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Using the pressure transmission coefficient of a transmitted wave to evaluate some of the mechanical properties of refractory metals

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ABSTRACT

Refractory metals have attracted increasing interest in recent years because of their use in many high-temperature applications. However, the characteristics of these metals calculated using loaded tests (such as tensile strength tests) differ considerably from those calculated using one of the most famous methods in NDT which is called time of flying of the wave (TOF).The present study presents two solutions based on calculating the pressure transmission coefficient (PTC) of the transmitted wave between the test sample and magnesium metal. The first is based on the development of a highly accurate algorithm that lowers the cost by determining the acoustic impedance of the test specimen to calculating mechanical properties. Up to 26 theoretical tests were done (10 of these tests for refractory materials) according to their known mechanical properties to verify the accuracy of the algorithm. The convergence in results ranged from 92% to 99%. The second solution was designed to solve the same problem for specimens with a thickness of less than 1 mm. Eight experimental tests were done (five using refractory materials) to verify the accuracy of the second solution, with the convergence in the results ranging from 94% to 97%. The relationships of the V_{rms} measured from the oscilloscope with the PTC and with the Fourier transform spectrum were derived. The results of this research were closer to the standard mechanical properties for refractory metals compared with several recent acoustic tests.

1. Introduction

The role of refractory materials in applications such as X-ray targets, electrical contacts [1], and the nuclear power industry [2] is becoming increasingly difficult to ignore. However, the calculated values of some mechanical properties (for refractory metals and their alloys) from TOF usually differ considerably from the actual values in load testing (tensile strength test), with differences ranging from 1% to about 50%.

The thickness of the specimen also limits acoustic testing, i.e., the pulse-echo technique [3] is only accurate when testing specimens at least 12.5 mm thick, and this hinders the using of this test in test samples such as the metal sheets, and plates. In addition the thickness (12.5 mm) means cost especially for the expensive metals and alloys.

Elastic modulus (E) is one of the important characteristics of metals and alloys. Therefore, this research focuses on the test, then the use of elastic modulus for highly accurately determining the other mechanical properties of refractory metals. Hancock et al. [4] one of the first researchers who referred to the classification the Young modulus (E) into static and the dynamic modulus of elasticity. Since 2003, [5] recommends defining elastic moduli using two values. The first is the static elastic modulus (E_s; or loaded elastic modulus) and the other type is the dynamic elastic modulus (E_D; or unloaded elastic modulus), which can be determined through unloading tests such as TOF [6,7]. Physics conversion relationships are widely used in testing the properties of materials, e.g., evaluating the time of flight (TOF) wave to determine the acoustic longitudinal wave speed (C_L) and transverse wave speed (C_s), and then converting them to E_{TOF} using the following formula:

$$E_{TOF} = \frac{C_L^2 \rho (1+\nu)(1-2\nu)}{(1-\nu)} \qquad (1)$$

where E_{TOF} is the modulus of elasticity calculated using the TOF method (in MPa), ρ is the density (kg/m^3), and ν is the Poisson's

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ratio $v = \frac{1-2(C_L/C_s)^2}{2-2(C_L/C_s)^2}$. C_L and C_s are in meters per second. This method is explained in detail by Ref. [3]. In fact the controversy revolves around the classification of the calculated modulus of elasticity calculated from loading and non-loading tests. This section explained side of this controversy as below.

Ciccotti and Mulargia [8] used Eq. (1) to calculate E_{TOF} and regarded E_{TOF} is E_D and then they compared it with the E_s for seismogenic rocks (in the Italian Apennines); they found that the E_D was 10% greater than the E_s. Furthermore, the difference between the E_s and E_D increases with the density of the specimens [9].

Recently several published papers studied this difference [10–15]. On the other hand, many published studies that used acoustic tests without referring to this difference and regarded the two (E_D and E_s) as the same and mentioned them as the modulus of elasticity (E) [16–27].

This research offers new insights into improving the accuracy of the readings and lowering the minimum dimensions of the specimens that can be tested, by calculating the pressure transmission coefficient of the transmitted wave between test specimens of various metals, especially refractory metals and magnesium, which is usually used as the control metal in all tests.

2. Theoretical part

The available data were collected from authorized sources of 26 materials [28–30]. These data include the specifications of eight metals and three alloys for refractory materials, as shown in blue in Table 1, whereas the other metals are non-refractory metals. In Table 1, E_s represents the elastic modulus calculated from the tensile test, whereas E_{TOF} is the elastic modulus calculated using Eq. (1). R_{TOF} represents the percentage of convergence between E_s and E_{TOF} (as shown Table 1), where:

$$R_{TOF} = 100 - \sqrt{\left(\frac{E_s - E_{TOF}}{E_s}\right)^2} \times 100 \tag{2}$$

Z in Table 1 represents acoustic impedance, where $Z = \rho \times C_L$.

