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EFFECT OF CAVITATION EROSION ON MATERIAL MECHANICAL PROPERTIES AND MACHINE ELEMENTS PERFORMANCE

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***Abstract**: Cavitation, a frequent phenomenon caused by the implosion of vapour or vapour-gas bubbles in fluid, commonly occurs in mechanical systems. Cavitation erosion leads to surface damage, which can reduce machine performance or even completely disrupt its operation. In addition to fluid characteristics and the geometry of machine elements, the selected material plays a significant role in cavitation erosion resistance. Previous research has concluded that cavitation erosion has a substantial impact on changes in the mechanical properties of materials. With the emergence and rapid development of additive manufacturing technologies, challenges related to the fabrication of complex geometry components have been effectively overcome. However, the impact of cavitation erosion on 3d-printed materials, particularly metals, remains largely unexplored. In addition to reviewing existing research on the influence of cavitation erosion on material properties, especially the load-bearing capacity and functionality of machine components, this study presents fundamental characteristics of cavitation erosion tested according to the ASTM G32 standard on specimens made from MS1 metal powder.*

Keywords: *Cavitation erosion, mechanical properties, machine elements, additive manufacturing, MS1*

1. INTRODUCTION

Due to a drop in fluid pressure below the saturation pressure at a given operating temperature, vapour bubbles—or vapour-gas bubbles if a non-condensable fluid is present—form in the fluid. When these bubbles reach a region of higher pressure, rapid condensation (implosion) occurs, leading to damage on the surface of the machine part [1 - 3]. This phenomenon was first observed as early as the 18th century by Euler while studying turbomachinery, and the term cavitation was first used in the literature at the end of the 19th century [4]. The phenomenon of bubble collapse was first analysed by Rayleigh for the case of a non-viscous and incompressible fluid. His interpretations were later supplemented, resulting in an equation describing the change in bubble size over time that also accounts for the influence of fluid characteristics—the Rayleigh–Plesset equation [5].

These equations refer to the symmetric collapse of bubbles that occurs due to a sudden increase in pressure in the surrounding fluid, which compresses the vapour or vapour-gas bubble. During the compression process, the pressure inside the bubble rises to very high values, which at a certain point prevents further compression, causing a rebound (implosion) of the bubble and the propagation of shock waves through the fluid that induce immense impact forces on the material surface. The implosion itself is a very short process, lasting 2–3 µs, during which pressures of up to $10^3 - 10^4$ MPa are generated [6]. However, if the bubbles are located near or directly on a solid surface, uneven ambient pressure causes deformation of the bubble wall and asymmetric collapse, resulting in the formation of a microjet of liquid that strikes the surface of the material and also causes localized damage, i.e., cavitation erosion of the part [7]. Although microjet formation is characteristic of asymmetric collapse, in some cases, the generation of a shock wave is also possible [8]. The entire process can be divided into four phases [9]:

- the incubation phase - there is no measurable damage
- the acceleration phase - the cavitation rate rapidly increases and reaches a maximum, mass loss of material is very intensive
- the deceleration phase is characterised by a decrease in cavitation rate, lower mass loss due to a liquid film formed in pits and lower energy delivery to the material
- the terminal phase, the final phase characterised by a constant erosion rate due to a changes in surface roughness, which in extreme cases can lead to complete disintegration of the component.

Cavitation is a common phenomenon in hydrodynamic flows, but in addition to that, wherever a fluid is present as a lubricant, there is a risk of cavitation erosion. Due to the specific geometry of machine elements exposed to fluid as a working medium or lubricating agent, local pressure drops are frequent. Furthermore, due to high rotational speeds, localised high-temperature fields are also possible, which can lead to fluid evaporation and bubble formation without any change in pressure. In addition to hydrodynamic cavitation, mechanical systems often exhibit pressure fluctuations in the fluid near a vibrating surface, leading to acoustic cavitation [10]. In certain fields, cavitation is a desirable phenomenon. In this context, a hybrid model of hydrodynamic–acoustic cavitation (HAC) has been developed, which offers significant advantages compared to the two individual models. However, this model is not realistic and does not occur in mechanical systems [11].

As regions of local low pressure in hydrodynamic cavitation occur due to changes in the geometry of a component, it is important to optimise the geometry in order to reduce the risk of cavitation. Difficulties in optimizing and manufacturing complex geometries of mechanical parts have largely been overcome through the use of additive manufacturing technologies [12].

