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Modulus of Elasticity and Poisson's Ratio of Various Metals from the on-off Tensile Testing Method

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***Abstract* - Modulus of elasticity and Poisson's ratio are two material properties whose values are often used as input parameters in design, stress analysis and simulation of structures or machine element components. So far, the determination of both material properties uses modern methods which require quite expensive measuring instruments and measuring tools that have a high level of accuracy. In this study, the use of the on-off method in tensile testing to determine the elastic modulus of four types of metals is investigated. The four types of metal are AISI 1018 steel, AISI 1045 steel, stainless steel 304 and aluminum 1100. The results obtained show that the elastic modulus obtained is close to the reference elastic modulus value. Meanwhile, the Poisson's ratio resulting from this method is still not close to the Poisson's ratio from the reference. For this reason, measuring instruments that have higher accuracy are needed to get good results.**

Keywords: Modulus of Elasticity, Poisson's Ratio, Tensile Tensile Testing, On-off Method, Metals.

I. INTRODUCTION

Two material properties whose values are often used as input parameters in design, stress analysis and simulation of structures or machine element components are modulus of elasticity and Poisson's ratio. The modulus of elasticity is a measure of material stiffness or material resistance to elastic deformation [1]-[4]. Stiff materials have a small elastic strain value when a force is applied. Meanwhile, Poisson's ratio represents the negative ratio of transverse and longitudinal strains[1]-[4]. Poisson's ratio is used for the structural design process where all dimensions change due to the application of force and in the application of elasticity theory in structural analysis. Most engineering structures are designed to experience small deformations in the elastic deformation region, namely in the straight portion of the stress-strain graph [5].

Determination or measurement of the modulus of elasticity is not only carried out on structures or components in the field of mechanical engineering which are mostly made of metal, but also for structures or components in fields such as civil engineering and biomedical. In the field of civil engineering, elastic modulus measurements are carried out in applications such as low strength concrete [6], fiber-reinforced concrete [7], High Performance Fiber Reinforced Concrete [8], ultra high performance concrete [9], mortar specimens [10] and several structures made from cementitious materials [11]. All measurements of the modulus of elasticity for these applications are generally carried out for assessing the flexural and shear stiffness of concrete elements, non-destructive testing, creating new equations to predict the modulus of elasticity in concrete with different ages, determining the value of the modulus of elasticity in mortar coatings.

Modulus of elasticity is also an important property in the field of biomedical implants. Differences in elastic modulus or stiffness values between metal and bone can cause stress shielding [4], [12]-[18]. If the modulus of elasticity of the implant metal is greater than the bone being replaced, then the transfer of the required stress to nearby bone will be hampered which would lead to bone resorption around the implant and the death of bone cells. This weakens the bone tissue next to the implant and will also cause pain in the bone.

The modulus of elasticity for materials varies. This depends on the type of atomic bonds that each material has [1]. Many methods have been used to obtain modulus of elasticity for various types of materials. For brittle materials such as ceramics, the modulus of elasticity can be obtained through three-point bend testing [1]. The three-point bend testing method was also used to obtain the modulus of elasticity for wood by Babiak et al [19]. They also used the four-point bending method to compare the results. For ductile materials, such as ductile cast iron, where the slope of the linear part of the stress-strain graph is not constant, Fang et al used a hyperbolic modulus plot (hyperbolic stress-strain response) to determine the elastic modulus value of ductile iron [20]. Unlike ordinary stress-strain graphs, in this method the x-axis on the graph is strain (in/in) and the Y-axis is strain/stress (1/psi). For cementitious materials, Bezerra et al used 3 methods to obtain the elastic modulus value, namely by (1) the static modulus test was performed in accordance with the Brazilian standard, (2) impact resonance test (IRT), the specimens were externally excited 5 times with an automated impact hammer, generating waves in the specimens that were

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recorded with an accelerometer, and (3) the ultrasonic testing [11]. Meanwhile, one of the methods used to predict the modulus of elasticity of polymers that range from soft elastomers to hard plastics is by impact testing [22]. The modulus of elasticity can also be determined from the natural frequency of a vibrating beam which is directly proportional to E [4].

In elastic deformation, we can also determine Poisson's ratio (υ). For isotropic materials, υ can be expressed in bulk modulus and shear modulus which are related to changes in size and shape respectively [22] Because the elastic strains are very small, accurate measurements of the elastic modulus and Poisson's ratio require a very sensitive extensometer in the tensile testing process. Accurate results canalso be obtained by measuring the speed of sound

In this study, we used the on-off method in tensile testing to determine the modulus of elasticity and Poisson's ratio of 4 metals. This method is used after obtaining an engineering stress-strain curve from the results of normal tensile testing.

