Application of the "Brazilian test" to determine the strength of materials obtained by electric pulse consolidation of powders

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Abstract. Testing of short cylinders according to the "Brazilian test" scheme is considered as a method of assessing the tensile strength of brittle materials obtained by electric pulse consolidation of powders. The paper presents a calculated using FEM and an experimental analysis of the behavior of short cylinders (thick disks) when loaded according to the "Brazilian test" scheme. The calculation shows the weak influence of the disk thickness on the average and maximum tensile stresses in the plane of symmetry of the disk. Results of testing of small samples made of cast iron and graphite are presented. It is shown a good correspondence between the results of the test samples from cast iron when using formula recommended by the ASTM Standard D3967 - 95a, and the strength of the material when tested in tension. The results of testing samples of graphite were 1.5 – 2 times less than its tensile strength. The results of testing small-size samples of heavy alloy WNiFe and aluminum oxide obtained by electric pulse consolidation of powders are presented. The influence of the pressure and current pulse on the fracture resistance of the alloy WNiFe and the sample thickness on the strength of $\text{Al}_2\text{O}_3$ is investigated. Thus, the possibility of testing small samples according to the "Brazilian test" scheme to determine the tensile strength of materials obtained by electric pulse consolidation of powders is demonstrated.

1. Introduction

Development of production technology of modern materials by consolidation of powders, welding and sintering regimes \cite{1,2} is carried out, as a rule, on small samples, the size of which often does not exceed 10–15 mm in diameter, and the thickness can vary from 1 to 10 mm. Standard mechanical test methods are often not applicable to such samples. Alternative test methods have to be used to evaluate the mechanical properties of the material. An example of such methods is compression of short cylinders in the plane of symmetry according to the "Brazilian test" scheme \cite{3}. This method is used to test brittle materials. The method is standardized in the USA \cite{4} to determine the tensile strength of rocks when testing samples with a diameter of at least 50 mm with a thickness-to-diameter ratio in the range of 0.2–0.75.

The aim of this work is to study the possibility of using the test of small samples according to the "Brazilian test" scheme to assess the tensile strength of brittle materials obtained by the method of electro-pulse consolidation of powders.
2. Calculation analysis of short cylinder compression according to the "Brazilian test" scheme

Simulation of the disk sample loading process was performed in the verified [5, 6] calculation complex ANSYS Mechanical version 16.2. The full calculation model is shown in figure 1.

![Figure 1. Full geometry of the computational model.](image)

Figure 2 presents the results of FEM modeling of the disk compression process: the distribution of $\varepsilon_x$ strains on the front surface of the sample and the distribution of the first main stresses on the front surface and the cross section of the sample. As a result of simulation, it was found that the maximum principal stresses at individual points can exceed the average stresses $\sigma_t$ by 2.5 times, which should affect the applicability of the formula recommended by ASTM D3967–95a for concentration sensitive brittle materials.

![Figure 2. Qualitative patterns of strain distribution $\varepsilon_x$ (a) and the first principal stresses (gray areas where $\sigma_1 < 0$) (b) in the disk sample under compression.](image)

The results of the analysis with the study of the influence of the ratio of the cylinder thickness to its diameter on the maximum tensile stresses are presented in [7]. It is shown that in the plane of symmetry of the disk YZ coinciding with the plane of its loading, there are tensile stresses $\sigma_t$ that lead to brittle fracture of the sample. Changing the ratio of the disc thickness to its diameter in the range of 0.3–1 has little effect on the maximum tensile stress.

3. Results of experimental study of short cylinders of model materials

Table 1 presents the mechanical properties and modulus of elasticity of the tested of model materials.
Table 1. Tensile/compressive strength and modulus of elasticity of the materials studied

| Material           | $\sigma_u^t$, MPa | $\sigma_u^c$, MPa | $E$, GPa |
|--------------------|-------------------|-------------------|----------|
| Cast iron SCH 10-40| 104               | 404               | 100      |
| Graphite ARV-1     | 13.8              | 37                | 11       |

3.1. Test cylinders of gray cast iron

The cylinders are made of grey cast iron with three sizes $D \times t$: $10 \times 4$, $15 \times 4$, and $10 \times 5$ mm.

