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EXPRESS AUTOMATED BALL INDENTATION MEASUREMENT OF MATERIAL PROPERTIES

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Abstract – The present work discusses the measurement of material properties, i.e. hardness and modulus of elasticity obtained in a single express test based on the Automated Ball Indentation (ABI) using equipment and method developed by the authors. The ABI results will be subsequently used as an input data for the Finite Element Analysis (FEA) and compared to other methods.

Keywords: Hardness, ABI, material properties, FEA, Express methods

1. INTRODACTION

The determination of mechanical properties of materials is very important for many industries and scientific research. The data obtained are then utilized in engineering design of products and equipment as well as process parameters. Tensile test is one of the most widely used mechanical tests which allows the obtaining of relationship between stress and strain of the material continuously, and the resultant tensile diagrams are used for estimation of mechanical properties of material: yield strength both the physical R_p and nominal $R_{p0.2}$, ultimate tensile strength R_m, modulus of elasticity or Young’s modulus E. The standardized tensile specimen is loaded until it breaks.

However, it is noteworthy that the continuous build-up in production and development of new materials and alloys, as well as processing methods and final products, makes the tensile test more time-consuming and expensive. This leads to the need of quicker and simpler testing methods which would also enable the user to test the materials and the whole products in a non-destructive way, and the hardness testing can be assigned to such tests.

The hardness test is based on indentation of testing material with the body of a standard shape (sphere, cone, and pyramid) and gives high accuracy results when the homogeneous materials are tested. Furthermore, correlations between the hardness number and some mechanical properties have proved to be useful in engineering practice, and are standardized in Russia, Germany and USA [1].

There are several examples of using the hardness measurements:

1. Determination of mechanical properties of semi-finished and final products.
2. Measuring of properties in micro-volumes, especially when material is susceptible to some local defects as during welding for example.
3. In-service testing of materials.
4. Applications in surface engineering, which is of a particular importance for the control over the degradation processes started at the surface of the product.
5. Automatization of the measuring (ABI) can make the production process continuous.

There are production and service risks in the engineering practice associated with the design, especially when the new materials or structures considered, which properties may change during service in different ways. The increasing use and availability of finite element models reduce costs and time spent on testing and verification of a particular design. The quality of the input data can significantly affect the result obtained using Finite Element Method (FEM) and there is a challenge for the testing methods of mechanical properties to be time and cost effective as well as precise. Therefore, the ABI test which has a great potential to satisfy this demand, may be considered.

Hardness testing methods can be divided into three groups according the measuring ranges: macro, micro, and nano; macro-indentation operates at loads applied to indenter from 2 N to 30 kN; micro-indentation uses loads lower than 2 N and indentation depth above 0,2 μm; nano-indentation is done to the depth below 0,2 μm.

The strategy for determination of mechanical properties of materials, and specifically for the modulus of elasticity, developed by Oliver and Pharr [2] is nowadays widely used in indentation at nano and micro levels. In this work authors discuss an alternative method for the calculation of the modulus of elasticity based on the data collected during macro-indentation ABI process. The results are further compared to tensile test and nano-indentation results.

2. MATERIALS AND METHODS

The present work was focused on ductile materials based on titanium and aluminum.

The main group of 5 aluminum alloys with variation in chemical composition, AlZn6Mg2Cu, AlMg1Si1Mn, AlMn1, AlCu4Mg1, AlZn5,5MgCu, and 1 titanium alloy Ti-6Al-4V, were subjected to mechanical tests.

Mechanical properties of the alloys were determined by using of the tensile testing machine INSTRON 5582 equipped with extensometer, according to standard ČSN EN ISO 6892-1; the nanoindentation tester Micro Materials with the Berkovich indenter type was used according to standard ISO 14577; and also the ABI test was performed by using the testing apparatus of a special design.

The use of extensometer is critical in terms of accuracy while measuring the modulus of elasticity with the application of Hooke's law after the tensile test; the Oliver–Pharr's approach was used after the nano-indentation test; and finally, the calculation algorithm of the modulus of elasticity after the ABI test is discussed further in greater details.

ABI test

Indentation tests were performed by a special ABI device Fig.6 (patent CZ 304637 B1), which is capable of continuous recording of load applied to indenter and indentation depth of the indenter. The measuring system comprises: the ABI device (Fig. 1), analog-to-data converter, PC with the software, tensile-testing machine Instron 5582 as a load-mechanism. Maximum indentation load was 2.5 kN and the indenter diameter of 5 mm.

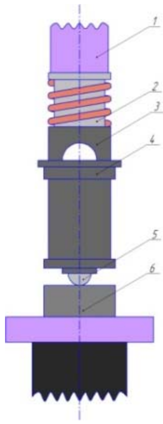

Fig. 1 ABI device: 1 – load mechanism, 2 – adapter, 3 – measuring device, 4 – depth and load sensors, 5 – ball indenter, 6 – specimen

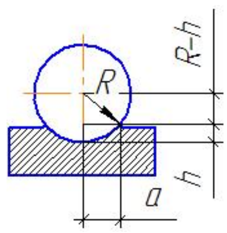

Fig. 2 Scheme for determination of a contact radius a

After the ABI test is done the load dependence of indentation depth "P-h" or indentation curve is plotted

$$P = F(h)$$

The next step is the calculation of a contact radius, schematically shown in Fig. 2, using the relationship

$$a = \sqrt{2Rh - h^2} \quad (1)$$

The following step is the calculation of the Meyer's hardness,

$$HM = \frac{P}{A} = \frac{P}{\pi a^2} \quad (2)$$

It is than necessary to determine the displacement of a lower point on the ball indenter [3],

$$W_0 = \frac{a^2}{R} \quad (3)$$

The calculated parameters are subsequently substituted in the Hooke's law

$$\sigma = E\varepsilon \quad (4)$$

after manipulating the Meyer's hardness we get

$$HM = EW_0 \quad (5)$$

Hence, the relationship for the modulus of elasticity is

$$E = \frac{HM}{W_0} \quad (6)$$

The Brinell hardness is calculated using equation

$$HB = \frac{P}{\pi Dh} \quad (7)$$

where D is diameter of an indenter.

