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Evaluation of the Elastic and Thermal Properties of WC/Fe-Ti Ceramic-Metal Composites Fabricated by Powder Metallurgy

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Abstract— Tungsten carbide (WC) is an attractive reinforcing material for iron and its alloys. This work was done to select a possible replacement for iron and titanium as a binder through a phase diagram approach using selected WC-X systems. Composite samples were produced from tungsten carbide, iron and titanium matrix powders by using a powder metallurgy. Prepared samples were sintered at the temperature of 1000 ºC under Ar shroud. The Young's modulus (*E*) has been calculated with density and the ultrasonic velocity measured through ultrasonic pulse-echo method and immersion method. All ultrasonic velocity measurements were made in mold with the same length and diameter. The hot-disk method was used to measure the thermal conductivity. There is a steady increase in the relation between elastic modulus and thermal conductivity. In addition, as seen in the SEM images, it can be also said that increasing the volume fraction of WC particles favored the grain refinement, have a stable structure improved the hardness and strength, but decreased the ductility. The results have been compared with the literature.

Index Terms— Composite, Young's Modulus, Pulse-Echo, Immersion, Thermal Conductivity

1 Introduction

Tungsten carbide composites are well known for its attractive physical and mechanical properties, such as high hardness, high chemical stability, high abrasion and oxidation resistance, low coefficient of thermal expansion, high fracture toughness and a certain amount of plasticity [1-2]. Wolfram Carbide (WC) also called tungsten carbide, tungsten cemented carbide, cemented carbide or simply carbide and WC-based hard alloys are widely used in cutting tools, mining tools, rock drill tips and moulds [3-7]. WC-based hard alloys were used to designate a metal matrix composite constituted by hard ceramic particles, normally WC, into a metallic matrix [8-9]. Tungsten carbide hard metal alloys consist of tungsten carbide and a ductile binder phase. Although cobalt wets tungsten carbide well and has good mechanical properties, it is of great interest to find the metals of comparatively more cost effective and less pollution so as partially or completely to replace the Co without compromising the properties of hard metal alloys. Among the iron group metals, Fe, Ni and Ti are considered as an ideal substitution of Co for in recent years in an attempt mainly to improve the properties of the binder [10-11]. Many conventional methods are employed to produce the composites such as powder metallurgy. Powder metallurgy (P/M) is a good method for fabrication of high melting material with better mechanical properties [12-14]. In this study, WC–Fe-Ti hard metal alloys were produced using the powder metallurgy technique. Moreover, the research carried out a series of experimental tests to explore the characteristics and properties of the same sintering temperatures on different specimens with varying amounts of Fe and Ti.

Evaluation of thermal and elastic properties of composite materials obtained in this study was investigated by using ultrasonic and thermal hot-disk techniques.

2 Materials and Methods

In this study we have examined changing with thermal conductivity of Young's modulus of calculated three different WC–Fe-Ti composites by ultrasonic techniques. We used two ultrasonic methods which are pulse-echo and immersion methods for the ultrasonic velocity measurements. Longitudinal and transverse ultrasonic velocities of samples have been measured by a pulse-echo method with a Panametrics 5800 model Olympus brand computer-controlled pulser-receiver (PR) and digital oscilloscope. We have used two probes that have the same frequencies; 4 MHz probe (Sonatest SLH4-102 T/R) to measure longitudinal velocities

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and 4 MHz T/R transverse probe (GE Inspection Technologies) to measure transverse velocities. In immersion testing take place in a liquid which conducts the beam of sound between the probe and test material with using 5MHz wide-band T/R probes (GE Inspection Technologies) to measure longitudinal and transverse velocities. After we calculated density of all the samples, we have obtained Young's modulus with using calculated densities, ultrasonic longitudinal and transverse velocity. Young's modulus in medium can be found by the following equation:

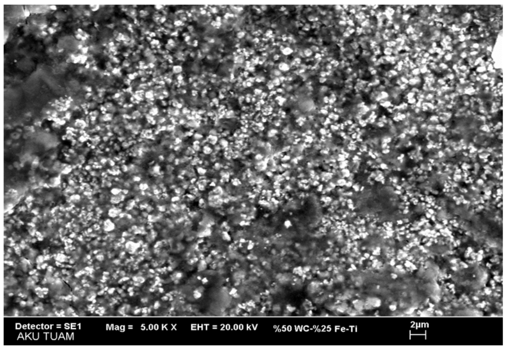
$$E = \rho V_T^2 \frac{3V_L^2 - 4V_T^2}{V_L^2 - V_T^2} \quad (1)$$

The WC-based metal–matrix composites were examined in this investigation. We classified the powders used for preparation of the WC - Fe - Ti composite samples as Alloy 1, Alloy 2 and Alloy 3. The nominal compositions of these alloys are given in Table 1.

Table 1. The nominal composition of the WC-Fe-Ti composites.

Samples	Compositions (wt%)			Fe/Ti ratio
	WC	Fe	Ti	
Alloy 1	50	37.5	12.5	3
	50	25	25	1
	50	12.5	37.5	1/3
Alloy 2	60	30	10	3
	60	20	20	1
	60	10	30	1/3
Alloy 3	70	22.5	7.5	3
	70	15	15	1
	70	7.5	22.5	1/3

All the powders were placed in a 15 mm diameter cylinder-shaped steel mold and pressed using a hydraulic press at a pressure of 20MPa at room temperature and sintered 1000°C in Argon atmosphere for 2 hours, allowing them to cool naturally. Sintered WC-based metal–matrix composite samples were characterized using Leo 1430 VP equipped with Röntec energy dispersive X-ray (EDX) model scanning electron microscopy (SEM). Fig. 1 shows the SEM images of WC–Fe-Ti alloys after sintering temperature treatments.



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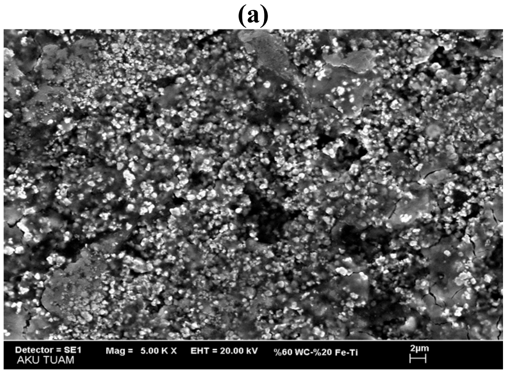

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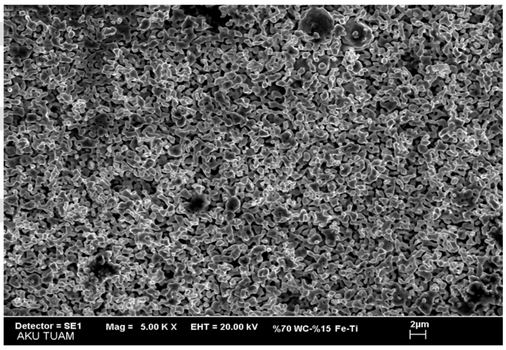

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Fig.1. SEM Images of a) $WC_{0,5}$+$Fe_{0,25}$+$Ti_{0,25}$ b) $WC_{0,6}$+$Fe_{0,2}$+$Ti_{0,2}$ c) $WC_{0,7}$+$Fe_{0,15}$+$Ti_{0,15}$ samples.

2.1. Thermal Conductivity Measurements

Hot disk method was used in this study for measuring thermal conductivity. The hot disk thermal conductivity technique represents a transient plane source method for rapid thermal conductivity and thermal diffusivity measurement. The main advantages of the hot disk technique is: wide thermal conductivity range, from 0.005 W/(m K) to 500 W/(m K); wide range of materials types, from liquid, gel to solid; easy sample preparation; non-destructive; and more importantly, high accuracy [15]. In this paper, using the basic theory of measuring the thermal conductivity of the hot disk sensor, the conductivity values

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will be read from the system and compared with the Young's modulus obtained by ultrasonic method.

