Powder Metallurgy Processed Ferrous Composites: A Review

Amiya Ranjan Malik, Bibhuti Bhusan Pani, Sushant Kumar Badjena

***Abstract:** This paper reviews processing and synthesis of particulate reinforced ferrous based Metal Matrix Composites (MMC) and Nanocomposites through Powder Metallurgy (P/M) method. By this route it is possible to manufacture MMCs with wide range of compositions and density. As a result there is improvement of wear resistance, abrasion resistance, corrosion resistance, mechanical properties and high temperature friction properties. The reinforcing particles commonly adopted were carbides, oxides, borides, nitrides, carbonitrides, complex carbides, intermetallics, synthetic materials etc. Apart from this it also reviews how several factors affect properties of MMCs.*

***Keyword:** Ferrous Matrix Composites, Nanocomposites, Particle reinforcement, Powder Metallurgy.*

I. INTRODUCTION

Ferrous metals and alloys are most studied because of its application in designing machine tools, automobile parts, structural steel, heavy duty production tools considering its strength, ductility, malleability, machinability, wear resistance, abrasion resistance, corrosion resistance, hot hardness etc. But with alloys there are limitations to the above resulting properties. So people have began to manufacture metal matrix composites (MMC) to get best properties than the alloys. The particulate reinforced MMCs people were adopting over fibre reinforced MMCs because of fibre damage, micro structural nonuniformity and contact damage between fibres during fabrication. The particulate reinforcement added to ferrous matrix by different authors are Titanium carbides (TiC), Vanadium carbides (VC), Tungsten carbides (WC), Tantalum carbide (TaC), Niobium carbide (NbC), Cementite (Fe_3C), silicon carbide (SiC), Alumina (Al_2O_3), Titanium dioxide (TiO_2), Titanium nitride (TiN), Titanium Diboride (TiB_2), Titanium carbonitrides (TiCN), intermetallics compounds, complex carbides and Carbon nanotubes (CNT). These refractory materials added through powder metallurgy process improve hardness, wear resistance, abrasion resistance, corrosion resistance etc.

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Powder metallurgy process is widely adopted because of its ease of manufacturing by mixing different powders of desired compositions, near net shape production, little to no wastage and ability to manufacture parts out of very high melting point materials which are difficult to process through smelting. But the limitation which is holding back this route is size of the part to be produced and complex shapes. The P/M process involves three steps powder blending, compaction, sintering to densify the part. The blending can be done by simple blender or ball milling and attritor mill. According to some authors ball milling is good for homogeneous distribution of different powder elements, but affect compressibility, for that annealing may be needed to improve it. Ultimately this would affect relative density. The compaction can be cold, warm, cold isostatic pressing, hot isostatic pressing. As hard ceramic particles whether formed in-situ or readymade powders added as reinforcement, would affect compactibility. The last, sintering which provide bonding, densification, strengthening of green part at particle to particle contact point in solid state and semi-solid state. The sintering can be done in vacuum or in any atmosphere. Some author tried sintering by different source of energy e.g. concentrated solar energy (CSE). Some post sintering treatment may be needed to relieve stress and to obtain final shape and size. Some author adopted coated particle to improve sintering while other added sintering activators. Apart from these the matrix can be of any ferrous alloy powder, be it cast iron powder, carbonyl iron powder, HSS steel or Stainless steel.

II. MANUFACTURING METHOD

O. N. Dogan et al. [1] had manufactured Fe-TiC MMC by P/M method using liquid phase sintering with varied volume fraction of TiC. They studied abrasion and erosion resistance of the MMC through single scratch test, pin-on-drum abrasion test, dry-sand/rubber-wheel test, impellor-in drum test, erosion test etc. E. Pagounis et al. [2] had studied Fe-TiC MMCs and its coefficient of thermal expansion. They manufactured MMC by P/M method. The same author had also studied ferrous based MMC (Fe-TiC, Fe-Al_2O_3, Fe-Cr_3C_2) manufactured through HIP [3]. T. Ram Prabhu et al. [4] had studied wear resistances and hardness by manufacturing Fe-SiO_2, Fe-Mullite MMC by P/M route. They had intended to use MMCs for high energy application. They prepared the uniform mixture using ball mill. Then compaction in uniaxial die at 450 MPa followed by pressure sintering at 25 MPa, 1020°C for 3h in hydrogen atmosphere.

