Research Article

Sintering and Hardness Behavior of Fe-Al₂O₃ Metal Matrix Nanocomposites Prepared by Powder Metallurgy

Pallav Gupta,¹ Devendra Kumar,¹ Om Parkash,¹ and A. K. Jha²

¹ Department of Ceramic Engineering, Indian Institute of Technology (Banaras Hindu University), Varanasi, Uttar Pradesh 221005, India

² Department of Mechanical Engineering, Indian Institute of Technology (Banaras Hindu University), Varanasi, Uttar Pradesh 221005, India

Correspondence should be addressed to Devendra Kumar; devendra.cer@iitbhu.ac.in

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The present paper reports the investigations on sintering and hardness behavior of Fe-Al₂O₃ Metal Matrix Nanocomposites (MMNCs) prepared by Powder Metallurgy (P/M) route with varying concentration of Al₂O₃ (5–30 wt%). The MMNC specimens for the present investigations were synthesized by ball milling, followed by compaction and sintering in an inert atmosphere in the temperature range of 900–1100°C for 1–3 hours using Powder Metallurgy route. Phase and microstructures of the specimens were characterized by XRD and SEM. Reactive sintering takes place in these materials. During sintering nano iron aluminate (FeAl₂O₄) phase forms. Characterization was done by measuring density and hardness. Results have been discussed critically to illustrate the effect of various processing parameters on sintering and mechanical behavior. It is expected that the results of these investigations will be useful in developing Metal Matrix Nanocomposites (MMNCs) for typical industrial applications.

1. Introduction

During the last few decades Metal Matrix Nanocomposites (MMNCs) have assumed an important position in industries as these are being used successfully in a wide range of applications due to improvement in the structural, mechanical, and electrochemical properties, respectively [1]. There are several routes which are put forth by researchers throughout the globe for the fabrication of the MMNC materials. Amongst them, the stir casting and Powder Metallurgy (P/M) are two prominent routes which play a vital role in development of quality MMNC products with improved structural, mechanical, and electrical properties [2]. P/M technique is used mostly because it yields homogenous product using smaller heat treatment schedule [3]. In this technology, metal powder is taken as a starting material and is mixed with ceramic reinforcement in a suitable quantity [4]. The mixture is compacted in a die and subsequently sintered in vacuum or inert atmosphere. To a large extent, the compaction of powder particles and sintering conditions decide the properties of

MMNC so formed. Another important factor which plays an important role in determining the properties of MMNCs is the particles size and particles size distribution [5, 6]. A considerable amount of research work has already been done on various technological aspects of MMNC using aluminum, copper, and magnesium as matrices [7, 8].

Chua et al. has reported that, for Mg-SiC composite, use of smaller particles of SiC results in relatively higher elastic modulus and tensile strength in a large number of thermal shock cycles [9]. It has also been reported by Rahimian et al. [8] that, for Al-Al₂O₃ composites, increase in the sintering time at 600°C from 60 to 90 min leads to reduction in hardness from 67 to 59 HB. This is explained by the fact that on sintering for 90 min at 600°C grain growth occurred, which according to Hall-Petch theory leads to lower strength and hardness. From the above discussion it can be seen that no systematic attempt has been made for studying the sintering and hardness behavior of iron based composites [10].

Recently, structural, mechanical, and electrochemical properties of Fe-5% Al₂O₃ metal matrix composite have been

TABLE 1: Nomenclature of specimens.

Sl. no.	Sintering temperature (°C)	Sintering time (h)	Specimen code 5% Al ₂ O ₃	Specimen code 10% Al ₂ O ₃	Specimen code 20% Al ₂ O ₃	Specimen code 30% Al ₂ O ₃
1	900	1	5AFe900(1)	10AFe900(1)	20AFe900(1)	30AFe900(1)
2	1000	1	5AFe1000(1)	10AFe1000(1)	20AFe1000(1)	30AFe1000(1)
3	1100	1	5AFe1100(1)	10AFe1100(1)	20AFe1100(1)	30AFe1100(1)
4	900	2	5AFe900(2)	10AFe900(2)	20AFe900(2)	30AFe900(2)
5	1000	2	5AFe1000(2)	10AFe1000(2)	20AFe1000(2)	30AFe1000(2)
6	1100	2	5AFe1100(2)	10AFe1100(2)	20AFe1100(2)	30AFe1100(2)
7	900	3	5AFe900(3)	10AFe900(3)	20AFe900(3)	30AFe900(3)
8	1000	3	5AFe1000(3)	10AFe1000(3)	20AFe1000(3)	30AFe1000(3)
9	1100	3	5AFe1100(3)	10AFe1100(3)	20AFe1100(3)	30AFe1100(3)

investigated by us. It was found that various properties of the nanocomposites vary with processing parameters and formation of the iron aluminate (FeAl_2O_4) phase [11, 12]. Wear behavior of the composites was studied at a fixed sliding velocity of 4 m/sec under a load of 0.5, 1.0, and 2.0 Kg for 1 hour of time interval, respectively. It was observed that at low load the adhesive wear was more active whereas at high load the abrasive wear was more prominent [13]. Various properties were found to improve on 5% addition of Al_2O_3 in iron matrix. The major motivation in the present case is the formation of the iron aluminate phase due to reactive sintering between iron and alumina particles. The present paper focuses on the study of various structural and mechanical characteristics by varying the amount of Al_2O_3 reinforcement in the iron matrix.