2. CAVITATION EROSION CORRELATION WITH MATERIAL MECHANICAL PROPERTIES

A crucial parameter in determining the potential occurrence of cavitation is the cavitation number (Eq. 1). The threshold value of this number is the critical cavitation number, and if the cavitation number is greater than the critical value, cavitation will occur [13].

$$\sigma = \frac{2(p - p_{\mathrm{sat}})}{\rho v^2} \tag{1}$$

where: p is a referent pressure, p_{sat} is a saturation pressure, ρ is a fluid density, and v is a fluid flow velocity.

The occurrence of cavitation depends solely on fluid parameters, while the condition for pressure to drop below the saturation pressure is determined by the operation of the system itself. However, the development of the cavitation mechanism and the extent of material damage are closely related to the geometry of the component and the properties of the material. Vibratory cavitation induces a more uniform distribution of damages, and the collapse itself is not as localised in character, while hydrodynamic cavitation acts locally [14]. Through a large number of experiments, a relationship has been established between the parameters of cavitation erosion, primarily cavitation resistance, and mechanical characteristics – tensile strength, strain energy, ultimate resilience, and hardness [15]. Cavitation erosion resistance (*CER*) is determined as the reciprocal value of the maximum instantaneous erosion rate, which is determined through the average erosion depth (*MDE)* (Eq. 2), where the instantaneous rate is obtained by integration, or as the ratio of the average erosion depth to the time interval of its formation.

$$CER = \frac{1}{MDER_{\max}} = \frac{1}{\left(\frac{\mathrm{d}MDE}{\mathrm{d}t}\right)_{\max}} \left[\frac{\mathrm{min}}{\mathrm{\mu m}}\right] \quad (2)$$

2.1 Tensile strength

Experiments conducted on nickel and copper alloys have shown that the ultimate tensile strength of the material can be correlated with the Maximum Depth Penetration Rate (MDPR) through the following equation [15]:

$$(MDPR)^{-1} = k(\sigma_{\mathrm{u}})^{2.3} \quad (3)$$

where *k* is a constant.

Due to the inverse proportionality, it is concluded that with an increase in ultimate tensile strength, the MDPR decreases, which indicates an increase in cavitation erosion resistance (CER).

2.2 Strain energy and ultimate resilience

The energy accumulated in a material during deformation is called strain energy. It exists concerning both plastic and elastic deformations. Strain energy is correlated with the reciprocal value of volume loss in the steady-state regime, which, in the case of cavitation, implies a constant material loss or erosion rate. When stress–strain data is unavailable, strain energy can be approximated using the yield strength and ultimate tensile strength, as the average of the two divided by two. Ultimate resilience, or Hobbs' ultimate resilience (*UR*), which represents the area under the stress–strain line assuming a linear relationship up to the fracture point, is correlated with the Mean Depth of Erosion Rate (*MDER*) [5].

$$MDER = k(UR)^{-1} \quad (4)$$

where *k* is a constat.

After the elastic deformations caused by the shock wave, plastic deformations occur, representing the major part of the surface deformation, and they take place when the impact pressure exceeds the yield strength. However, additional stress waves also appear, predominantly shear waves, which cause brittle fracture on the surface of the specimen during the incubation stage of cavitation. This was confirmed by SEM analysis of experimental samples exposed to vibratory cavitation [16]. The geometry of pits is not constant, and the radius of a pit is most commonly 15 to 30 times greater than its depth, while in extreme cases this ratio ranges from 2 to 500 [17].

2.3 Hardness

Based on experiments conducted on stainless steel, a correlation between cavitation erosion resistance (CER) and material hardness was established through the following equation [18]:

$$\boldsymbol{CER = 2.6\exp(-7) * (HV * F_{\mathrm{mat}})^{2.4}} \quad \mathbf{(5)}$$

where *HV* is hardness in Vickers and F_{mat} is the material factor (ratio of original surface and eroded surface hardness).

As cavitation resistance increases with increasing material hardness, surface hardening techniques such as post-processing thermal or mechanical treatments, as well as coating applications, can be employed to enhance resistance [13, 19].

3. MACHINE ELEMENTS UNDER CAVITATION CONDITIONS

Cavitation in mechanical systems can lead to reduced functionality or even complete disintegration of mechanical components. The first observations of cavitation were related to propellers [4]. In addition to propellers, valves, due to their role in regulating fluid flow, are exposed to local pressure drops caused by increased velocity, as well as pipes at cross-sectional contractions, are often damaged due to cavitation erosion [20]. A less-explored area involves bearings and gears, the review of which will be the subject of this chapter.

