A Review of Metal Injection Molding- Process, Optimization, Defects and Microwave Sintering on WC-Co Cemented Carbide

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Abstract. This article is about a review of optimization of metal injection molding and microwave sintering process on tungsten cemented carbide produce by metal injection molding process. In this study, the process parameters for the metal injection molding were optimized using Taguchi method. Taguchi methods have been used widely in engineering analysis to optimize the performance characteristics through the setting of design parameters. Microwave sintering is a process generally being used in powder metallurgy over the conventional method. It has typical characteristics such as accelerated heating rate, shortened processing cycle, high energy efficiency, fine and homogeneous microstructure, and enhanced mechanical performance, which is beneficial to prepare nanostructured cemented carbides in metal injection molding. Besides that, with an advanced and promising technology, metal injection molding has proven that can produce cemented carbides. Cemented tungsten carbide hard metal has been used widely in various applications due to its desirable combination of mechanical, physical, and chemical properties. Moreover, areas of study include common defects in metal injection molding and application of microwave sintering itself has been discussed in this paper.

1. Introduction
Since decades ago, WC-Co hard metal (WC) is the preferred material for wear components and cutting tools since its exhibit excellent combination of high strength and wear. The cemented carbides are produced by using metal injection molding (MIM) method as MIM has proven to be a promising technology that can produce a small and complex part in bulk quantity [1]. Recently, MIM process and optimization have gained numerous attractions in producing cemented carbide components due to the advantages. Taguchi method used in optimization of MIM was proposed by many authors in the journal. Taguchi method was proven as an effective optimization tools to obtain the optimal injection parameter [2] specifically to produce WC-Co part via PIM method since the improper molding parameters will encounter the defect during its process [3]. During sintering, the biggest problem is to retain small average grain size in the sintered product because of higher sintering temperature used will increase the size of powders. Thus, microwave sintering (MW) has been studied in this paper. Microwave sintering is a novel sintering technology, which possesses some unique characteristics in comparison with the conventional sintering, whereby microwave sintering has emerged in recent years as a new method for sintering a variety of materials that has shown significant advantages against conventional sintering procedures [4].
2. Advances in Metal Injection Molding (MIM)

The metal injection molding (MIM) process gains significant credibility over the last 20 years and has become dominant in the industry. Like powder metallurgy, MIM relies on shaping metal particles and subsequent sintering those particles [5]. Hence, MIM product is very competitive with most other metal component fabrication routes since the material produces successfully in delivering higher mechanical strength compare to others. MIM is more like plastic injection molding, but with metal [5-7]. Thus, the MIM concept relies on plastic molding technology to shape a powder polymer feedstock into desired shape [8]. This MIM process is capable to manufacture very complex shape to a large-scale production of metals. Thus, MIM drawing much attention as a promising technique with high manufacturing precision with and without secondary finishing.

2.1. Metal Injection Molding Process

The typical metal injection molding process involved several stages which are mixing, injection molding, debinding and sintering. Through the mixing process, a homogeneous feedstock was formed by mixing a selected volume ratio of the metal powder with a binder. The binder is important because it was the main reason that provided the metal powders' flow ability and permeability, which was necessary for metal injection molding [8-9]. The process of injection molding took place to change the homogenous feedstock into the desired shape which identified as the green part. Then, in the debinding stage, the molded parts were processed with the binder system. Debinding was the most crucial step among the entire steps involved, because it determines whether the process was success or fail [10]. The specimen after debinding stage was called as a brown part. Finally, this brown part was sintered to remove the residual binders and bond the metal powder particles together to produce sintered part [11]. The sintering process was performed to give required mechanical properties of the sintered product; also, known as sintered body. This technology provides a substitute technique for manufacturing small, complex, precision parts, but very cost effective in high run volumes. Thus, the development and improvement of binders results in faster debinding procedures, cost reduction and less environmental defects [6]. Figure 1 shows the example of green body, brown body and sintered part, respectively.

![Figure 1: The example of the green body, brown body and sintered part, respectively [12].](image)

Based on previous literatures, MIM has been a reasonable process for small precision component which it would be cost high to produce by other methods. This type of process could produce small parts with complex shapes from all types of material like metals, plastics, ceramics, composites, and inter-metallic compound. In defining the accomplishment of MIM production, the assortment of the binder system has an important inspiration. Recently, among the MIM research community's, they do have concerns in opportunities in improvising a novel binder system. Modification of the binder may hold promise for future development, but even a wider understanding of the role of the variables involved could improve process and quality control [11].

