

WC-Co Particles Reinforced Aluminum Matrix by Conventional and Microwave Sintering

Ehsan Ghasali^{a,b,}, Amir Hossein Pakseresh^a, Maryam Agheli^c, Amir Hossein Marzbanpour^b,
Touradj Ebadzadeh^a*

*^aCeramic Department Materials and Energy Research Center, Imam Khomeini Blvd,
Meshkin-Dasht, P.O. Box 31787-316, Karaj, Iran*

^bSama Technical and Vocational Training College, Islamic Azad University, Eslamshahr, Tehran, Iran

*^cDepartment of Materials Engineering, Semnan University, P.O. Box 35131-19111,
Semnan Province, Iran*

Received: July 12, 2015; Revised: October 1, 2015

Metal matrix composites of Al-WC (10, 15 and 20 wt%) were prepared by microwave (without holding) and conventional sintering (held for 1 hour) processes at various temperatures between 650-950 °C. The results indicated that the highest density of conventional and microwave sintering corresponds to $97.4 \pm 1.2\%$ and 98.6 ± 0.8 of theoretical density, respectively; The highest bending strength of conventional and microwave sintered samples were 223 ± 12 and 256 ± 12 MPa, respectively. XRD patterns showed the decomposition of WC particles and formation of Al_3W and $Al_{12}W$ interfacial reaction product phases in both processes. SEM studies showed that WC reinforcement particles were more likely to be agglomerated in microwave compared to conventional sintering process.

Keywords: metal matrix composite, tungsten carbide, aluminum, microwave sintering

1. Introduction

Particulate reinforced aluminum matrix composites (PRAMC) have received considerable attention because of high specific modulus, low coefficient of thermal expansion, good wear resistance and their high specific strength. These brilliant properties of PRAMC make them promising candidates for use in aerospace and automobile industries.

The PRAMCs have been usually produced via powder metallurgy and casting, while achieving a homogenous distribution of reinforcement in the base alloy in comparison with casting technique¹. Low density, high conductivity and high toughness accompanied by a low price made aluminum as one of the best materials in some metal matrix composites in comparison with other light metals such as magnesium (Mg)². The corrosion resistance of aluminum is the other characteristic which is very important for use in PRAMC composites in different environments. In spite of all these advantages, the low tensile strength of aluminum has limited its applications³.

Ceramic particles (e.g. Al_2O_3 , SiC, TiC and WC) have been added to aluminum matrix in order to overcome its low tensile strength and increase hardness and tolerate temperatures.

Tungsten carbide (WC) is a 6B transition metal carbide which has superior properties such as high hardness, high wear and corrosion resistance that makes it appropriate choice for reinforcement applications⁴.

Using powder metallurgy method to produce aluminum composites reinforced with ceramic particles such as SiC

will result in a homogenous distribution of reinforcement in the matrix, which in comparison with other methods like casting and thixoforming has fewer problems⁵. Reinforcement segregation, clustering, high localized residual porosity and poor interfacial bonding are problems found in other forming techniques⁶. The rest of the composite production methods such as spray deposition are expensive which render their applications⁷. Producing net-shape components and minimizing machining process are the other advantages of using powder metallurgy. In aluminum metal matrix composites, machining process is an important problem as a result of high tool wear due to the inherent abrasiveness of the hard ceramic (e.g. SiC) particles. On the other hand, the determining step in metallurgy powder process is the best method for sintering process⁸.

Nowadays microwave sintering of ceramics has received more attention due to its specific characteristics⁹. In conventional heating method slow heating rates and long dwell times during a sintering cycle result in exaggerated grain growth phenomenon. The microwave heating is the volumetric process and very efficient to obtain a very high heating rate due to the interaction of microwaves with ceramic materials. A fraction of the time required to complete microwave rather than conventional sintering. In microwave heating, the rate of grain growth decreases due to a decrease in sintering time. Therefore, samples sintered in a microwave process obtain a uniform microstructure with small grains and consequently, a high mechanical strength¹⁰.

Microwave heating has been extensively used for ceramics sintering and hard metals treatments, but for the

*e-mail: ehsan_ghasali@yahoo.com

first time Roy et al.¹¹ reported the effective coupling of microwaves and metals in powder form. On the other hand, B. Gnanasundarajayaraja² investigated the effect of WC additions on aluminum metal matrix sintering by conventional heating. In the present work, the effect of Co particles additions on the interfacial reaction of aluminum-tungsten carbide composites has been studied. The resulting microstructure and mechanical properties of final composites sintered by conventional and microwave methods have been investigated.