Loading of the samples was carried out using an INSTRON test machine in a special device providing strict parallelism of the reference planes. Simultaneously with the loading of samples using the method of digital image correlation [8, 9] and the use of equipment Vic-3D RT recorded the movement of surface points of each sample. Distribution patterns of deformation $\varepsilon_x$ surface points of the cast iron sample at the initial stage of loading, the stage preceding the destruction and the destruction stage are shown in figure 3.

![Figure 3. The color pattern of the strain distribution $\varepsilon_x$ in the surface of iron sample points: (a) initial stage of loading, (b) stage preceding the destruction, (c) stage destruction.](image)

The distribution of tensile strains $\varepsilon_x$ (red zone - maximum strain) exactly corresponds to the pattern of distribution of tensile stresses in the calculation analysis, which indicates the identity of the results obtained by calculation and experimental methods. Symmetrical patterns of strain distribution with respect to the X and Y axes are observed at all stages of sample loading. In the contact area of the stamp and wheel surface points is implemented plane stress with principal stresses $\sigma_t$, tensile and compressive stresses $\sigma_c$, and as a result, significant shear stresses equal the semi-sum of their absolute values. Shear stresses cause shear cracks, which, when connected, lead to the destruction of the sample in the plane of symmetrical, where the maximum tensile stresses, which is confirmed by the nature of the destruction of the sample. Step fracture of the sample indicates that the rupture of the sample occurs under the action of shear stresses. No explosive fracture characteristic of a brittle rupture from normal stresses was observed. We observed a slow departure of one half of the sample from the other, which is usually inherent in plastic destruction. The beginning of destruction of samples is associated with the maximum loads recorded by the test machine.

Table 2 summarizes the test results of 9 cast iron cylinders: the maximum load corresponding to the beginning of the destruction of all tested samples, and the breaking stresses calculated by the formulas:

$$\sigma_t = \frac{2P}{\pi tD}$$  \hspace{1cm} (1)

$$S_0 = \frac{P}{tD}$$  \hspace{1cm} (2)

where $P$ is the maximum load sustained by the sample, $t$ is the thickness of the sample, and $D$ is its diameter. The average stress values calculated by formula (1) were close to the tensile strength values...
of the material. Thus, the formula (1) recommended by ASTM D3967–95a can be used to calculate the destructive stresses when testing metal brittle discs according to the "Brazilian test" scheme.

3.2 Graphite cylinder tests
Cylinders made of graphite were three sizes $D \times t$: $8 \times 4$, $8 \times 8$, and $8 \times 12$ mm. The destruction of the graphite sample occurs at maximum load in the linear nature of the curves until fracture of the specimen. Table 3 shows the test results of the graphite samples and the resistance of the graphite fracture.

Table 2. The fracture resistance of cast iron, determined by the formulas (1) and (2).

| Sample | Size, mm | $P$, kN | $\sigma$, MPa | $S_0$, MPa |
|--------|----------|---------|---------------|-------------|
| 1      | $10 \times 4$ | 5.3     | 85            | 134         |
| 2      | $10 \times 4$ | 6       | 96            | 151         |
| 3      | $10 \times 4$ | 7       | 111           | 174         |
| 4      | $10 \times 4$ | 6.8     | 109           | 171         |
| 5      | $10 \times 4$ | 7       | 112           | 176         |
| 6      | $10 \times 5$ | 9       | 115           | 180         |
| 7      | $10 \times 5$ | 8.8     | 112           | 176         |
| 8      | $15 \times 4$ | 8.3     | 88            | 138         |
| 9      | $15 \times 4$ | 7.5     | 80            | 126         |

The average stress values $101 \pm 158.4$

Table 3. Graphite fracture resistance determined by formulas (1) and (2).

