Australian Journal of Basic and Applied Sciences, 8(15) Special 2014, Pages: 126-129

AENSI Journals
Australian Journal of Basic and Applied Sciences
ISSN:1991-8178
Journal home page: www.ajbasweb.com

Determination of Static Modulus of Elasticity of Refractory Metals and Alloys from Acoustic Impedance Tests

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ARTICLE INFO
Article history:
Received 15 September 2014
Accepted 5 October 2014
Available online 25 October 2014

Keywords:
Modulus of elasticity, Acoustic impedance, Refractory metals

ABSTRACT

It is known that the modulus of elasticity of materials obtained from acoustic impedance tests do not match the static modulus of elasticity, ES values obtained from traditional tensile tests, especially for refractory metals and alloys. This study proposes a new mathematical relationship between ES and the acoustic impedance, Z of the test material. The relationship was tested with the material property data of 30 materials comprising of 8 refractory metals, 5 refractory alloys and 17 non-refractory metals. A fifth order polynomial equation was accepted as the best fit to this relation. Results for the refractory metals and alloys tested, except for vanadium, using the proposed equation, gave ES values with accuracy between 88% and 98%. For non-refractory materials, the accuracy was between 77% and 99.3%. The results for refractory materials and alloys are significantly more accurate compared to modulus of elasticity values obtained from wave time-of-flight (TOF) acoustic impedance tests. For non-refractory metals, the proposed method did not improve on the TOF method but the results for the two methods only differed by less than 20% for most cases.

To Cite This Article: Arshed Abdulhamed Mohammed, Sallehuddin Mohamed Haris and Mohd Zaki Nuawi, Determination of Static Modulus of Elasticity of Refractory Metals and Alloys from Acoustic Impedance Tests. ***Aust. J. Basic & Appl. Sci.,*** *8(15): 126-129, 2014*

INTRODUCTION

Traditionally, the modulus of elasticity, E of materials is obtained from loading tests such as the tensile test. Alternatively, non-destructive methods, for example from acoustic transmissibility tests have been proposed for the same purpose. However, it has been observed that results obtained from the two methods could differ significantly especially for refractory metals. In 2003, it was recommended that two distinct values of E be used. The first is the static modulus of elasticity, E_S, obtained from tensile tests. The second is the dynamic modulus of elasticity, E_D, which can be obtained from non-loading tests such as acoustic impedance tests (Eurocode1, 2003).

Typically, E_D is obtained from ultrasonic tests using the wave time-of-flight (TOF) method. Several ultrasonic laws may be used to calculate E_D from these ultrasonic tests. For example, the law $E_D = 2\rho C_s^2(1+v)$, where ρ is the density (kg/m^3), C_s is the acoustic shear wave speed (m/s), and ν is the Poisson's ratio have been used to calculate E_D for seismogenic rock in the Italian Apennines (Ciccotti, 2004). The E_D value obtained was found to be 10% greater than E_S. The relationship $E_D = \frac{\rho C_s^2(3C_L^2-4C_s^2)}{C_L^2-C_s^2}$, where C_s and C_L are respectively, the shear and longitudinal wave velocities, have also been used (Majumdar, 2008; Savin, 2013). Guile *et al*. (2008) suggested that the difference between E_S and E_D increases as the specimen's density increases.

Results:

Table 1 lists some material properties for 30 types of solids materials which includes 8 refractory metals and 5 refractory alloys. The values for v, C_L, ρ, E_S and E_D were collected from several different sources (Cardarelli, 2008; Halevy, 2010; Sathish, 1999; Center, 2012; Yadav, 1995; Chinn, 2002; Toolbox, 2012; Bakar, 2013; Abid, 2013). Refractory metals and their alloys are marked in red. In this work, E_D was obtained from the TOF method based on the following law (Olympus, 2012):

$$E_D = \frac{C_L^2\rho(1+v)(1-2v)}{(1-v)}. \quad (1)$$

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R_D is the percentage difference between E_S and E_D, given by

$$R_D = \sqrt{\left(\frac{E_S - E_D}{E_S}\right)^2} \times 100 \tag{2}$$

The relationship between the acoustic impedance, $Z = C_L\rho$, and $N = E_S\rho$ for these materials is shown in Figure 1, where refractory metals and their alloys are marked by red triangles. The following fifth order polynomial fit was chosen to represent the curve:

$$E_N = \frac{603473 - 122241\,Z - 8311.8Z^2 - 192.303Z^3 + 2.10354\,Z^4 - 0.00816227\,Z^5}{\rho}\ . \tag{3}$$

In Table 1, R_N is the percentage difference between E_S and E_N, calculated from

$$R_N = \sqrt{\left(\frac{E_S - E_N}{E_S}\right)^2} \times 100 \tag{4}$$

Discussion:

Referring to Table 1, the R_D values for non-refractory materials range from 0.5% to 8%, while for refractory metals and alloys, it is in the range of 0.5% to 50%. Clearly, there exists a significant difference between E_S and E_D, especially for refractory metals.