2. Experimental Procedures

In this research, WC powder (99.5% purity, 1 μm average particle size) is reinforced with the base aluminum powder (1056-merck). Cobalt powder with purity of 99.8% and mean particle size of 5 μm was used as additive. The required amounts of Al, WC and Co powders were taken in three separated batches with the compositions given in Table 1.

The batches were prepared through mixing the determined of powders using Spex (Mixer mill – 8000D). In the next step, the bar shape samples with the dimensions of 25*5*5 mm were compacted at 250 MPa using a uniaxial press. Microwave and conventional sintering were performed at 650, 750, 850 and 950 °C in graphite bed without holding and held for 1 hour, respectively. Densities of sintered samples were measured using Archimedes method. Three point bending strength of samples were examined with Santam-STm 20 and X-ray diffraction analyses were performed by Philips X² Pert System to determine the phases in sintered samples. Microstructural investigations of sintered samples were carried out using a SEM (Stereoscan 360, Leica Cambridge).

3. Result and Discussion

Figures 1 and 2 show the variation of relative density versus temperature for microwave and conventional sintered samples. As Figure 1 shows the highest relative density corresponded to A series of samples which have lower amounts of reinforcement among the other series of samples. Increasing sintering temperature had no positive effect on the relative density of samples and the maximum density was achieved at 650 °C.

Figure 2 shows the increase of relative density (± 0.8% standard deviation) of conventional sintered samples with the increasing sintering temperature. It seems that longer sintering time in conventional process makes more diffusion time for aluminum atoms to promote sintering process for higher relative density. The highest relative density corresponds to A series of samples which similar to microwave sintered specimens.

Figures 3 and 4 demonstrate the XRD diffraction patterns of microwave and conventional sintered of C series samples. As expected, the peaks corresponding to Al and WC are identified in the XRD pattern. In XRD patterns of

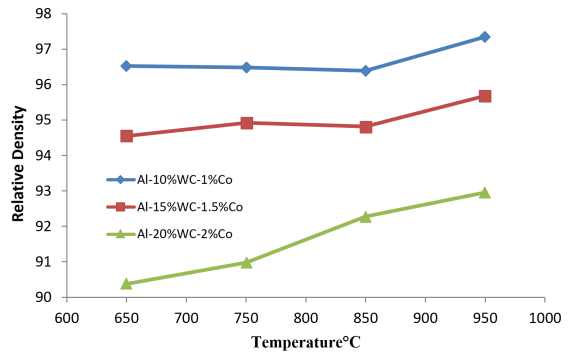


Figure 1. Variation of relative density vs temperature in microwave process.

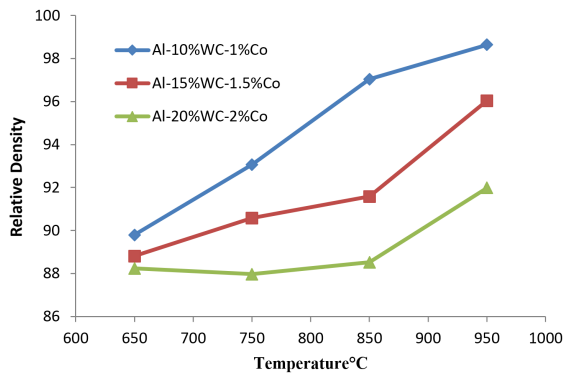


Figure 2. Variation of relative density versus temperature in conventional process.

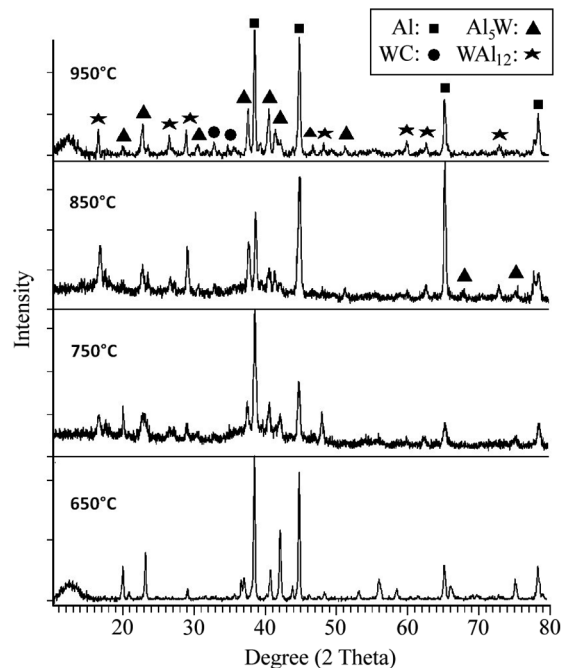


Figure 3. XRD patterns of microwave sintered samples at 650, 750, 850 and 950 °C.