3.1 Gears

Several important parameters influence the intensity of cavitation in gears. The lubrication system and the viscosity of the fluid have a significant impact on the formation of cavitation zones. In elastohydrodynamic lubrication (EHL), due to high rotational speeds, shear stresses in the fluid increase, and the lubricant film in the gear mesh becomes thinner. This results in an insufficient amount of oil being entrained into the meshing zone and a sudden pressure drop at the outlet, which leads to cavitation. Another very important parameter is the torque, which causes gear vibrations and leads to pressure fluctuations. As the torque increases, the oil film becomes more compressed, and the process intensifies. In addition, the gear tooth profile, deformed by the impact of cavitation jets, further deviates from the ideal geometry, which enhances the intensity of vibrations [21]. The increased temperature that occurs at high speeds in the contact zone due to elevated friction has a significant impact. Therefore, supplying a sufficient amount of lubricant is crucial to avoid the occurrence of high temperatures. Under low loads and high rotational speeds, vapour fluctuation intensifies, leading to increased surface damage [22, 23]. These phenomena have been confirmed by the agreement between experiments and CFD models with and without thermal effects [24]. In addition to cavitation erosion, separated metal particles can cause abrasive erosion.

3.2 Bearings

During bearing operation, due to shaft rotation and the forces transmitted to the bearing, eccentricity occurs in the rotation. In this case, an inlet and outlet region are formed in the fluid flow field, i.e., a convergent and divergent zone. In the convergent zone, which represents the fluid volume within the minimum clearance between the shaft and the bearing, the fluid film is very thin. At this location, friction and the temperature field induced by shear forces within the fluid are increased, resulting in a rise in pressure. At the outlet of the convergent zone, a pressure field lower than atmospheric appears, leading to cavitation. Cavitation can occur in three forms: vaporous, gaseous, and vapour-gas [25, 26]. Temperature in the fluid film plays a crucial role. With the increase in rotational speed and load (which increases eccentricity), the temperature within the fluid film rises. The temperature rise can be prevented by increasing the number of lubricant supply grooves, with the dependence being nearly linear, as well as by supplying the fluid at higher pressure [27]. Cavitation in bearings can cause an increased coefficient of friction, reduced load-carrying capacity, power loss, etc. [28]. A phenomenon that accompanies cavitation erosion is abrasive wear due to the increased concentration of metallic particles in the fluid.

4. EXPERIMENTAL RESULTS OBTAINED ON MS1 STEEL

Test samples in the form of cylinders with a diameter of 10 mm and a height of 5 mm for acoustic cavitation testing according to the ASTM G32 standard were obtained by cutting from the wider section of standard specimens used for bending fatigue testing according to the ISO 1143 standard [29]. The specimens were produced by laser sintering of MS1 metal powder using DMLS technology without thermal postprocessing (as built) with vertical direction [30]. The chemical composition of the powder is given in Table 1 [31].

Chemical composizion coresponds to the European classification 1.2709, the American 18% Ni Maraging 300, and the German X3NiCoMoTi 18-9-5.

After cutting, the test samples were polished to avoid the impact of surface roughness on the propagation of cavitation damage. The total duration of the experiment was 4 hours, during which the samples were dried every 30 minutes, and their mass loss was measured, as published in the paper [32].

Table 1. Chemical composition of MS1 powder

Element	Percent(%)	Element	Percent(%)
Ni	17 - 19	Cu	0.5
Co	8.5 – 9.5	C	0.03
Mo	4.5 – 5.2	Mn	0.1
Ti	0.6 – 0.8	Si	0.1
Al	0.05 – 0.15	P	0.01
Cr	max. 0.5	S	0.01
Fe	Balance		

Based on the mass losses, the *MDE* and the Cumulative Volume loss were determined according to equations 6 and 7, and showed in Tables 2 and 3.

$$\Delta V = \frac{\Delta m}{\rho}\ [10^{-3}\mathrm{mm}^3] \qquad (6)$$

where ρ is the density of the MS1 part, and according to the EOS: ρ = 8 g/cm^3.

$$MDE_{\Sigma_i} = \sum_{i=0}^{n=8} \Delta MDE_i \sum_{i=0}^{n=8} \frac{4\Delta m_i}{\rho \pi d^2} 10^3 [\mu\mathrm{m}] \qquad (7)$$

Table 2. Cumulative Volume Loss

Exposure time [h]	ΔV [µm]
0.5	0.01750
1	0.04750
1.5	0.06000
2	0.10500
2.5	0.11875
3	0.13875
3.5	0.15250
4	0.18875

However, the relationship between volumetric loss and strain energy in the steady-state period cannot be examined because the experiment duration was not long enough to reach the region of constant erosion rate.