2.2. Optimization of Metal Injection Molding

The most important factor in injection molding was the settings of process parameters in the specific component or product. Many current study focused on obtains the optimal combination of parameters for specific products. By conducting variance analysis and signal-to-noise ratio analysis of orthogonal experimental results, researchers resolved the optimal levels and the impact of each parameter [13]. Typical injection molding process contains three main phases, which were filling, packing and cooling. These phases were normally controlled and influenced by the injection parameters [14]. A study [15] found that the molding conditions should be optimized for the cemented carbides injection molding as the results of flexural strength measurements of injection molded compacts depended on it. Five process parameters have been employed (injection rate, injection pressure, melt temperature, metering size and part thickness) to discuss the effects towards the thickness of molded ultra-thin wall plastic parts. For achieving the product with higher quality, it is very essential and significant to analysis the
processing conditions during injection molding [16]. The example procedures of the Taguchi method for metal injection molding process are shown in Figure 2 [15].

![Diagram of the Taguchi method for metal injection molding](image)

**Figure 2: The procedures of the Taguchi experiment for metal injection moulding [15].**

On the experimental studies, Taguchi parameter design is generally used to identify important processing conditions as well as to obtain the combination of optimum processing conditions which improving the quality of products [17]. The Taguchi method is a powerful problem solving technique for improving the process/product performance and has been widely used in the application of surface quality, shrinkage, weld line strength, warpage, flow balance etc. [18] In order to optimize the injection process parameters, Taguchi method and the analysis of variance (ANOVA) was used to find out the ANOVA were used as the effective solutions. Taguchi method not only help to obtain the optimal process parameter settings, but the most competitive advantages of products' quality and costs can be achieved. Besides, the effects of injection factors are verified using Taguchi method on the quality of compacts, and also identify the significant factors of the process. In summary, acknowledging the effects of injection factors on the quality of compacts is in favor of optimization of plastic injection molding process parameters [19].

According to prior studies [18], the Taguchi analysis method was utilized for maximizing the EMI shielding in a minimum number of experiments. The optimal settings of control factors which would acquire the greatest SE value were identified by using the Taguchi optimization technique. The main control factors of the injection molding process had been rectified by using ANOVA. Basically, the full factorial method is used based on the standard experimental design. However, according to Taguchi method, it is still acceptable if only a few factors are investigated. As for another example, the Taguchi method with L18 orthogonal array was used in the present study [3]. Several parameters of injection molding were considered; powder loading, injection temperature, holding pressure and injection rate, while the density of the green body as a response factor. According to the study [3], L18 orthogonal array (OA) was chosen as the experimental design for the optimization of parameter in injection molding for WC-Co feedstock. The OA has 1 control factor with 2 levels, and another 3 control factors with 3 levels (refer Table 1), and because all the control factors are orthogonal, so interaction effects are not studied.
Table 1: Control parameters for injection-molding step [3].

| Factor (unit)            | Level 1 | Level 2 | Level 3 |
|--------------------------|---------|---------|---------|
| Injection rate (ccm/s)   | A       | 10      | 20      | -       |
| Powder loading (% vol)   | B       | 59      | 61      | 63      |
| Injection temperature (°C)| C       | 140     | 150     | 160     |
| Holding pressure (bar)   | D       | 1700    | 1800    | 1900    |

Based on the result, the major contribution is holding pressure (factor D). The highest holding pressure could lead to the highest density of the green part. Powder loading (factor B) is the second most contribution. The green part is packed more densely due to higher powder loading, thus make the density of the green parts increases. Injection temperature (factor C) is still important since the temperature of materials has an effect on the viscosity of the melt, but for the injection rate (factor A), the significance is too low and can be neglected [3].

2.3. Common defects in Metal Injection Molding Process

The MIM process includes several processing steps and if care is not taken, defects may occur in each processing step. The defects encountered could be caused by mechanical factors or by processing related factors. A study [2] concluded that defect those found in conventional plastic injection molding are similar to metal injection molding parts. Basically, the defect happens due to improper molding parameters. In Table 2 shows the defect encountered during MIM, the causes and remedies of these defects.