Table 1. Different compositions of batches.

series	Al (wt %)	WC (wt %)	Co (wt %)
A series	89	10	1
B series	83.5	15	1.5
C series	78	20	2

microwave-sintered samples (Figure 3), two intermetallic phases marked as Al_5W and $Al_{12}W$ were detected after sintering at 650 and 750 °C. In Figure 5, it seems that Al_5W solid solution is formed as the result of the decomposition of WC (20 %wt). But probably the rapid heating and cooling rate of microwave process resulted in the formation of low amounts of $Al_{12}W$.

It is obvious that that temperature plays a vital role in the interface reaction of Al-WC composite materials. During sintering process, matrix alloy in liquid state permeates into

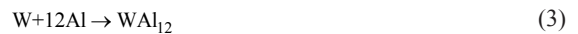
interspaces of WC particles and their surfaces, and touches WC particles tightly. In this case, thermal decomposition reaction takes place on the edges and surfaces of WC particles. These probable interface reactions can be described by the following reactions¹²:



Since W_2C is in metastable phase under preparation temperature, a possible phase change can occur as follows:



W atoms produced in reaction (1) and (2) leave the surfaces of WC particles and enter into the liquid phase of matrix alloys. When the concentration of W atoms in liquid phase exceeds its maximum solubility, $Al_{12}W$ compound comes into being:



As preparation temperature increases, the phase change takes place in $Al_{12}W$ and Al_5W forms:



Most researchers believe that carbon reacts with Al to form Al_4C_3 at the interface reaction. In the present work, Al_4C_3 can be formed at interface due to the thermal decomposition of WC and the formation of carbon. However, Al_4C_3 peaks were not detected by XRD analysis probably due to the low amount of formed Al_4C_3 .

Figure 4 shows the more intense peaks of Al_5W phase formed at 950 °C in conventional compared to microwave heating due to a lower heating rate and longer holding time in the former. Microwave heating provides higher temperature at the interface of Al and WC particles than entire volume of sample because of superior absorption of microwaves at the surface of WC particles which lead to accelerating the reactions as reported above.

Structures and lattice parameters of intermediate phases are listed in Table 2. By decomposition of supersaturated (Al) solid solutions, two intermediate phases were detected.

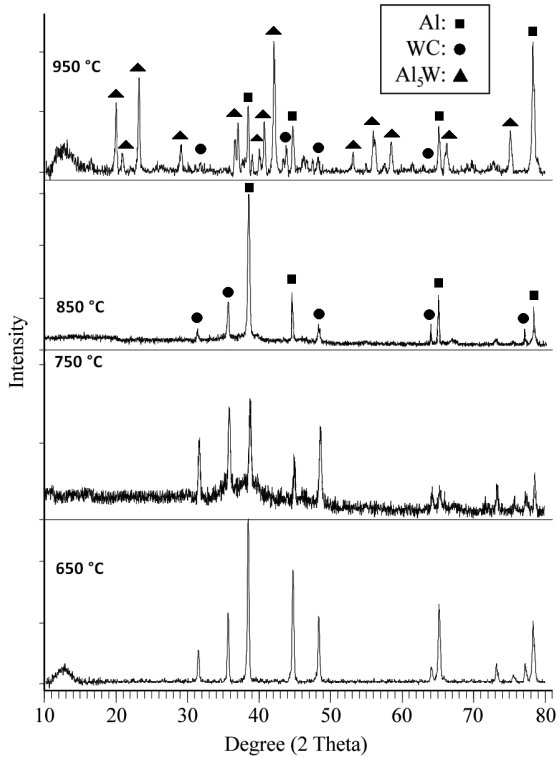


Figure 4. XRD patterns of conventional sintered samples at 650, 750, 850 and 950 °C.