We propose a new relationship (Equation 3), which provides another value of modulus of elasticity, E_N. It was found that, for all refractory metals and alloys, with the exception of vanadium, E_N matches the static modulus of elasticity, E_S more closely compared to E_D, obtained using the TOF method.

Figure 2 shows a bar chart where the values of E_S, E_D and E_N for each refractory metal and alloy except vanadium are compared. Apart from Niobium, the difference between E_N and E_S for each material is less than 13%. The E_N value for Niobium, although being 19% less than E_S, still improves on the E_D value whose difference to E_S is 52%.

For non-refractory materials, in most cases, the E_D value was found to be closer in magnitude to E_S compared to the E_N value. However, the difference between the absolute values of E_D and E_N is in general not too significant, being less than 20% in most cases. The exceptions to this trend are lead, whose E_D is very much closer to E_S than E_N, and magnesium, whose E_N value is closer to E_S than E_D.

The allowable range of acoustic impedance, Z is limited by the validity range of Equation 3 which is between 24×10^6 and 100×10^6 Kg/m^{2}s. This range would be sufficient for most materials.

Conclusion:

E_S and E_D are significantly different, especially for refractory metals and alloys. We have proposed a new relationship which gives E_D values obtained from acoustic impedance tests that are closer to the E_S value, especially for refractory metals and alloys. This method only requires the material to be tested by longitudinal wave transmission, whereas the TOF method requires both longitudinal and shear wave transmission. This makes the proposed method simpler and less expensive as only one piezoelectric transducer would be required to produce the longitudinal wave.

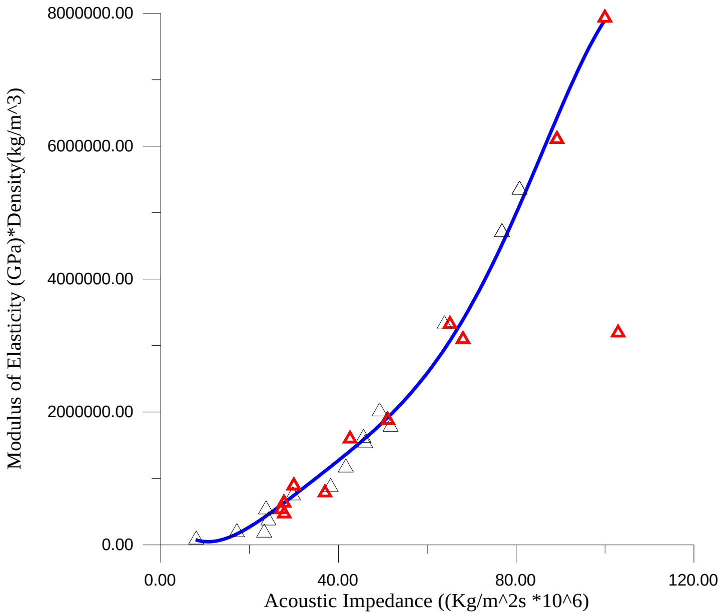

Fig. 1: Relationship between the acoustic impedance Z and N for different materials.

Table 1: Material properties listed in increasing values of *N*.