Table 2: Defect frequently found in metal injection molding [2].

| Defect type       | Possible cause                                      | Remedies                                                                 |
|-------------------|-----------------------------------------------------|--------------------------------------------------------------------------|
| Flash             | Too high a pressure inside the die, poor flatness of mold surface along the parting line, venting channel too large | Use large tonnage machine, proper tool making, use a lower injection speed and molding pressure, optimize the switch point |
| Sticking in the cavity | Too high a molding pressure, not enough thermal shrinkage, early ejection, improper mold design or making method. | Use lower injection speed, molding/holding pressure and mold temperature, increase cooling time, eliminate undercut and increase draft angle, adjust the ejection area and location, redesign the binder |
| Sink mark         | Thermal shrinkage, low density                      | Increase molding/holding pressure and injection speed, decrease mold temperature, increase gate area, add venting channels, decrease speed when passing thick sections |
| Voids             | Trapped gas, absorbed moisture                      | Increase holding pressure, decrease injection speed, increase mold temperature, increase gate area, moves the gate to thick section |
| Burn marks        | Overly heated binders                               | Decrease injection speed and feedstock temperature, increase gate area, change gate location |
| Weld lines        | Cold feedstock in the die                           | Increase injection speed, mold temperature, and feedstock temperature, enlarge the gate opening, add venting channels or overflow wells near weld line locations, move gate location, redesign parts to avoid stream partition |
| Flow mark         | Cold feedstock in the die                           | Increase injection speed, mold temperature, and feedstock temperature, enlarge the gate opening, change gate location |
3. Nanostructured Cemented Carbide (WC-Co)

Nanostructured cemented carbide (WC-Co) had become one of the most researched powder metallurgy materials in engineering. However, their potential presentations are not becoming a trend. This material was characterized by a combination of fine grained homogenous microstructure. It has good mechanical properties, whereby these mechanical properties were based on the developed microstructure in the sintered parts. This sintered parts were governed by several causes which are the percentage of tungsten carbide (WC), the contiguity of WC grains, crystallite size, and the mean free path of the binding phase [20-21]. The direct use of WC carbide as cutting tool material was impossible since it was brittle and very high temperature sintering process. For this reason, a metallic binder was usually added to tungsten carbide, which insures the required strength of the material without reducing its hardness. The use of nano crystalline WC powder as a component of hard alloys is one of the most perspective way to produce the nanostructured hard alloys, in having good mechanical properties, fine-grained microstructure and reduced sintering temperature [22].

Hard metal composition can be divided into three grades, which are straight grades, micro grain grades, and alloyed grades. Straight grades are primarily WC in a Co binder, but may contain small amounts of grain growth inhibitors. This grade also generally contains 3-12 wt. % Co. The WC grain size usually ranges from 1 to 8 μm. As the grain sizes decrease, toughness also decreases, but the hardness and strength increase [1]. Cemented tungsten carbide (WC-Co) consists of tungsten carbide grains embedded in a metal binder phase [23]. WC-Co have been widely used as machining, cutting, mining and drilling tools, as well as wear parts and chip-less forming tools, due to their extremely high hardness, excellent wear resistance and good toughness. In addition, the application of the metal binder phase provides an economical and viable method to produce cemented tungsten carbide components – liquid phase sintering.

Although the ultrafine cemented carbides (0.1 – 0.6 μm average size) has higher hardness and wear resistance, the fracture toughness of ultrafine hard metals is inferior to that of coarse grained cemented carbides, which can impact the application on shock environment [24-26]. With the design of WC grain size and distribution in ultrafine hard metals can improve the fracture toughness of ultrafine hard metals obviously, and achieve the combination of proper hardness and fracture toughness in ultrafine WC-(micron WC-Co) systems [27-29]. However, it was known for a long time that cemented tungsten carbides with high cobalt contents had high toughness and low hardness and vice versa [30-32].

Improvement of hardness and toughness of cemented carbides can be achieved with a decrease in WC grain size to nanoscale [33]. Previous study [34], used a newly developed the WC tungsten carbide nano powder with average size of 150 nm. One of the biggest problems of sintering nano scaled powders is the retaining of small average grain sizes in the sintered product [2,33-34]. For that reason, the addition of grain growth inhibitors, GGI, is suggested [22]. According to the literature, the tiny pores between carbide grains will be filled by binder system. The binder particles in nanostructured WC-Co hard metals should be much finer in size as well as to allow sintering at lower temperatures and in shorter periods of time, thereby improving the microstructure and reducing grain growth [21,34]. A study [35] said that the influence of WC particle size on WC-Co cemented carbides fracture toughness, analyses the mechanism of particle size effect on fracture toughness of cemented carbides. However, the microstructure and fracture mechanism of the ultrafine WC (micron WC-Co) hard metals have not been investigated systematically.

