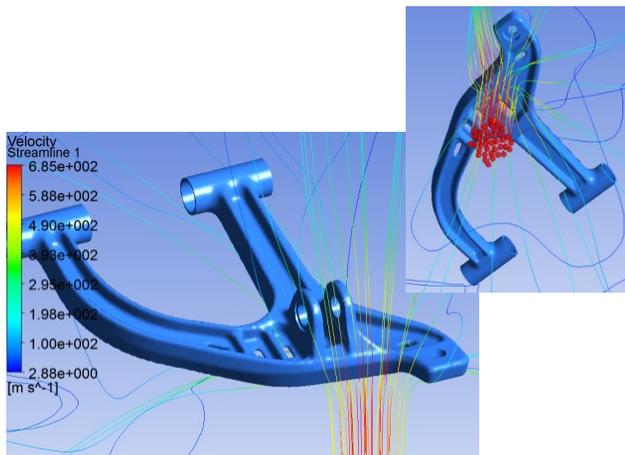


Fig. 7. Distribution of speed of selected flow tracers during simulation of IED cargo explosion

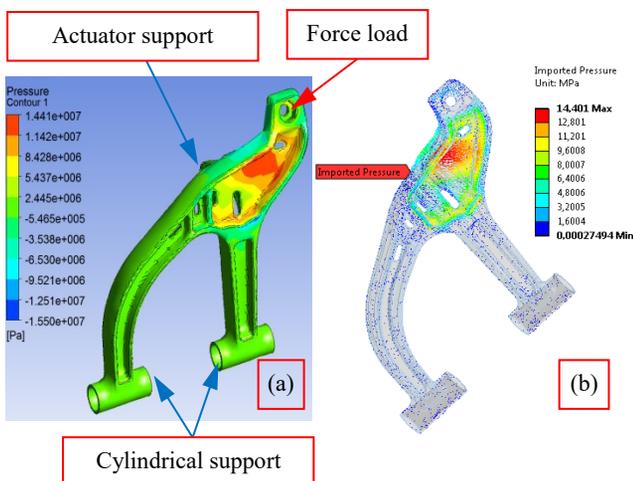


Fig. 8. Distribution of pressure from the shock wave front impact module, on the surface of the cast element (a) and pressure map imported into the strength analysis module (b)

The pressure distribution on the surface of the casting element (Fig. 8) was implemented as an initial condition for analysis of the stress distribution and displacement in the developed swing arm structure, taking into account the boundary conditions assigned to the kinematic node of the model. The maximum stress in material was achieved, assuming only the shock wave pressure. The impact of loads on the driving forces during the ride and on the mass of the vehicle is not taken into account. Additionally, in the analysis, the actuator model was adopted as a rigid rod. This simplification is due to the inertia of the actuator which, at the assumed time of the $t = 1.2$ ms explosion, will not react properly because the assumed valve response time for a single actuator is set at $t = 0.25$ s.

The analysis allowed to determine the maximum values of stresses, as determined by the Huber-Mises hypothesis, and their distribution is shown in Figure 9.

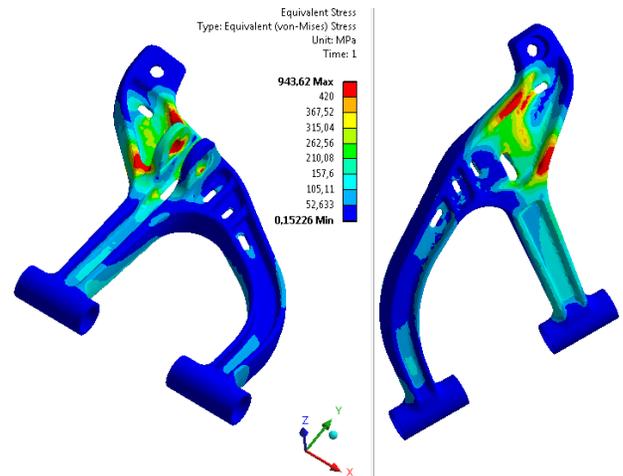


Fig. 9. Areas of concentration von Mises stresses in casts under impact of shock wave pressure

The impact of the IED explosive charge under the vehicle wheel causes a strong stress concentration, located in the front of the rocker arm, and a maximum value of over 940 MPa exceeds the permissible strength of the construction material.