From calculated values of R_{TOF} in Table 1, it is so clear that E_S is so close to E_{TOF} for non-refractory metals like AL, Zn, Brass and Ag. This means that TOF is suitable for non-refractory metals. While, in the same table, the values of R_{TOF} showed mismatches or a big difference between E_S and E_{TOF} for refractory metals and their alloys, especial for Ti, Zr, Nb, and Ta and their alloys. To find out the real reasons behind these results, it must refer to the origin of Eq. (1) which means the development equation of motion of wave in isotropic media which is Navier government equation as shown in below [31]:

$$(\lambda + \mu)u_{j,ij} + \mu u_{j,ij} + \rho f_i = \rho \ddot{u}_i \quad (i,j = 1,2,3) \text{ (Navier government equation)}$$

where λ, μ are Lame constants and u is the displacement of particles. Eq. (1) was derived base on neglected the term of $\rho \times f_i$ which represents the body force [32], where the body force is forces that acts throughout the volume of a body which are gravity, magnetic, electrostatic attraction [33]. In fact body forces can be neglected for normal materials [32] such as AL, Zn, brass and Ag, therefore it can be seen the acceptable correspond between E_S and E_{TOF} for these metals in Table 1. While this simplification is un-acceptable for the materials have electrostatic force like Ti, Zr, Nb, and Ta. The electrostatic force (F) can be determined from the electric potential energy, this energy associated with the configuration of a particular inside the metal and this energy depend on two things first, the

Table 1
Mechanical properties of some metals and alloys.

Metal Name	υ	C_L	ρ (kg/m^3)	E_s (GPa)	E_{TOF} (Gpa)	R_{TOF} %	Z (Kg/m^2 s) *10^6	$E_S \times \rho$ GPa. kg/m^3	PTC	E_{S1} (GPa)	R_S %
Magnesium	0.35	5740	1738	45	35.67	79.28	9.97	78210	1.73	41.79	92.88
Aluminum	0.35	6350	2699	70	67.8	96.87	17.13	188930	1.35	69.27	98.95
Beryllium	0.075	12800	1850	287	299.41	95.67	23.68	530950	1.11	278.61	97.07
Ti-6Al-4V	0.342	5800	4430	114	96.04	84.24	25.69	505020	1.05	112.9	99.03
Titanium	0.345	6100	4450	120	105.4	87.83	27.14	534000	1.01	122.68	97.76
Zirconium	0.38	4262	6506	97	63.13	65.08	27.72	631082	1.01	89.7	92.47
Zinc	0.249	4170	7133	104	103.55	99.57	29.74	741832	0.95	114.46	89.93
Niobium	0.397	3480	8570	104	49.53	47.62	29.82	891280	0.95	103.93	99.93
Vanadium	0.365	6000	6160	127.6	128.7	99.13	36.96	786016	0.81	132.36	96.26
Brass	0.34	4430	8520	100	108.63	91.36	37.74	852000	0.8	102.35	97.64
Silver	0.367	3640	10500	82.7	79.91	96.63	38.22	868350	0.79	86.622	95.25
Copper	0.343	4660	8941	130	124.62	95.86	41.66	1162330	0.74	136.85	94.72
Titanium Carbide	0.182	8270	5150	310	323.69	95.58	42.59	1596500	0.73	255.37	82.37
Steel 4340	0.28	5850	7800	206	208.8	98.63	45.63	1606800	0.69	207.57	99.23
Iron	0.29	5900	7800	196	207.19	94.28	46.02	1528800	0.69	212.51	91.57
Chromium	0.21	6850	7190	279	299.7	92.57	49.25	2006010	0.65	273.35	97.97
Cobalt	0.32	5730	8900	211	204.2	96.77	50.99	1877900	0.63	200.12	94.84
Hafnium	0.26	3840	13310	141	160.4	86.23	51.11	1876710	0.63	136.77	97
Nickel	0.312	5810	8902	199.5	215.46	91.99	51.72	1775949	0.62	226.43	86.49
Tantalum	0.342	3400	16654	185.7	124.07	66.81	56.62	3092647	0.58	173.78	93.58
Uranium	0.25	3370	18950	175	179.34	97.51	63.86	3316250	0.52	178.94	97.74
Molybdenum	0.293	6370	10220	325	313.98	96.61	65.1	3321500	0.51	339.67	95.48
Rhodium	0.26	6190	12410	379	388.62	97.45	76.81	4703390	0.45	371.98	98.14
Ruthenium	0.25	6530	12370	432	439.55	98.25	80.77	5343840	0.43	415.66	96.21
W Ni Fe	0.29	5040	17700	345	343.09	99.44	89.2	6106500	0.39	359.14	95.9
Tungsten	0.28	5180	19300	411	405.08	98.56	99.97	7932300	0.35	407.46	99.13