4. Microwave Sintering Process

Sintering is a useful method for manufacturing parts from powders, by heating the material until its particles adhere to each other. To obtain higher densities and improving porosity in the sintered parts, enhanced sintering techniques can be applied. In the past two decades, the possibility of fabrication of nanostructured WC–Co hard metals from tungsten carbide (WC) nano powders were evaluated by a lot of researchers [36]. Sintering of nano crystalline WC–Co, retaining the nano scaled grain sizes, is a matter of great interest. The required result has not been achieved using liquid phase sintering, thus many trials using non-traditional methods have been used to achieve this goal. The effect of temperature, time and composition variation toward the sintering behavior of nanostructured WC–Co composite is studied [37].

As reported in previous studies, the cemented carbide was fabricated mainly by two kinds of technologies, one is the liquid-state sintering, such as vacuum sintering (VS) and hot isostatic pressing (sinter-HIP) [38]; the other is the recently developed rapid sintering, such as microwave sintering (MS), ultrahigh pressure rapid hot consolidation (UPRC) and spark plasma sintering (SPS) [38]. The common sintering techniques used for sintering cemented carbide in industries were VS and sinter-HIP techniques which known for having the advantages of low cost and large-scaled production. But, they have a disadvantage in controlling the grain
growth due to the slow heating rate and high sintering temperature, and thus have big difficulty to obtain the ultrafine and nano crystalline cemented carbides. The primary concern in all these methods is in the grain size of the WC component, because it has been established that significant improvements in the mechanical properties can be attained with finer grain size [38-39]. Sintering temperature plays an important role during the process. A study [41] reported that the sintering temperature of W can be decreased from 2800 °C to 1400 °C by using less than 1 wt. % addition of transition metals, such as palladium and nickel. Ni had an important effect on promoting the densification process, which reduced the sintering temperature greatly [42-43]. The increased density with increasing sintering temperature because large quantities of Co melted at high temperature and flowed to fill the pores [44]. However, the hardness of the sintered part decreased as temperature goes higher which may be due to the grain growth, as coarse grain is inferior in hardness to fine grain [45-46]. The TRS gradually increased with increasing sintering temperature.

The consolidation of WC–Co powder has been investigated using a variety of techniques [47]. The unique characteristics of microwave sintering technology to attract growing attention of any developer. These typical characteristics such as volumetric heating, non-thermal effect and selective heating are beneficial to prepare material using microwave sintering compared to conventional sintering methods as well as enhanced diffusion processes, decreased sintering temperatures, accelerated heating rate, shortened processing cycle, reduced energy consumption, fine and homogeneous microstructure, and improved mechanical properties, and being environmentally friendly [48-50]. It is well recognized that microwave heating is accompanied by the “non-thermal effects”, caused by alternating microwave electromagnetic field, and often attributed to enhance the sintering process by improving densification and limiting the grain growth [50]. More importantly, microwave heating exhibit the inside-out direction of heat flow. Thus, to form a hybrid heating process, microwave heating processes use SiC as an auxiliary heating medium [51]. As a new sintering technology, microwave sintering (MWS) is increasingly being used in the preparation of oxide and some non-oxide ceramics, carbide semi metals and alloy materials [52-54]. The relevant experimental results clarify that the microwave sintering can effectively improve the activation energy, promote densification, improve the microstructure properties of the materials and shorten processing periods [55].

4.1. Comparison of Microwave Sintering (MS) and Conventional Sintering

Microwave sintering of cemented carbide like WC – Co has been investigated since 1991 after pioneering work of previous authors [56-57]. A study by [56] investigated on the microwave sintering of 0.1 – 1µm sized WC particles with cobalt as the binder and compared the results with conventional sintering of the same powders. They reported sintered one. They also showed that the microwave reaction sintering of W, C, and Co powders yielded sintered WC-6Co compacts with fine and uniform microstructure (with an average grain size of 0.6µm) which exhibited a 10% increase in hardness values in comparison to the tools made by conventional routes [57].