Table 3. Mean Depth of Erosion (*MDE*)

Exposure time [h]	*MDE* [µm]
0.5	0.22282
1	0.60479
1.5	0.76394
2	1.33690
2.5	1.51197
3	1.76662
3.5	1.94169
4	2.40323

Due to relatively large time intervals for mass measurements, the *MDER* cannot be approximated by a function, and its first derivative used to determine the maximum. Instead, the *MDER* was determined as the ratio of the *MDE* for each interval to the duration of the interval according to Equation 6. *MDE* for each interval is obtained based on the difference in values from Table 2, by subtracting the previous interval from each subsequent one.

$$MDER_i = \frac{\Delta MDE_i}{\Delta t_i} \left[\frac{\mu\mathrm{m}}{\mathrm{h}}\right] \qquad (8)$$

The obtained values are shown in Table 4.

Table 4. Mean Depth Erosion Rate (*MDER*)

Exposure time [h]	*MDER* [µm/h]
0.5	0.44563
1	0.76394
1.5	0.31831
2	1.14591
2.5	0.35014
3	0.50930
3.5	0.35014
4	0.92310

According to Equation 2, based on the maximum MDER = 1.14591 [µm/h], the CER can be calculated, and the value is: CER = 0.87267 [h/µm].

In order to obtain a constant *k* from equation 4, ultimate resilience must be calculated first. Ultimate resilience can be determined using the following expression [5]:

$$UR = \frac{1}{2}\frac{\sigma_{\mathrm{ult}}^2}{E}\ [\mathrm{MPa}] \qquad (9)$$

Where σ_{ult} is the ultimate tensile strength and E is the modulus of elasticity. For MS1 steel parts, according to the manufacturer, in the Z axis direction, these values are 1100±100 MPa and 150±20 GPa [31].

Calculated *UR* is 8.067 MPa.

Based on equation 4 coefficient *k* can be determined, and the value is 9.24406, but still cannot be used as completely accurate because it needs to be approved by several series of experiment.

Before the start of the experiment, the hardness of the samples was measured using a ZWICK ROELL device and amounted to 427 HV, with a deviation of less than 5%. Based on Equation 5, the material factor is determined: $F_{mat} = 1.62*10^{-9}$, which is negligibly small and corresponds with the measured hardness after the experiment, which remained unchanged.

After the experiment, surface topography was not performed, so the relationship from Equation 3 cannot be analysed, as the k factor for MS1 is unknown.

5. CONCLUSIONS

Cavitation erosion is a common phenomenon associated with fluid flows that can lead to permanent damage and dysfunction of machine elements. A large number of factors influences the occurrence and development of the cavitation mechanism, primarily the characteristics of the fluid, the geometry and material of the part, and the operating conditions.

There are several mechanisms for the development of cavitation, but hydrodynamic and acoustic cavitation are characteristic of mechanical systems. Numerous experimental studies have established relationships between cavitation erosion parameters and the mechanical properties of materials.

Machine elements that are primarily affected by cavitation include propellers, valves, and pipes, but also gears and bearings, whose behaviour in this area has been scarcely researched. For gears and bearings, CFD models are mostly used to simulate cavitation, which are later validated through experiments. It has been determined that rotational speed, lubrication method, lubricant selection, and load have a significant impact on both the occurrence of vibrations and the development of high temperatures, which exacerbate the effects of cavitation. In order to mitigate this phenomenon, it is necessary to optimize all of these parameters.

However, there is a lack of research on cavitation erosion related to additive manufacturing technologies, particularly 3D-printed metals, which are increasingly used for producing machine elements due to faster production rates in serial manufacturing, as well as the ability to overcome challenges related to complex geometries.

This study analysed the known relationships between erosion parameters and material properties on test samples produced using DMLS technology from MS1 metal powder. A proportionality coefficient was determined for the correlation between *MDER* (at its maximum value) and *UR*, as well as the material factor, which was compared with the measurements and showed excellent agreement. However, a large number of additional tests are still needed for the value of this factor to be considered fully accurate.

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