II. MATERIALS AND METHODS

Four types of metals that have different strengths and ductility, i.e. low carbon steel (AISI 1018), medium carbon steel (AISI 1045), stainless steel (SS304), and aluminum (Al1100) were used in this study. The chemical composition of the four metals can be seen in Table 1-4. The shape and dimensions of the specimen can be seen in Figure 1.

Table1: Chemical Composition of Low Carbon Steel (AISI 1018)

Fe (%)	C (%)	Mn (%)	P (%)	S (%)
99.2	0.20	0.361	0.0163	<0.002

Table 2: Chemical Composition of Medium Carbon Steel (AISI 1045)

Fe (%)	C (%)	Mn (%)	P (%)	S (%)
97.5	0.586	0.746	0.0136	0.004

Table 3: Chemical Composition of Stainless Steel (SS304)

Fe (%)	C (%)	Cr (%)	Ni (%)	Mn (%)	Si (%)	P (%)	N (%)
71.5	0.02	18.3	8.3	1.07	0.312	0.034	0.05

Table 4: Chemical Composition of Aluminum (Al 1100)

Al (%)	Cu (%)	Mg (%)	Si (%)	Fe (%)	Mn (%)	Zn (%)	Ti (%)
99.04	0.118	0.003	0.24	0.424	0.02	0.063	0.023

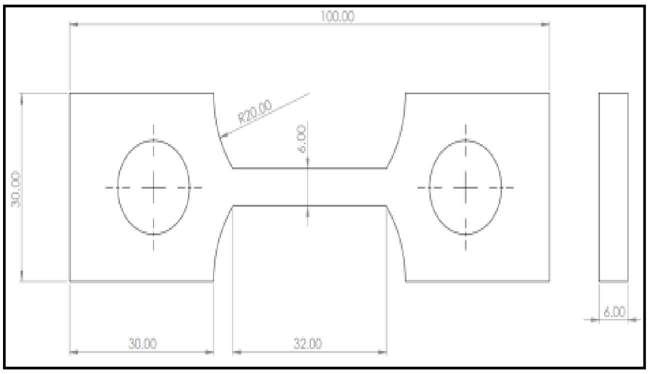

Figure 1: Tensile Test Specimen

The testing was carried out in two stages. The first stage, tensile testing is carried out as normal tensile testing. The stress-strain curve produced from each type of metal will be used as a reference for carrying out tensile tests using the on-off method. In second stage, tensile testing is only carried out in the elastic deformation area (see Fig. 2). There are three points on each linear curve of the stress-strain graph where the on-off method is applied to the tensile testing machine (point 1, point 2 and point 3 in fig. 2). Initially the tensile testing machine is turned on and tensile testing is carried out until a certain strain is reached at point 1. Then the tensile testing machine is turned off. Measurements of the increase in specimen length (ΔL), reduction in thickness (Δt) and reduction in width (Δw) of the specimen in three positions in the gauge length area were carried out. The force that occurs up to point 1 is recorded. After all measurements have been carried out, the tensile testing machine is turned on again. When it reaches point 2 the tensile test machine is turned off again. All measurements made at point 1 are carried out again. The same thing is done again when the test reaches point 3.

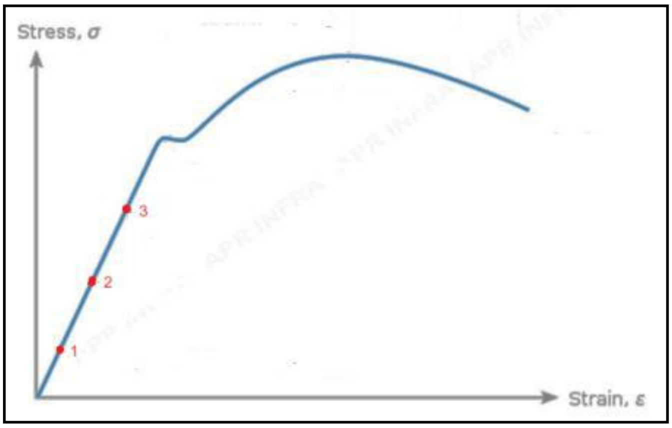

Figure 2: Three Points in Elastic Deformation Area when carrying Out the On-off Method

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III. RESULTS AND DISCUSSIONS