As is well known, microwave sintering greatly reduces the time as well as the energy expended when compared to conventional sintering due to the inherent difference in the heating mechanism of the two methods and the possibility of achieving very fast microwaves are employed. Figure 3 shows the Comparison of mechanism of vacuum and microwave heating.

Figure 3: Comparison of mechanism of vacuum and microwave heating (the intensity of colour represents the heat energy) [58].
The formation of partial liquid phase can explain the different between microwave heating and conventional prepared hard metal. From Figure 3(a), the probable temperature distribution of conventional and microwave heating where inhomogeneous temperature distributions can be formed in the form of layered structure during the conventional heating.

However, Figure 3(b) shows randomly scattered hot spots can be formed in microwave processing materials due to the inhomogeneous temperature distributions, but it is feasible to control the power of hot spots. For vacuum sintering, the surface of the sample is where the heat started to enter and dissipates inside due to thermal conduction. Hence, the temperature on the surface is higher than the sample. By heat transfer process, larger sample size and lower heating conductivity will take a longer time since the heating rate is limited. However, for microwave sintering, the heat is deposited directly inside the samples, and the heating rate is only limited by the power of the microwave source, which can be increased by controlling the magnetron. Hence, the temperature inside the sample is higher than on the surface because of the volumetric heating properties of microwave. Therefore, with a heating conduction distance, d, the difference between conventional and microwave heating can be described (provided that they have the same temperature sources). From Figure 3, the distance of heating conduction for conventional heating is a half of the sample thickness (~1 cm), but that is a half of the center distance between two hot spots (~100 µm) for microwave heating. This shows that the required time for microwave heating is 10–100 times less than that for conventional heating to reach the same temperature [59].

Previous works [59] have shown the result of sintered WC-8Co samples prepared using different preparation method. The heating rates in the range of 30–40 °C/min were controlled. The microwave sintering process requires only one-sixth time of that in the vacuum sintering. Compared with the vacuum sintering, the microstructures of the prepared samples can be optimized by microwave sintering while the geometrical shape of all obtained samples was well maintained, and no bubble forming or distortion was observed. The microstructures of samples prepared by different sintering methods are given in Figure 4. The mean grain size prepared by microwave irradiation which can be seen from Figure 4 is much smaller compared with that prepared by vacuum sintering. The mean chord intercept method is used to analysis the microstructure. The mean grain sizes were obtained, which are 2.7 µm and 3.7 µm by microwave irradiation and vacuum sintering, respectively. Also, it is reported that samples obtained have more uniform grain size by using microwave sintering method. Smaller grains and narrower grain distribution give the microwave sintered samples more superior mechanical properties.

![Figure 4: SEM micrographs of sintered WC-8Co samples by different preparation methods: (a, c) Microwave irradiation (1450 °C, 5 min); (b, d) Vacuum sintering (1450 °C, 120 min) [58].](image)

4.2. Application Microwave Sintering (MS)

The long sintering time is required in order to get full sintering by conventional sintering methods. The coarsening of the particles will be formed and thus decreasing of mechanical properties. As a new sintering
technology, microwave sintering (MWS) is increasingly being used in the preparation of oxide and some non-oxide ceramics, carbide semi metals and alloy materials [60]. With finer microstructure and higher mechanical properties, MS has proven to be an effective technology to fabricate the ceramics. The coupling interaction between the whole ceramic sample and the electromagnetic waves resulting in heat produced in microwave sintering. Therefore, heating is more rapid and uniform [61]. Furthermore, because of its very fast heating rate and reduced processing time, MS technique was successfully employed to synthesize NiZn, MgCuZn and NiCuZn ferrites [62].

MS is one of the techniques to achieve fast and relatively uniform. The present study [63], investigates the sintering response of a 92.5W–7.5(Ni–Fe) alloy with a non-optimal matrix composition that has been consolidated through microwaves and compares its densification, microstructure and mechanical properties conventionally sintered compacts. The overall heating rate in a microwave furnace was 20°C/min, where there is a reduction in the process time of W–Ni–Fe compact in the microwave furnace compare to conventional furnace. Using much lower power consumption in a microwave furnace can heat the same compact. An author reported that MS still provides better physical and mechanical properties, although it requires about 75% less processing time than required by conventional method and [64].