| Sample | Size, mm | $P$, kN | $\sigma$, MPa | $S_0$, MPa |
|--------|----------|---------|---------------|-------------|
| 1      | $8 \times 4$ | 307     | 6.1           | 9.6         |
| 2      | $8 \times 8$ | 660     | 6.6           | 10.3        |
| 3      | $8 \times 8$ | 695     | 6.9           | 10.9        |
| 4      | $8 \times 8$ | 595     | 5.9           | 9.3         |
| 5      | $8 \times 12$ | 1100    | 7.4           | 11.5        |
| 6      | $8 \times 12$ | 1108    | 7.4           | 11.5        |

The strength of graphite, calculated by the formula (1), was about 1.5–2 times lower than the true (see table 1), which can be explained by the more fragile state of graphite. This is confirmed by the difference between the diagrams of deformation of samples of cast iron and graphite: the diagram of plastic deformation and fracture of cast iron and brittle fracture of graphite (figure 4).

![Figure 4](image-url)  
**Figure 4.** Test charts for cylinders of (a) cast iron ($10 \times 4$ mm) and (b) graphite ($8 \times 8$ mm).
4. The test of cylinders obtained via the high-voltage consolidation of powders

4.1. Study of samples of alloy WNiFe

To obtain samples of heavy alloy WNiFe by high-voltage consolidation used industrial powder composition 90W–7Ni–3Fe, obtained by mechanical mixing of the components. Data on the composition and density of the powder are given in Table 4.

| Element | ρ, g/cm³ | Weight, % | ρtheor, g/cm³ |
|---------|---------|-----------|---------------|
| W       | 19.25   | residue   |               |
| Ni      | 8.902   | 6.93      | 17.13         |
| Fe      | 7.874   | 3.12      |               |

Various modes of sintering in the manufacture of cylindrical samples from the alloy WNiFe were investigated. The supplied voltage varied from 4.5 to 5.8 kV and the pressure from 150 to 250 kPa. The beginning of destruction of samples is associated with the maximum loads recorded by the test machine. Tests of samples allowed determine the levels of pressure and voltage pulses during their compaction, providing optimal strength characteristics of the alloy WNiFe. Figure 5 shows the dependence of the material resistance to rupture of the voltage pulse level for samples sintered under the same pressure of 200 and 250 kPa.

![Figure 5. The dependence of the fracture resistance of the applied voltage at sintering at the same pressure.](image)

At a pressure of 200 kPa, there is an increase in the strength of the samples with an increase in the voltage pulse to a value of 5.4 kV, then a decline. The growth and decrease in strength occurred against the background of the development of plastic deformations that preceded the brittle destruction of the samples.

At a pressure of 250 kPa, we obtained an absolutely brittle fracture without noticeable traces of plastic deformation.

4.2. Testing of samples of aluminum oxide obtained by SPS

Al₂O₃ powder was placed in a graphite matrix and pressed down by punches on both sides with a constant force, and was heated by passing a pulsed current through the matrix.
The results of the "Brazilian test" of cylindrical samples with a diameter $D = 10$ mm made of aluminum oxide powder by the method of electro pulse consolidation and calculated by the formula (1) are presented in figure 6.

![Figure 6](image)

**Figure 6.** The test results of samples of aluminum oxide.

We note a good correspondence between the results obtained by the test of short cylinders according to the "Brazilian test" scheme and the results of the test of thin aluminum oxide disks [10] with a diameter of 15 mm and a thickness of 1.5 mm for bending on the annular support. Thin discs made by the SPS of ultradisperse (UD) powder spherical, collapsed under the stress of 171 MPa. The use of pre-pulsed magnetic pressing UD powder increased its strength to 202 MPa.

5. **Conclusions**

Thus, the possibility of testing small cylindrical samples according to the scheme of the “Brazilian test” and indirect determination of tensile strength of materials obtained from powders by the method of electric impulse action is demonstrated by calculation using FEM and experimentally.

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