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The same author in another work, reinforced Fe matrix with silicon carbide (SiC) using same set of manufacturing condition [5]. They studied wear resistance, density, porosity and hardness. Sainatee Chakthin et al. [6] had also studied Fe-MMC reinforced with SiC and WC by P/M method and studied its mechanical properties. Danqing Yi et al. [7] had studied effect of coating of reinforcement particles on MMC through Hot Isostatic Pressing (HIP). Coating TiC particles with Ni by Electroless plating, mixing Ni coated TiC and carbonyl iron powder in ball mill with alcohol as process control agent while drying in hydrogen atmosphere and cold isostatic pressing at 200 MPa for 15 min. Then the green compacts were pre-sintered at 1200°C for 3h followed by HIP at 1230°C and 150 MPa for 4h. Xiao Zhi-Yu et al. [8] had manufactured Fe-NbCp MMC by Die Wall Lubricated Warm Compaction (DWLWC) because it is difficult to obtain good compressibility and formability with hard ceramic particles as reinforcement. They mixed the powders in attritor as well as ball mill with DWLWC at 120°C and 600 MPa followed by sintering at 1280°C for 80 min in dissociated ammonia atmosphere. From the comparison between DWLWC produced MMC with cold compaction MMC they concluded DWLWC produced MMC was high density and crack free. B. Sustarsic et al. [9] had also manufactured Fe-NbC MMC by uniaxial cold compaction at 850 MPa with vacuum sintering between 1160°C and 1280°C. F. Velasco et al. [10] had studied high speed steel-NbC and HSS-TaC MMCs by P/M method (700 MPa, 1190-1230°C) through vacuum sintering. There is variation in manufacturing settings by different author that ultimately affects the final product. There has been report of manufacturing of ferrous Nanocomposites by P/M method. H. Fallahdoost et al. [11] had manufactured MMC by reinforcing ferrous alloy by Nano-alumina powders and sintering at N_2-10%H_2 reducing atmosphere. They studied wear resistance and density of MMC. Pallav Gupta et al. [12] had also manufactured Nano-alumina reinforced ferrous MMC by P/M method and studied its corrosion behaviour. C. Parswajinan et al. [13] had also manufactured Nano-MMC by reinforcing ferrous matrix with Multi wall Carbon nanotubes (MWNT) powders by P/M method. They followed blending by ball mill, compaction in uniaxial die, then sintering. T. J. Goodwin et al. [14] had manufactured Nano-MMC from Nano-powders of iron and Cementite (Fe_3C) by a new technique called Mechanosynthesis (MS) followed by electric Field Assisted Sintering (FAS). They blended the powders in ball mill. The FAS include two steps, first applying AC of 750 A for 30s in equal on and off of 30ms, second applying DC resistance heating at 450°C for 3 min in air. During this cycle compaction pressure was maintained at 60 MPa. This method not only reduces production time but also composite with close to full density was achieved. Eugene E. Feldshtein and Larisa N. Dyachkova [15] had added Nanocrystalline powders of Ultrafine Grained Diamond (UFGD) with ferrous powders and manufactured MMCs. Ping Han et al. [16] had also studied effect of oxide addition on Fe-based Diamond composites. Katie Jo Sunday et al. [17] had manufactured ferrous MMCs by incorporating an Al_2O_3 coating on ferrous powders. It includes ball milling for 12 hr thereby formation of agglomerates of Al_2O_3 on iron particles with compaction at 3GPa and sintering at 500°C or 900°C for 1hr in argon and hydrogen atmosphere. F. Velasco et al. [18] had studied high speed steel-TiCN MMC by P/M method. B. Gomez et al. [19] had also studied Fe-TiCN MMC by P/M method. They followed similar process with slight variation in treatment conditions. G. Herranz et al. [20] had manufactured High speed steel-VC MMC by P/M method which includes sintering by Concentrated Solar Energy (CSE). Guangming Zhang et al. [21] had manufactured iron matrix composites with TiC and VC for application as friction material in automobile brakes, clutches from Vanadium bearing titanomagnetite. They adopted in situ Carbothermic reduction with P/M method and studied sinterability. See detailed manufacturing process in reference [22]. D. Lou et al. [23] had studied Fe-WC MMC by Hot Isostatic Pressing (HIP). S. C Tjong and K. C. Lau [24] had also manufactured Fe-TiB_2 MMC by HIP. They studied mechanical and wear properties. J. Abenojar et al. [25, 26] had studied ferrous MMCs with intermetallics and carbides. They conducted sintering in combined hydrogen and nitrogen as well as pure hydrogen atmosphere. They compared effect of carbide and intermetallics on the MMCs. There have been several reports of manufacturing ferrous MMCs by casting, Self Propagating High Temperature Synthesis (SHS), Exothermic dispersion method, Plasma Smelting in which reinforcements were produced In-Situ. So Wang Jing et al. [27] had manufactured (Ti, V)C reinforced ferrous MMCs by combining In-Situ and P/M method. They have taken Ferrovanadium powders, Titanium powder, Carbon black powder, Ferromolybdenum powder with iron powders followed by compaction and sintering at high temperatures at 1380-1440°C. Similarly many authors had studied ferrous MMCs by P/M method [28, 29, 30, 31].