Another study [4] using Al2O3/Ti (C, N) ceramic tool materials were fabricated by one-step and two-step MS respectively. Two-step MS can effectively restrain grain growth, but the density of sintered part is lower than one-step sintering. The optimal mechanical properties were obtained by one-step MS with sintering temperature 1550 °C and the holding time of 10 min. The application of microwave sintering is well known resulting in a better quality and an excellent overall performance [65]. Cu–W alloy is manufactured by using the MS method and the influence of temperature on the properties of the Cu–W alloy was experimentally investigated. The MS must combine vacuum sintering technology since metal tungsten powder with strong oxidizing. This to ensure the tungsten powder is not oxidized during the sintering process.

In the past two decades, the consolidation of WC–Co powder has been investigated using a variety of sintering techniques. Because its exhibit unique characteristics compared to conventional sintering methods, the MS technology was increasing attract attention. According to [66], no abnormal grain growth is observed in the microwave-prepared sample also the grain distribution of the microwave-prepared sample is contracted owing to the uniform microstructure. The preparation of tungsten cemented carbides by using MS method will be very efficient. However, it has many disadvantages towards the equipment costs and inflexibility of product shape. Hence, in order to undertake the application in the future, further research is required to understand the mechanisms of MS.

5. Conclusion

Based on this study it can be concluded that, metal injection molding (MIM) is widely known technology to form metals and alloys into desired shape. Since this MIM technology is growing rapidly in Malaysia, hence it will give a good prospect for Malaysian Industries to get involved in this technology and share the benefits. Optimization of metal injection molding parameters is required to obtain the optimal combination parameters which effectively can reduce cost and time consuming for the process as well as reduce the defect in the final product. The application of microwave for sintering process is developing as a novel and innovative technology with many advantages over conventional sintering. The comparison of microwave sintering over conventional sintering has been discussed in this study where showing the potential of microwave sintering to be developed in the future. Perhaps this research work will pave the way for the future consultancy works in this field of research and to help strengthen the industries and try to promote the application of this technology especially in tool and die industries.

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References

[1] L. Johnson D.F. Heaney N.S. Myers. 21- Metal Injection Molding (MIM) of heavy alloys, refractory metals, and hardmetals. Handbook of Metal Injection Molding. A volume in Woodhead Publishing Series in Metals and Surface Engineering. 2012 (pp. 526-567).
Amin SYM, Muhamad N, Jamaludin KR. Optimization of injection molding parameters for WC-Co feedstocks. *J Teknol (Sciences Eng.* 2013;63(1):51-54.

K.S. Hwang. 10- Common Defect in metal injection molding (MIM). Handbook of Metal Injection Molding. A volume in Woodhead Publishing Series in Metals and Surface Engineering. 2012 (pp. 235-253).

Yin Z, Yuan J, Cheng Y, Wang C, Wang Z, Hu X. Microstructure and mechanical properties of Al2O3/Ti(C, N) ceramic tool materials by one-step and two-step microwave sintering. *Mater Sci Eng A.* 2016;670:159-165.

R.M. German. 1- Metal Powder Injection Molding (MIM): key trends and markets. Handbook of Metal Injection Molding. A volume in Woodhead Publishing Series in Metals and Surface Engineering. 2012 (pp. 1-25).

German RM, Bose A. Injection Molding of Metals and Ceramics Metal Powder Industries Federation. Princeton, NJ. 1997.

Zhu B, Qu X, Tao Y. Powder injection molding of WC-8%Co tungsten cemented carbide. *Int J Refract Met Hard Mater*. 2002;20(5-6):389-394.

Abolhasani H, Muhamad N. A new starch-based binder for metal injection molding. *J Mater Process Technol*. 2010;210(6-7):961-968.

German RM, Bose Animesh. *Injection Molding of Metals and Ceramics*. new jersey: metal powder industries federation; 1997.

S. Banerjee C.J. Joens. 7- Debinding and Sintering of Metal Injection Molding Components. Handbook of Metal Injection Molding. A volume in Woodhead Publishing Series in Metals and Surface Engineering. 2012 (pp. 133-180).

Jamaludin MI, Kasim NAA, Nor NM, Ismail MH. Development of porous Ti-6Al-4V Mix with palm stearin binder by metal injection molding technique. *Am J Appl Sci*. 2015;12(10):742-751.

Stanimirovic Z, Stanimirovic I. Ceramic Injection Moulding. *Some Crit Issues Inject Molding*. 2012:131-147.