3.1 Modulus of Elasticity

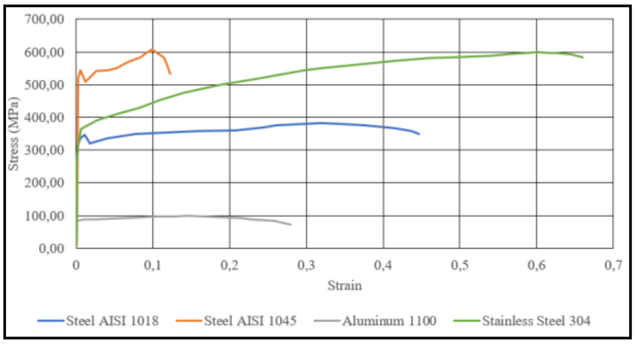

Figure 3: Stress-Strain Curve of 4 Types of Metals

Fig. 3 is the stress-strain curve for the four types of metals used in this study. The linear equation in the elastic deformation region is determined using the equation:

$$y = mx + c \qquad (1)$$

Where:

m is the slope of the line which is also the modulus of elasticity of the metal. The modulus of elasticity of the four metals can be seen in table 5.

Table 5: Modulus of Elasticity from the Normal Tensile Tests

Metals	Modulus of Elasticity (GPa)
Steel AISI 1018	182
Steel AISI 1045	222
SS304	145.4
Aluminium 1100	67.6

Table 6 is the result of engineering stress and strain calculations from three points in the elastic deformation region. Stress and strain were obtained from equations:

$$s = \frac{F}{A_0} \qquad (2)$$

$$e = \frac{\Delta L}{L_0} \qquad (3)$$

Where:

F is the force measured at points 1, 2 and 3 (N)
A_o is the initial cross-sectional area of the specimen (mm^2)
ΔL is the amount of increase in length measured at points 1, 2 and 3 (mm)
L_o is the initial length of the specimen (mm)

The stress and strain obtained from 3 points are then connected into a straight line and the linear equation is determined. After obtaining the linear equation, the gradient of the line (m) can be determined. The line gradient (m) is the modulus of elasticity of the metal (see Table 6). The stress-strain curves of all metals obtained from three points can be seen in Fig. 4.

Table 6: Modulus of Elasticity from Engineering Stress-Strain Curve in the Elastic Deformation Region

Metals	Point	Strain	Stress (MPa)	Modulus of Elasticity (GPa)
Steel AISI 1018	1	0.000734	147.06	204.6
	2	0.001101	220.59	
	3	0.001467	294.12	
Steel AISI 1045	1	0.000761	158.26	202.3
	2	0.001142	234.75	
	3	0.001522	313.87	
SS304	1	0.000782	153.47	198.4
	2	0.001173	230.20	
	3	0.001564	306.93	
Aluminium 1100	1	0.000381	27.13	74.1
	2	0.000761	54.27	
	3	0.001142	81.40	

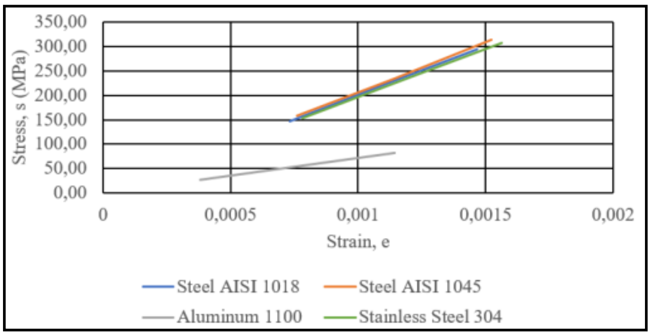

Figure 4: Engineering Stress-Strain Curve in the Elastic Deformation Region

Table 7 is the true stress-strain value from the stress-strain curve in the elastic deformation region, where stress and strain are calculated using the equations:

$$\sigma = \frac{F}{A_i} \qquad (4)$$

$$\varepsilon = ln(e+1) = ln\frac{L}{L_o} \qquad (5)$$

Where:

A_i is the cross-sectional area of the specimen at points 1, 2 and 3 (mm^2)
e is the engineering strain (see equation 3)
A_i is calculated from the product of w_i and t_i, where w_i is the width of the specimen and t_i is the thickness of the specimen measured at points 1, 2 and 3.
L is the length of the specimen measured at points 1, 2 and 3 (mm)

True stress-strain at three points can be seen in table 7. From these 3 points a straight line and the linear equation can be known. Modulus of elasticity can be determined by knowing the gradient of the linear equation according to equation 1.

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From the results, it can be seen that there is a slight increase in the modulus of elasticity of the metal on the true stress-strain curve when compared with the modulus of elasticity obtained from the engineering stress-strain curve.

Table 8 is modulus of elasticity obtained from www.matweb.com. Modulus of elasticity obtained from the normal tensile test results (see Table 5) shows a fairly large difference in the modulus of elasticity value with the modulus of elasticity data on the matweb.com. This can occur due to misalignment at the beginning of the tensile testing process so that the data in the linear region from the zero point is not completely linear (see Fig. 6) Meanwhile, tensile testing using the on-off method produces an elastic modulus that is close to the actual elastic modulus value.