III. RESULTS AND DISCUSSION

Majority of work shows improvement of hardness and wear resistance as hard ceramic reinforcement were added to ferrous matrices. With TiC there was increase in hardness as well as wear resistance [1]. Although density close to 100% was achieved only with Ni-coated TiC powders [7]. This was due to Ni layer on TiC acted as good binding agent at the interface and elimination of pores. This resulted in increase of both hardness and tensile strength. With increase in volume of SiC and silica(SiO_2) in ferrous matrix there was improvement in hardness, wear resistance and decrease in composite density [5, 4]. Similar phenomena were observed in case of composite having mullite in Fe matrix. With high volume of NbC as reinforcement there was improvement of tribological properties (Hardness and Wear resistance) of MMC [8]. Also with slightly less volume of NbC the mechanical as well as tribological properties were better. This was possible due to high hardness of NbC, good wetting between NbC and Fe alloy which leads to good binding between them with DWLWC in achieving high density MMCs.

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Similar work with NbC as reinforcement, following uniaxial cold compaction, the major densification was achieved by Super-Solidus Liquid Phase Sintering (SLPS) [4]. But NbC content was limited in MMC (0.5%) compared to DWLWC because hardness of MMC decreases with increase in volume of NbC. This was due to inability of cold-compaction for densification with hard NbC. In the final MMC, NbC was present as agglomerates. Apart from this with increase in sintering temperature up to 1250°C, highest hardness was achieved. With further increase in sintering temperature, the MMCs get over-sintered and hardness decreases. Work with Fe-NbC, Fe-TaC and Fe-(NbC+TaC) MMCs by other authors also reported improvement of wear resistance and hardness [10]. They reported that with increase in volume of NbC in Fe matrix the hardness increases and further hardness increases with increasing sintering temperature. Similar behaviour was reported for Fe-TaC MMCs too, but for Fe-NbC MMCs was lower and for Fe-(NbC+TaC) MMCs was least. For density the Fe-TaC was lowest among all MMCs, the Fe-(NbC+TaC) MMCs in between the two. This would reduce weight of MMCs and increase its use in low weight application. So with NbC as reinforcement the difference in manufacturing setting (compaction pressure, sintering temperature, sintering time and atmosphere) resulted into varied properties from density, hardness and volume content of NbC in final MMCs. Similar work has been reported by some author where carbides of combined Ti and V produced in-situ [27]. They also reported successful formation of (Ti, V)C complex carbide. The improvement in density and microhardness with increase in volume of VC has been reported [20]. Not only this but also decrease of optimum sintering temperature, sintering time with increase in volume of VC in the MMCs has been reported. Similarly improvement in abrasive resistance and hardness has been reported by using WC as reinforcement through HIP [23]. Ferrous Nanocomposites reinforced by alumina, MWNTs and Cementite have shown improvement in properties. With alumina being resistant to oxidation, corrosion and wear due to its structure, which improves wear resistance of MMCs but decreases density as well as hardness with increasing volume of alumina [11]. MWNTs, on the other hand improve tensile strength, compressive strength and hardness of MMC with increasing volume of MWNTs [13]. When Cementite as reinforcement with Fe matrix was manufactured by FAS technique, there was significant decrease in processing time [14]. With less sintering time, less sintering temperature and less compaction pressure the $Fe\text{-}Fe_3C$ Nano-composites resulted into high microhardness and density close to theoretical density. The UFGD Nano-particles due to their high hardness, high thermal conductivity and resistant to chemical as well as wear have been used as reinforcement to Fe-matrix [15]. This resulted into increase in compressive strength with UFGD content, reduces friction coefficient, wear rate and obtain higher density at low compaction pressure.