Zhang J, Wu D, Zhou J, Wang J. Multi-objective optimization of process parameters for 7050 aluminum alloy rib-web forgings’ precise forming based on Taguchi method. Procedia Eng. 2014;81(October):558-563.

Xie XC, Lin CG, Jia CC, Cao RJ. Effects of process parameters on quality of ultrafine WC/12Co injection molded compacts. *Int J Refract Met Hard Mater*. 2015; 48:305-311.

K. Golombek, G. Matula, J. Mikula, L.A. Dobrzanski. Influence of binder composition on the properties of feedstock for cemented carbides, Arch. Mater. Sci. Eng. 51 (2011) 116–124.

M.C. Song, Z. Liu, M.J.Wang, T.M. Yu, D.Y. Zhao, Research on effects of injection process parameters on the molding process for ultra-thin wall plastic parts, J. Mater. Process. Technol. 187–188 (2007) 668–671.

K.M. Tsai, C.Y. Hsieh, W.C. Lo, A study of the effects of process parameters for injection molding on surface quality of optical lenses, J. Mater. Process. Technol. 209 (2009) 3469–3477.

Chen CS, Chen WR, Chen SC, Chien RD. Optimum injection molding processing condition on EMI shielding effectiveness of stainless steel fiber filled polycarbonate composite. *Int Commun Heat Mass Transf*. 2008;35(6):744-749.

W.C. Chen, G.L. Fu, P.H. Tai, W.J. Deng. Process parameter optimization for MIMO plastic injection molding via soft computing, Expert Syst. Appl. 36 (2009) 1114–1122.

Amin SY, Muhamad N, Jamaludin KR, Fayyaza A, Yunn HS. Ball milling of WC-Co powder as injection molding feedstock. InApplied Mechanics and Materials 2012 (Vol. 110, pp. 1425-1430). Trans Tech Publications.

Amin SY, Muhamad N, Jamaludin KR, Fayyaz A, Yunn HS. Characterization of the feedstock properties of metal injection-molded WC-Co with palm stearin binder system. Sains
Kurlov AS, Leenaers A, Scibetta M, Rempel AA. MICROSTRUCTURE OF NANOCRYSTALLINE WC POWDERS AND WC-Co HARD ALLOYS. 2011;27:165-172.

Jia K, Fischer TE, Gallois B. Microstructure, hardness and toughness of nanostructured and conventional WC-Co composites. Nanostructured Materials. 1998 Jul 31;10(5):875-91.

Zhao S, Song X, Wei C, Zhang L, Liu X, Zhang J. Effects of WC particle size on densification and properties of spark plasma sintered WC–Co cermet. International Journal of Refractory Metals and Hard Materials. 2008 Nov 30;27(6):1014-8.

Sun L, Jia C, Cao R, Lin C. Effects of Cr 3 C 2 additions on the densification, grain growth and properties of ultrafine WC–11Co composites by spark plasma sintering. International Journal of Refractory Metals and Hard Materials. 2011;27:165-172.

Jia K, Fischer TE, Gallois B. Microstructure, hardness and toughness of nanostructured and conventional WC-Co composites. Nanostructured Materials. 1998 Jul 31;10(5):875-91.

Liu C, Lin N, He Y, Wu C, Jiang Y. The effects of micron WC contents on the microstructure and mechanical properties of ultrafine WC–Co cermet. International Journal of Refractory Metals and Hard Materials. 2009 Mar 31;27(2):288-99.

Lin N, He Y, Wu C, Zhang Q, Zou J, Zhao Z. Fabrication of tungsten carbide–vanadium carbide core–shell structure powders and their application as an inhibitor for the sintering of cemented carbides. Scripta Materialia. 2012 Nov 30;67(10):826-9.

Fabijanić TA, Alar Ž, Ćorić D. Influence of consolidation process and sintering temperature on microstructure and mechanical properties of near nano- and nano-structured WC-Co cemented carbides. International Journal of Refractory Metals and Hard Materials. 2016 Jan 31;54:82-9.

Chang SH, Chang PY. Study on the mechanical properties, microstructure and corrosion behaviors of nano-WC-Co-Ni-Fe hard materials through HIP and hot-press sintering processes. Mater Sci Eng A. 2014;618:56-62.