Based on the data from the analysis, the values and distribution of the material safety factor fields, understood as the ratio of the adiabatic yield point of the assumed material to the maximum local stress value, were estimated. The schematic distribution shown in Figure 10 confirms that the modeled zone will take over the most shock wave load.

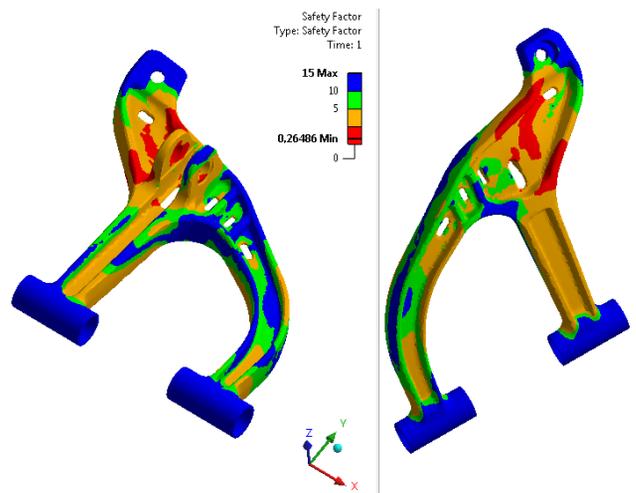


Fig. 10. Location of potential material destruction zones based on estimated safety factor

The start-up process of destruction of the rocker arm will make it possible to minimize the transfer of critical forces to the chassis of the vehicle (movable sleeves) and thus, in the event of damage, to guarantee further vehicle mobility by facilitating the replacement of the damaged suspension member.

6. Conclusion

Analysis of the stress distribution in the cast structure of the shock absorbing shock absorber element allowed to estimate and locate the areas most exposed to damage. Due to the specifics of the model, it is difficult to reconcile two divergent assumptions: to ensure the trouble-free operation of the suspension components in difficult terrain and to be susceptible to damage due to fast-changing external loads.

Appropriate modeling of the shape of the structure, based on the numerical simulation guidelines, has allowed the development of a cast with specially designed zones that are "initiators" of destruction, absorbing a significant part of the energy transmitted by the shock wave. This process, in the event of an explosion under the wheel of the vehicle, will allow for easier destruction of the suspension component, limiting the possibility of transferring heavy loads to the kinematic nodes of the vehicle frame.

On the basis of the simulation of the influence of the maximum shockwave pressure (assumed $p_{max} = 15$ MPa) on the casting structure, the maximum velocity of the wavefront in the contact area with the lower surface of the swingarm at $V \leq 680$ m/s was determined. This value corresponds well with the literature data on the shock wave front after a given time since the initiation of the explosion.

The imported pressure field affecting the lower surface of the rocker arm allowed for the estimation of the maximum value of reduced stresses and the location of the concentration of the highest strain of the rocker arm material. The maximum value of reduced stress of approximately 940 MPa is critical for the AlZnMgCu alloy to be installed. Such a load on the structure of the swingarm structure will lead to its destruction in the assumed areas in the event of detonation of IED cargo with a mass not exceeding 5kg.

The integration of the obtained results from the analysis of flow phenomena and operational analyze allowed to stated that the process of shaping the rocker arm structure has led to the modeling of the structure fulfilling both assumptions: resistance to operating loads and susceptibility to explosive pressure change.

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- Statutory activity no 11.11.170.318/task10: Numerical analysis of fatigue phenomena in foundry materials. "Numeryczna analiza zjawisk zmęczeniowych w tworzywach odlewniczych".

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