In some work TiCN powder were being used as reinforcement with M3/2 HSS powder to manufacture MMCs [18]. As increase in sintering temperature there has been increase in density of MMCs due to formation of liquid phase and hence good binding between matrix and reinforcement. But we have to control the optimum sintering temperature up to which we can get improved properties, otherwise above that temperature the material would get over-sintered and hence reduces its properties. This work reports improvement of Transverse Rupture Strength (TRS), hardness and wear resistance [18]. In another work TiCN has been used as reinforcement with M2 HSS matrix [19]. In this work [19] there was improvement in wear resistance, but the size of TiCN was less than the matrix which eliminates the need for blending by high energy milling and volume of TiCN was up to 50%. But in the previous work [18] the size of TiCN was close to the matrix. This was the reason for less volume of reinforcement in composite mix where size difference between matrix and reinforcement is insignificant. In some work using powder reinforcement of similar size as matrix, blending for 5h and through HIP, the limitation of volume of TiB_2 in Fe matrix has been avoided [24]. With increasing volume of TiB_2 the hardness and wear resistance goes on increasing. Some author used intermetallics as reinforcement powder with ferrous matrices. With increase in volume of low density Cr_2Al as well as $TiCr_2$ the density of MMC decreases significantly [25]. With both reinforcement the hardness of MMCs increases up to certain volume of reinforcement, the tensile strength remain close to the monolithic ferrous alloy. These reinforcements also improve wear resistance of the MMCs. These reinforcements were also sintered in different atmosphere (25% N_2+75% H_2, pure H_2, vacuum) to study the effect on properties [26]. The reinforcement particles react with Fe matrix and diffusion of element from reinforcement to matrix. This results into formation of Al and chromium carbide (CrC) in $Fe\text{-}AlCr_2$ system, TiC and Cr in $Fe\text{-}Cr_2Ti$ system. Al, which was formed at the interface, is a weak link and hence no strengthening effect. But TiC, which was formed would have good wetting with matrix, Cr diffused into matrix and the 25% N_2+75% H_2 atmosphere result into highest tensile strength due to solid solution strengthening of matrix by N_2 and highest wear resistance compared to other atmosphere.

IV. CONCLUSION

From the above discussion we could conclude, for manufacturing ferrous MMCs, these factors like compatibility (Wetting, Reactivity) between matrix and reinforcement, size of particles, shape of particles, volume of reinforcement, blending mechanism (ball milling, attritor milling), compaction mechanism (Cold or Warm compaction, CIP, HIP, DWLWC), compaction pressure, sintering temperature, sintering time, sintering mechanism (FAS, SLPS, CSE), sintering atmosphere (H_2, Ar, H_2+N_2, N_2) would affect final product. Based on influence of the above factors we could design MMCs with desired properties such as Tensile Strength, Compressive Strength, Wear Resistance, Abrasion Resistance, Corrosion Resistance, Thermal Conductivity, Hardness, Microhardness, Toughness and workability etc.

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