Table 7: Modulus of Elasticity from True Stress-Strain Curve in the Elastic Deformation Region

Metals	Point	Strain	Stress (MPa)	Modulus of Elasticity (GPa)
Steel AISI 1018	1	0.000733	147.55	204.7
	2	0.0011	222.07	
	3	0.001466	297.56	
Steel AISI 1045	1	0.000761	158.28	205.6
	2	0.001141	234.83	
	3	0.001521	314.58	
SS304	1	0.000782	153.49	197.9
	2	0.001172	230.27	
	3	0.001563	308.06	
Aluminium 1100	1	0.00038	27.14	71.6
	2	0.000761	54.28	
	3	0.001141	81.56	

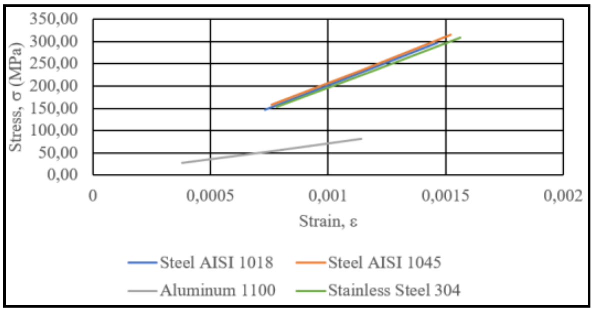

Figure 5: True Stress-Strain Curve in the Elastic Deformation Region

Table 8: Modulus of Elasticity from www.matweb.com

Metals	Modulus of Elasticity (GPa)
Steel AISI 1018	200
Steel AISI 1045	206
SS304	193
Aluminium 1100	68.9

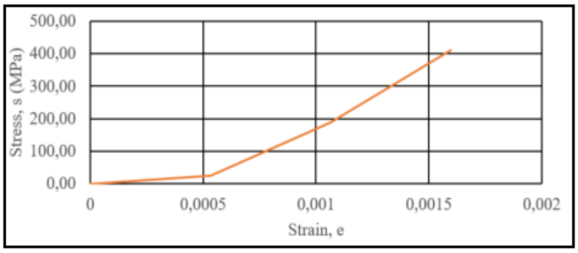

Figure 6: Misalignment in Tensile Testing

3.2 Poisson's Ratio

Poisson's ratio is obtained using the equation:

$$\upsilon = \frac{\varepsilon_w}{\varepsilon_L} = \frac{\varepsilon_t}{\varepsilon_L} \qquad (6)$$

ε_w, ε_t and ε_L are strains calculated using the following equations:

$$\varepsilon_w = \frac{w_o - w_i}{w_o} \qquad (7)$$

$$\varepsilon_t = \frac{t_0 - t_i}{t_o} \qquad (8)$$

$$\varepsilon_L = \frac{L_i - L_o}{L_o} \qquad (9)$$

Where:

w_o, t_o and L^o are the initial width, initial thickness and initial length of the specimen in the gauge length area(mm).
w_i, t_i and L_i are the width, thickness and length of the specimen measured at points 1, 2 and 3 (mm).

Poisson's ratio, which is the ratio between the strain in the width direction and the strain in the length direction, cannot be determined because the change in width is very small. Meanwhile, the Poisson's ratio, which is the ratio of strain in the thickness direction and strain in the length direction, can be seen in table 9. From the results, only the Poisson's ratio for AISI 1018 steel is the same as the Poisson's ratio data from the reference (www.matweb.com). Poisson's ratio for AISI 1045 steel and Stainless steel 304 is slightly different from the reference. A large difference occurs in the Poisson's ratio for aluminum 1100. This probably occurs because the measurement process does not use very precise measuring instruments (accuracy above 0.001 mm).

Table 9: Poisson's ratio of 4 metals

Metals	ε_t	ε_L	Poisson's Ratio	Poisson's Ratio (matweb.com)
Steel AISI 1018	-0,00033	0,001101	-0.30	-0.29
Steel AISI 1045	-0,00039	0,001142	-0.34	-0.29
SS304	-0,00033	0,001173	-0.28	-0.29
Aluminium 1100	-0,00032	0,000761	-0.42	-0.33

IV. CONCLUSION

Based on the results of this experimental investigation, the following conclusions are drawn:

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- The on-off method in Tensile testing can be used to determine the modulus of elasticity of metals well, but not to determine the Poisson's ratio.
- The modulus of elasticity resulting from this on-off method provides results that are close to modulus of elasticity from the reference.
- Poisson's ratio resulting from the on-off method in Tensile testing has not provided satisfactory results. For this reason, measuring instruments that have higher accuracy are needed to get good results.

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