Finite Element Analysis

It is known that the Hooke's law is used when elastic deformation is applied σ = F(ε). The finite element model built in ANSYS Multiphysics was used to prove the existence of this elastic region during the indentation of a ball indenter. The axisymmetric (PLANE42) and contact elements (TARGE169, CONTA175) were used for the analysis. Testing material was considered to be multilinear isotropic and the basic points of a «σ - ε» diagram were introduced. Each part was meshed separately with the application of special elements CONTA175 in the contact points of contacting surfaces. The mesh was refined in the lower part of an indenter to increase the calculation precision of the model.

5. RESULTS AND DESCUSSION

Fig. 3 shows the finite element model that comprises the specimen 1, indenter 2, and indenter holder 3. The view of the model deformed at 0.5 kN is presented in Fig. 4 which shows no uplift of a plastically deformed material around the indent at a given mesh and boundary conditions.

However, the uplift is seen at higher loads, which is indicated in Fig. 5. This confirms the applicability of eq. 6 for the determination of the modulus of elasticity using the starting portion of an indentation curve.

The indentation curves obtained for aluminum alloys are presented in Fig. 6 which are characteristic for materials behavior at loading-unloading and also, similarly to tensile diagram, contain elastic region, elastic-plastic and plastic regions. [4]

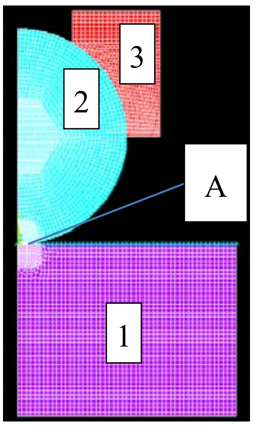

Fig. 3 Finite element model

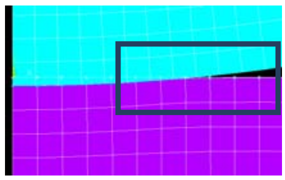

Fig. 4 Deformed Finite element model, region A, P=0.5kN

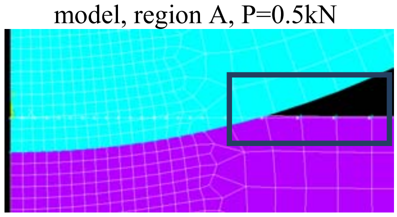

Fig. 5 Deformed Finite element model, region A, P=5kN

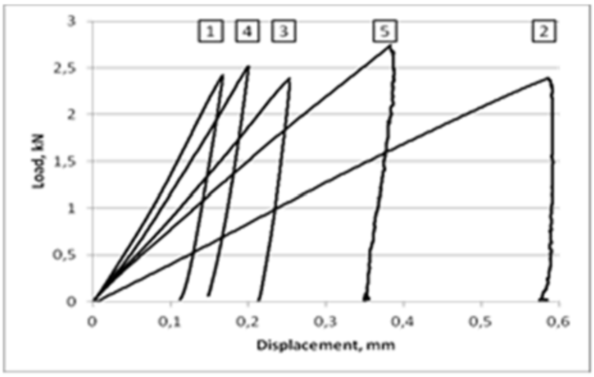

Fig.6 Indentation curves obtained for:
1 - AlZn6Mg2Cu, 2 - AlMg1Si1Mn, 3 - AlMn1,
4 - AlCu4Mg1 and 5 - AlZn5,5MgCu

Mechanical properties (hardness and modulus of elasticity) determined using the novel methodology are summarized in Tab. 1 and show no significant deviation from those obtained in a standard way, close to 8 %, which is well within the engineering error.

Table 1 Mechanical properties of aluminium alloys

№	Alloy	HB, [MPa] Std.	HB, [MPa] ABI	E, [GPa] Std.	E, [GPa] ABI
1	AlZn6Mg2Cu	125	136	70 ÷ 80	77,1
2	AlMg1Si1Mn	30	26		78,6
3	AlMn1	55	67		79,3
4	AlCu4Mg1	105	101		74,2
5	AlZn5,5MgCu	-	51	75,5*	74,4
6	Ti-6Al-4V	-	304	114**	124

* Measured with extensometer
** Nanoindentation

6. CONCLUSIONS AND FUTURE WORK

The results of FEA are in good agreement with the experimental results and show the applicability of the new method to determination of the modulus of elasticity, with the deviation of calculated values, from those obtained using standard procedures (Std.), within 8 %.

Further studies using different materials including brittle and plastic materials are needed to verify the methodology, as well as the corresponding improvements in the FEM part of the solution.

The discussed method is shown to be fast and reliable in obtaining the mechanical properties of materials, which high quality results can be used for FEM analysis as input data, enabling the determination of stress-strain conditions for different materials and structures. The other benificial property of the computational modeling is a special focus on the transient events at critical loading of a material, which locations can eventually evolve into the source of degradation. Therefore, the critical behavior of a material can be predicted.

The present work demonstrates the mutual evolution of an FEM and experiemental procedures that may lead to the development of better computing codes with real behavoir of materials.

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