Kumar A, Singh K, Pandey OP. Sintering behavior of nanostructured WC-Co composite. Ceram Int. 2011;37(4):1415-1422.

Wei CB, Song XY, Fu J, et al. Microstructure and properties of ultrafine cemented carbide–Differences in spark plasma sintering and sinter-HIP. Mater Sci Eng A. 2012;552:427-433.

El-Eskandarany MS. Structure and properties of nanocrystalline TiC full-density bulk alloy consolidated from mechanically reacted powders. J Alloys Compd 2000; 305:225–38.
[40] Fu L, Cao LH, Fan YS. Two-step synthesis of nanostructured tungsten carbide–cobalt powders. Scripta Mater 2001; 44:1061–8.

[41] Kim HC, Jeong IK, Shon JJ, Ko IY, Doh JM. Fabrication of WC-8 wt.%Co hard materials by two rapid sintering processes. Int J Refract Met Hard Mater. 2007;25(4):336-340.

[42] Shye Yunn, Heng, Norhamidi, Muhamad, Abu Bakar S, Fayyaz A, Amin SM. Effect of sintering temperature on the mechanical and physical properties of WC- 10 % Co through micro Powder Injection Molding (μ PIM ). 2016;(October).

[43] Mamen B, Song J, Barriere T, Gelin JC. Experimental and numerical analysis of the particle size effect on the densification behaviour of metal injection moulded tungsten parts during sintering. Powder Metall. 2015;270(Part A):230-243.

[44] M. Mahmoodan, H. Aliakbarzadeh, R. Gholamipour, Sintering of WC–10%Co nano powders containing TaC and VC grain growth inhibitors, Transactions of Nonferrous Metals Society of China 21 (2011) 1080–1084.

[45] X.L. Shi, G.Q. Shao, X.L. Duan, Z. Xiong, H. Yang, Characterizations of WC–10Co nanocomposite powders and subsequently sinterkip sintered cemented carbide, Materials Characterization 57 (2006) 358–370.

[46] Cheng JP, Agrawal DK, Komarneni S,MathisM, Roy R. Microwave processing ofWC– Co composites and ferroic titanates. Mater Res Innov 1997;1:44–52.

[47] Bykov YV, Rybakov KL, Semenov VE. High-temperature microwave processing of materials. J Phys D: Appl Phys 2001;34:R55–75.

[48] Guo Y, Yi J, Luo S, Zhou C, Chen L, Peng Y. Fabrication ofW–Cu composites by microwave infiltration. J Alloys Compd 2010;492:L75–8.

[49] Tang S, Liu D, Li P, et al. Microstructure and mechanical properties of functionally gradient cemented carbides fabricated by microwave heating nitriding sintering. Int J Refract Met Hard Mater. 2016;58:137-142.

[50] Bao R, Yi JH, Peng YD, Zhang HZ. Effects of microwave sintering temperature and soaking time on microstructure of WC–8Co. Trans Nonferrous Met Soc China (English Ed. 2013;23(2):372-376.
based cermet cutting tool materials fabricated by microwave sintering. *Ceram Int.* 2015;41(10):15017-15023.

[61] Yin Z, Yuan J, Wang Z, Hu H, Cheng Y, Hu X. Preparation and properties of an Al2O3/Ti(C,N) micro-nano-composite ceramic tool material by microwave sintering. *Ceram Int.* 2015;42(3):4099-4106.

[62] Zhu J, Ouyang C, Xiao S, Gao Y. Microwave sintering versus conventional sintering of NiCuZn ferrites. Part I: Densification evolution. *J Magn Magn Mater.* 2015;407:308-313.

[63] Upadhyaya A, Tiwari SK, Mishra P. Microwave sintering of W-Ni-Fe alloy. *Scr Mater.* 2007;56(1):5-8.

[64] Zhou Y, Wang K, Liu R, Wang XP, Liu CS, Fang QF. High performance tungsten synthesized by microwave sintering method. *Int J Refract Met Hard Mater.* 2012;34:13-17. doi:10.1016/j.ijrmhm.2012.02.016.

[65] Xu L, Yan M, Peng J, et al. Influences of temperatures on tungsten copper alloy prepared by microwave sintering. *J Alloys Compd.* 2014;611:34-37.

[66] Bao R, Yi J, Zhang H, Peng Y. A research on WC-8Co preparation by microwave sintering. *Int J Refract Met Hard Mater.*