Common Name	(ν)	C_L	ρ	E_S	E_D	R_D %	N=E.ρ	$Z=C_L.\rho$	E_N	R_N %
		(m/s)	(kg/m^3)	(GPa)	(GPa)		$kg/m^3.GPa$	Kg/m^2s*10^6	(GPa)	
Magnesium(Ma)	0.29	4602	1738	45	28.09	37.57	78210	7.998276	38.79	13.78
Lead(Pb)	0.44	2050	11350	16	14.72	8	181600	23.2675	35.02	118.92
Aluminum(Al)	0.35	6350	2699	70	67.81	3.12	188930	17.13865	56.02	19.96
Tin(Tn)	0.36	3320	7298	50	47.86	4.28	364900	24.22936	60.65	21.30
Ti-6Al-4V	0.342	5800	4430	114	96.044	15.75	505020	25.694	115.87	1.64
Beryllium(Be)	0.075	12800	1850	287	299.42	4.32	530950	23.68	225.27	21.50
Titanium(Ti)	0.345	6100	4450	120	105.41	12.15	534000	27.145	131.50	9.58
Zirconium(Zr)	0.38	4262	6506	97	63.13	34.91	631082	27.728572	94.45	2.62
Zinc(Zn)	0.249	4170	7133	104	103.55	0.43	741832	29.74461	100.53	3.33
Vanadium(V)	0.365	6000	6160	127.6	128.71	0.86	786016	36.96	177.42	39.04
Silver(Si)	0.367	3640	10500	82.7	79.92	3.36	868350	38.22	110.43	33.54
Niobium(Nb)	0.397	3480	8570	104	49.53	52.37	891280	29.8236	84.14	19.08
Copper(Cu)	0.343	4660	8941	130	124.62	4.13846154	1162330	41.66506	150.38	15.67
Silicon Carbide(SiC)	0.22	12382	3610	470	484.77	3.14255319	1696700	44.69902	419.10	10.82
Iron(Fe)	0.29	5900	7800	196	207.2	5.71428571	1528800	46.02	203.67	3.91
Titanium Carbide	0.182	8270	5150	310	323.6	4.38709677	1596500	42.5905	270.92	12.60
Steel 4340(ST)	0.28	5850	7800	206	208.8	1.3592233	1606800	45.63	200.78	2.52
Nickel(Ni)	0.312	5810	8902	199.5	215.46	8	1775949	51.72062	218.04	9.29
Hafnium(Hf)	0.26	3840	13310	141	160	13.47	1876710	51.1104	142.81	1.28
Cobalt(Co)	0.32	5730	8900	211	204.21	3.21	1877900	50.997	212.74	0.82
Chromium(Cr)	0.21	6850	7190	279	299.71	7.42	2006010	49.2515	247.91	11.14
Tantalum(Ta)	0.342	4100	16654	185.7	124.08	33.18	3092647.8	68.2814	204.15	9.93
Hafnium- Iridium (HfIr)	0.269	5006	20564	415	40.09	90.33	8534060	102.94338	398.07	4.07
Uranium(Ur)	0.25	3370	18950	175	179.3	2.45	3316250	63.8615	154.49	11.71
Molybdenum(Mo)	0.293	6370	10220	325	313.52	3.52	3321500	65.1014	298.75	8.07
Rhodium(Rh)	0.26	6190	12410	379	388.63	2.54	4703390	76.8179	363.01	4.21
Ruthenium(Ru)	0.25	6530	12370	432	439.56	1.75	5343840	80.7761	411.80	4.67
W Ni Fe	0.29	5040	17700	345	343	0.57	6106500	89.208	363.23	5.28
Tungsten(W)	0.28	5180	19300	411	405.09	1.43	7932300	99.974	410.51	0.117
Titanium diboride (TiB_2)	0.11	12600	4620	551	713.52	29.49	2545620	58.212	523.45	4.99

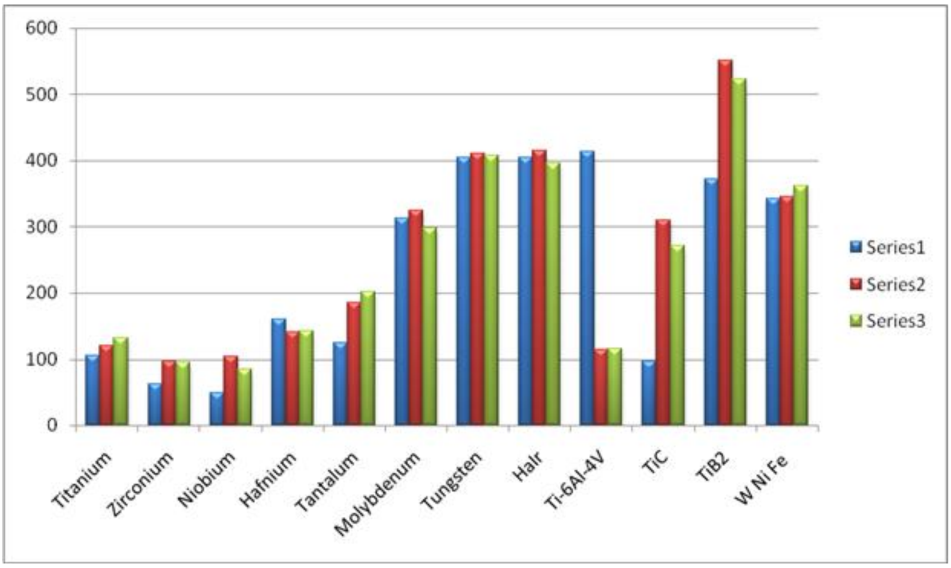

Fig. 2: Comparison of ED (blue), EN (green) and ES (red) for individual refractory metals and alloys.

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