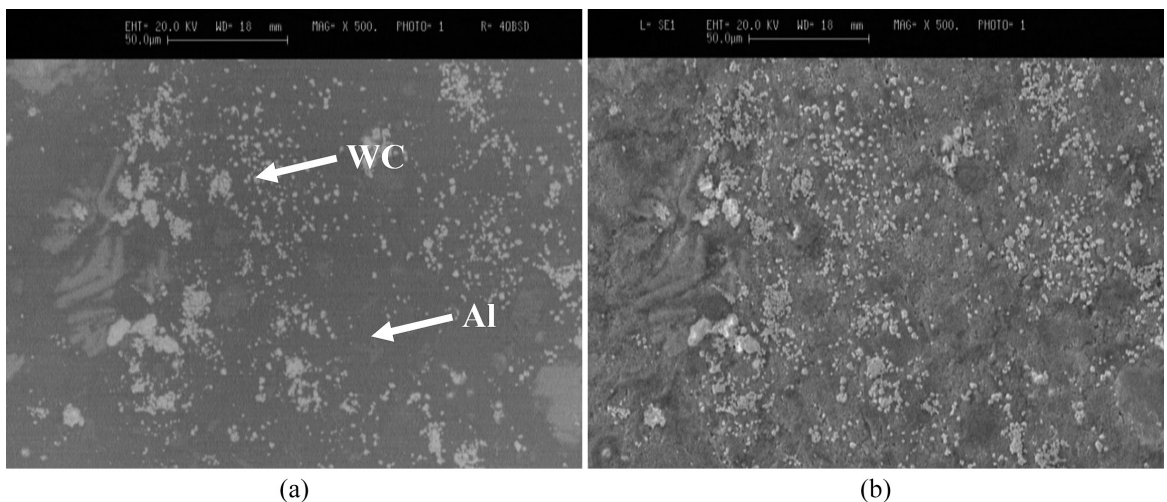


Figure 5. SEM micrographs of A series of samples sintered at 750 °C in conventional furnace: (a) Backscattered and (b) secondary electron.

Surayanarayana has shown that one of these phases is identical in structure with the equilibrium phase $\text{Al}_{12}\text{W}^{(13)}$. Probably due to higher W content the lattice parameter of the bcc cell is greater. The second phase mentioned by Tonejc¹⁴ has tetragonal structure and also the stoichiometry Al_{12}W .

Table 2. Crystal structure and lattice parameters of intermediate phases^{13,14}.

phase	Structure	Type	a [nm]	b [nm]	c [nm]
Al_{12}W	bcc	Al_{12}W			
Al_{12}W	tetr			0.7874	
Al_5W	hex	Al_5Mo		0.88578	
Al_4W	mon		1.7771	0.5218	100.2

It seems that this tetragonal modification is stable above 870 °K. Probably on cooling, there occurs a polymorphic transformation into the bcc structure.

Figure 5 illustrates SEM micrographs of A series of samples sintered at 750 °C in conventional furnace, showing a nearly homogeneous distribution of reinforcements in the aluminum matrix.

Figures 6 and 7 show SEM micrographs of A series of samples sintered in microwave furnace at 650 and 750 °C, respectively. Figure 6 shows an appropriate interface between Al and WC reinforcement particles which provides an optimal structure in terms of mechanical properties.

By increasing sintering temperature near the melting of aluminum (660 °C), more aluminum particles are surrounded by the substantial oxide film (Al_2O_3) until the sintering