3 Results and Discussion

In this study, it is aimed to produce composite samples at different ratios and to investigate some physical properties of the obtained samples by different methods.

Experimental results obtained with ultrasound velocities, elastic modulus, thermal conductivity and density values belong to the samples generated by adding Fe and Ti binder phases into ceramic-based WC powder are given in Table 2.

Table 2. Ultrasound velocities, elastic modulus, thermal conductivity and density values of WC-Fe-Ti composite sample.

Sample	*Pulse-Echo Method*			*Immersion Method*			*Thermal Conductivity* (W/mK)	*Density* (g/cm^3)
	V_L (m/s)	V_T (m/s)	E (GPa)	V_L (m/s)	V_T (m/s)	E (GPa)		
$WC_{0,5}+Fe_{0,375}+Ti_{0,125}$	3345	2679	55.6	3483	2885	43.4	7.29	6.4
$WC_{0,5}+Fe_{0,25}+Ti_{0,25}$	3573	2814	67.2	3702	2898	73.8	8.75	6.2
$WC_{0,5}+Fe_{0,125}+Ti_{0,375}$	3958	3007	93.2	4320	3293	110.1	9.82	6.3
$WC_{0,6}+Fe_{0,3}+Ti_{0,1}$	3532	2603	82.2	3633	2544	88.4	4.96	6.7
$WC_{0,6}+Fe_{0,2}+Ti_{0,2}$	4049	2775	105.8	4061	2718	105.1	6.61	6.5
$WC_{0,6}+Fe_{0,1}+Ti_{0,3}$	4327	2885	119.0	4358	3097	123.5	8.76	6.5
$WC_{0,7}+Fe_{0,225}+Ti_{0,075}$	3859	2571	98.9	3757	2479	93.1	2.41	6.8
$WC_{0,7}+Fe_{0,15}+Ti_{0,15}$	4526	2738	119.9	4239	2550	104.4	3.76	6.6
$WC_{0,7}+Fe_{0,075}+Ti_{0,225}$	4603	2768	121.2	4856	2901	133.7	4.73	6.5

While longitudinal ultrasonic wave velocity values increase depending on WC_x volume ratio in WC-Fe-Ti composite sample, there is a decrease in transverse ultrasound wave velocity values. The reason for this is that considering the signals taken from more interior region and atomic placements in transverse wave measurement made perpendicular to the axis, pulling force is not enough for one to move the other because of the distance among the atoms causing weakened wave velocity. In addition, in Gür's [16] another study, composite material from Al powder with different amount of reinforced SiC particle was produced. A high Al/SiC particle size ratio causes SiC segregation (deposition, accumulation) along the borders of Al powder and thus causes to obtain low ultrasonic velocities related to homogeneous distribution of reinforcement. If this physical condition is also considered then the decrease in longitudinal and transverse wave speeds could be explained. There is a linear relationship between Young's modulus and thermal conductivity in WC-Fe-Ti composite materials used in this study. This relationship is shown in Fig. 2.a-c. These situations are found to be compatible with metal-based composite materials and alloys from the previous studies. Fig. 1 shows microstructure morphology observations of WC–Fe-Ti alloys after the same sintering temperature treatments. Obviously, the distribution and sizes of Fe-Ti binders are not uniform at lower WC ratio, as shown in Fig. 1a and b. When examined the SEM photograph given in Figs.1a and 1b, it can be seen that the structure includes pores and the pores do not show a homogenous distribution. Conversely, the uniform distribution and sizes of Fe-Ti binders appeared in 70% WC ratio sintered WC–Fe-Ti alloys, as shown in Fig. 1c. Moreover, the coarsening phenomenon evidently disappeared in $WC_{0,7}+Fe_{0,15}+Ti_{0,15}$ alloys , as shown in Fig. 1c. This could be attributed to the increasing bonding between the grains, decreasing porosity of samples and also a good indicator of correct rating process. The increase of intergranular bonding should result with