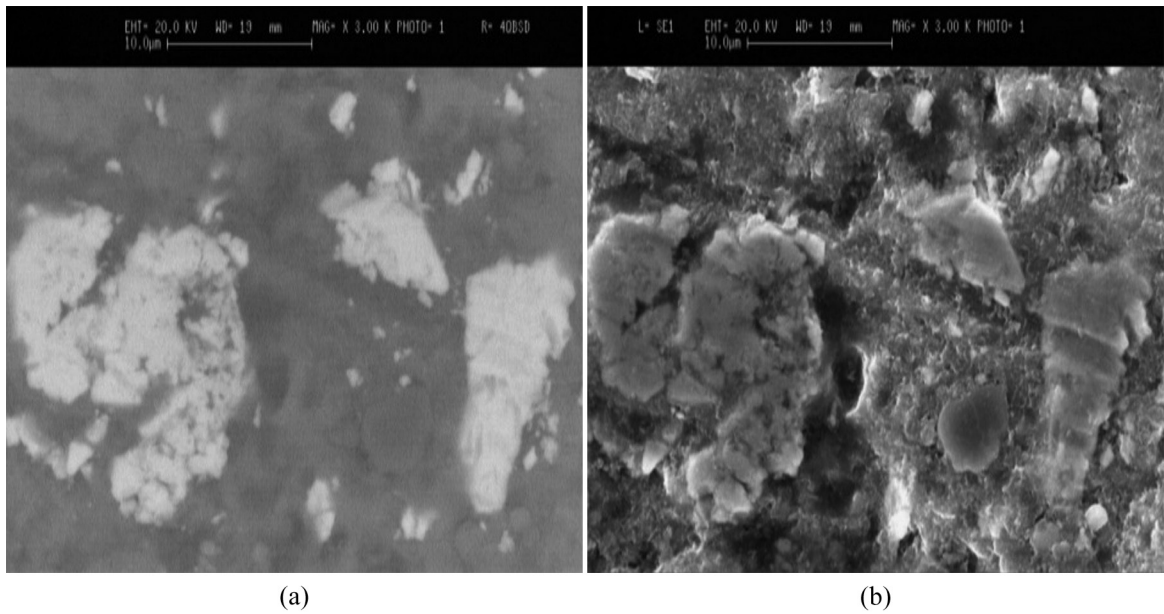


Figure 6. SEM micrographs of A series of samples sintered at 650 °C in microwave furnace: (a) Backscattered and (b) secondary electron.

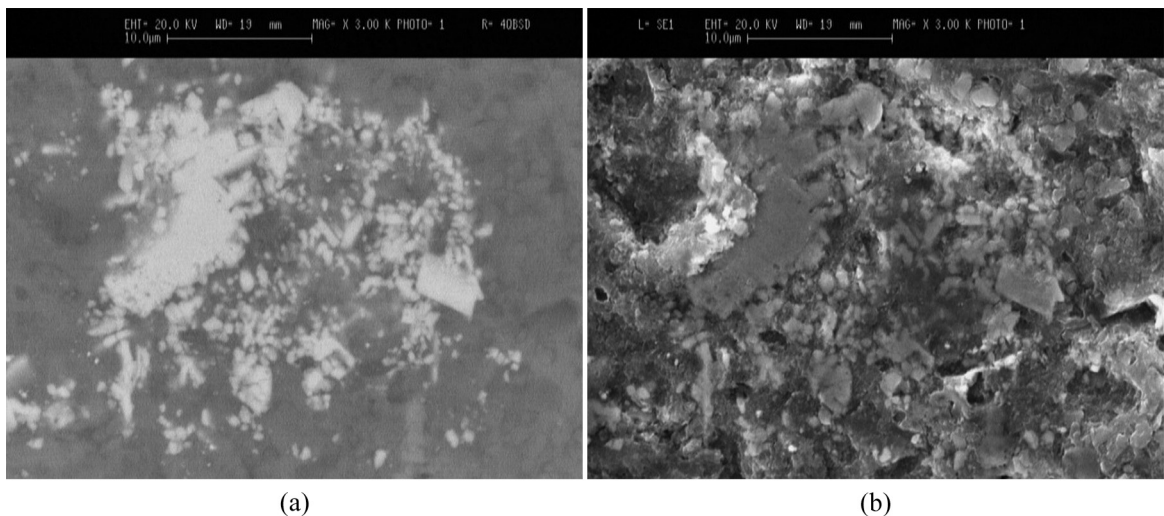


Figure 7. SEM micrographs of A series of samples sintered at 750 °C in microwave furnace: (a) backscattered and (b) secondary electron.

temperature goes beyond the melting temperature of aluminum. The aluminum particles begin to melt and their volumes increase and become large enough to smash the oxide layer, making contact and then weld of leaked aluminum particles¹⁵. Some samples were sintered at temperatures greater than the melting point of aluminum which implies that WC particles prevent aluminum particles from getting too close to one another. Apart from the interfacial reaction between Al and WC particles, with the increase in the sintering temperature the agglomeration of WC particles, which is detrimental for mechanical properties, was increased (Figure 7). However, as discussed previously, the higher sintering temperature caused in higher relative density.

Figures 8 and 9 presents the effect of sintering temperature on the bending strength of samples sintered in microwave and conventional furnace, respectively.

The results were clearly shown that the bending strength in microwave sintered samples had the same trend with increasing WC composition for all sintering temperatures (Figure 9). The highest amounts of bending strength for all compositions were obtained by A series which had higher relative density among others. With the increase in sintering temperature, the bending strength values (± 12 MPa standard deviation) increased due to the increase of the agglomeration of reinforcement particles at sintering temperatures over 650 °C.

The bending strength values of composites (Figure 9) varied with the increase in sintering temperature and had

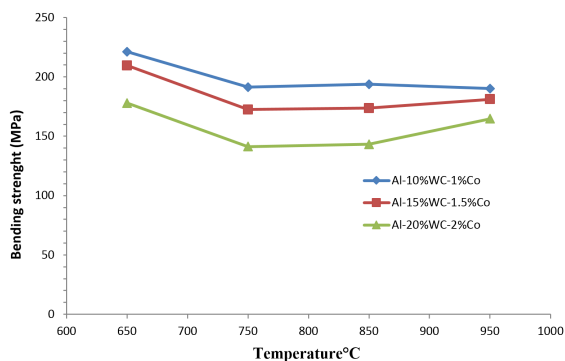


Figure 8. The variations of bending strength values with sintering temperature in conventionally sintered samples.

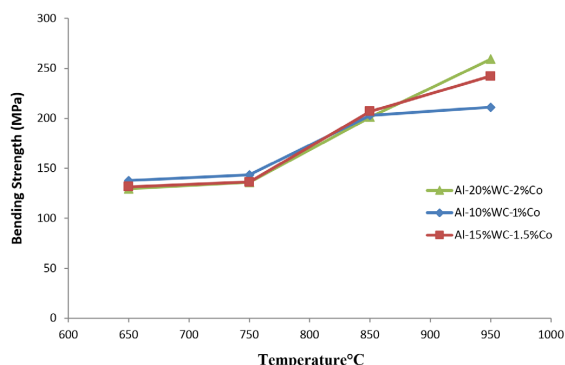


Figure 9. The variations of bending strength values with sintering temperature in microwave sintered samples.

similar changes to values obtained by relative density measurements (Figure 2). The maximum bending strength obtained at 950 °C for C series which had the highest relative density among all specimens. Maybe the formation of Al_5W phase had a positive effect on bending strength of samples sintered at evaluated temperatures but this phenomenon was not observed in microwave sintered samples due to the influence of other parameters on bending strength such as the distribution of reinforcements, relative density and etc.

As comparison between the result of this research and other aluminum matrix composite, the bending strength of ZnO coated aluminum borate whiskers reinforced 2024 Al composites were calculated by Yue et al.¹⁶. The results were shown by them revealed that the optimum bending strength was 480 ± 20 MPa. On the other hand, the optimum bending strength as result of this work is 256 ± 12 MPa which had almost identical reinforcement amounts compared with ZnO coated aluminum borate whiskers reinforced 2024 Al composites, demonstrate that the mechanical properties obtained by this work is considerable. The mentioned composite were fabricated by Yue et al., used coated whiskers as reinforcement have effective role in mechanical properties (specially bending strength). But in this work applying particulate reinforcement conducted to comparable result with simple starting materials and appropriate preparation process considering time and energy saving.

4. Conclusions

The considerable conclusions of the studies on Al-WC metal matrix composites are as follows:

1. Al-WC composites were prepared successfully using microwave and conventional techniques with the highest relative density of $97.4 \pm 1.2\%$ and 98.6 ± 0.8 , respectively.
2. It was found that the decomposition of WC and also the formation of Al_5W and $Al_{12}W$ (interfacial reaction products) in microwave and conventional sintering occurred at 650 and 850 °C, respectively.
3. The SEM micrographs showed uniform distribution of reinforcements in conventional process and agglomeration of reinforcements in microwave process at the early stage of sintering.
4. The maximum bending strength of 223 ± 12 and 256 ± 12 MPa was obtained in microwave sintered sample (10 wt% WC at 650 °C) and conventional sintered sample (20 wt% WC at 950 °C), respectively.
5. Almost the higher mechanical properties were achieved by conventional sintering compared to microwave sintering; while microwave sintering had the best advantage of time and energy saving with acceptable properties.

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