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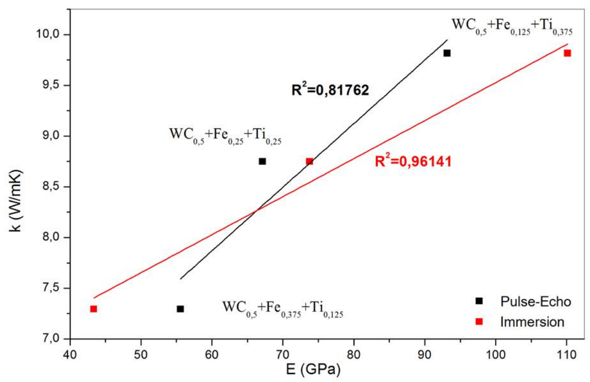
the increased propagation speed of the wave since the wave will face less particle boundaries in the sample.



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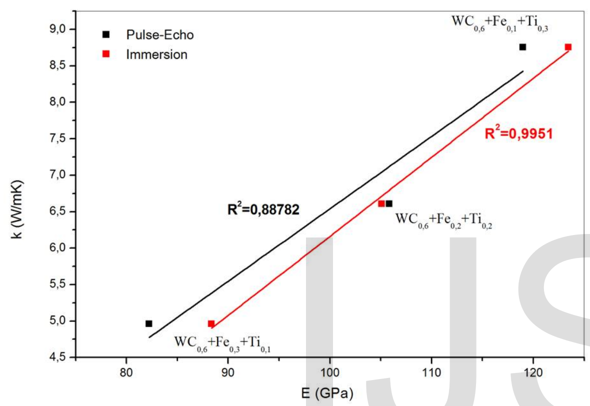

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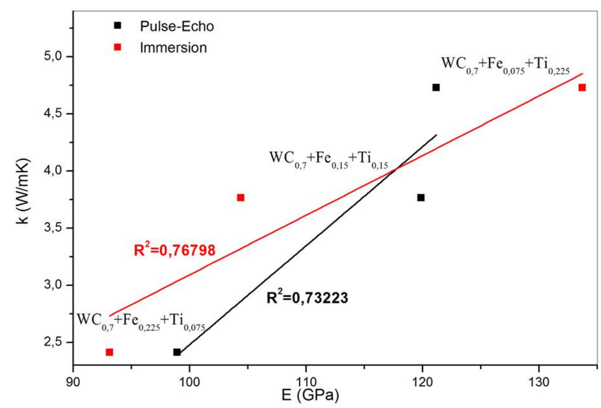

(c)

Fig. 2. Thermal conductivity and Young modulus graph of (a) $WC_{0.5}$–Fe–Ti, (b) $WC_{0.6}$–Fe–Ti, (c) $WC_{0.7}$–Fe–Ti composite sample.

With the increase in the Fe/Ti ratio, the crystal structure gradually changed and more rounded WC grains were obtained, while the WC grain size gradually decreased and was more uniformly distributed. Longitudinal and transverse ultrasonic wave velocity, Young's modulus and thermal conductivity values gradually decreased with an increase in the Fe/Ni ratio. One of the most important factors affecting ultrasonic wave velocity is porosity. The relationship between ultrasonic wave velocity and porosity in WC-Fe-Ti composite specimens is inversely proportional and as the amount of porosity increases, ultrasonic wave velocity propagation also decreases.

4 Conclusion

In this study, the relationship between thermal and elastic properties of WC-Fe-Ti composites was investigated. The reliability of measurement was also tested by using two different methods. When the graphs are examined, a steady increase was obtained in thermal conductivity and Young's modulus for produced composites. Existing differences were attempted to be explained with a reasonable approach. Also, in this work, the effects of different Fe/Ti ratios on the microstructure, physical properties and mechanical properties (like porosity) behaviour of WC-Fe-Ti composites observed. With the decrease in the Fe / Ti ratio, the amount of porosity in the structure decreased. As a result, longitudinal and transverse ultrasonic wave velocities are increased in pulse-echo and immersion methods.

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