In the present paper results of a systematic study on sintering and hardness behavior of Fe- Al_2O_3 Metal Matrix Nanocomposites (MMNCs) prepared by Powder Metallurgy have been reported. The experimental studies have been carried out to correlate the effect of phase and microstructure with mechanical properties. It is expected that the outcome of these experimental studies will be helpful in designing and developing Metal Matrix Nanocomposites for critical industrial applications.

2. Experimental Work

2.1. Preparation of Test Specimens. Electrolytic iron metal powder having 99.5% purity and particle size in the range of 49–58 microns and active aluminum oxide having particles size in the range of 63–210 microns are used as starting materials. Composite selected for present investigation contains aluminum oxide (Al_2O_3) in 5, 10, 20, and 30% by weight. Mixed powders were ball milled dry with the powder to ball ratio of 1 : 2 using zirconia balls as the grinding and mixing media [14]. Mixed powders were compacted using a hydraulic press under a constant load of 7 tons. Green compacts were sintered in an argon atmosphere in the temperature range of 900°C to 1100°C for 1–3 hours. After sintering, the compacts were machined on gap or extension type lathe machine. Thereafter, the surface of the specimens was polished. A nomenclature, for example, 5AFe900(1), is given to

each specimen. Here 5 denotes the percentage of aluminum oxide, A denotes aluminum oxide, Fe denotes iron, 900 denote the sintering temperature in °C, and 1 denotes time of sintering in hour. Sintered specimens are of 13 mm diameter and 20 mm height. There were four systems and in each system there were 9 specimens which were sintered for 3 different temperatures and time. Thus, 36 specimens were prepared for the present investigations. Table 1 illustrates the nomenclature of specimens. Specimen having 5% and 10% of aluminum oxide showed good strength whereas specimen having 20% and 30% showed poor strength and was brittle in nature. The reason for this has been discussed in the results and discussion part of the paper.

2.2. Experimental Measurements. Phase determination was done by powder X-ray diffraction (XRD) using Rigaku Desktop Miniflex II X-ray diffractometer employing $\text{Cu-K}\alpha$ radiation and Ni-filter. Microstructure was studied using inspect S-50, FP 2017/12 scanning electron microscope. Cylindrical specimens of 12 mm diameter and 2 mm thickness were used for SEM studies. Specimens were polished using various grades of emery paper (1/0, 2/0, 3/0, and 4/0) and then finally using diamond polish. Nanocomposite specimens were etched with HCl for 20 sec and then washed with acetone.

Density was determined from the mass and dimensions (i.e., radius and height). Hardness was measured on a Rockwell hardness tester using 1/8" H scale steel ball indenter having a major loading capacity of 60 Kg. Reading of the H type indenter was read on the red scale present on the dial gauge of the instrument.

3. Results and Discussion

3.1. X-Ray Diffraction. Representative XRD patterns of specimens with different Al_2O_3 contents, sintered in the temperature range of 900°C–1100°C, are shown in Figures 1, 2, 3, and 4, respectively. Figure 1 shows XRD patterns of the specimens (a) 5AFe900(2), (b) 5AFe1000(2), and (c) 5AFe1100(2), respectively. Diffraction peaks present in the specimen were matched with the XRD-JCPDS files of different compounds. It was found that Fe, Al_2O_3 , and FeAl_2O_4 phases were present

FIGURE 1: XRD of specimens (a) 5AFe900(2), (b) 5AFel000(2), and (c) 5AFel100(2) respectively.

FIGURE 2: XRD of specimens (a) 10AFe900(2), (b) 10AFel000(2), and (c) 10AFel100(2) respectively.

FIGURE 3: XRD of specimens (a) 20AFe900(2), (b) 20AFel000(2), and (c) 20AFel100(2) respectively.

FIGURE 4: XRD of specimens (a) 30AFe900(2), (b) 30AFel000(2), and (c) 30AFel100(2) respectively.

in this nanocomposite specimen. Specimens 5AFe900(2) and 5AFel000(2) show presence of Fe, Al_2O_3 , and FeAl_2O_4 phases. The number of peaks in the 5AFel000(2) specimen was more in comparison to specimen 5AFe900(2). Specimen 5AFel100(2) also showed presence of Fe, Al_2O_3 , and FeAl_2O_4 phases. Formation of iron aluminate phase in the present case is due to the reactive sintering phenomenon. XRD plot of 5% Al_2O_3 reinforced iron based metal matrix composite shows traces of Al_2O_3 and FeAl_2O_4 phases. Amount of iron aluminate phase depends upon the reaction between iron and alumina particles. Since the percentage of alumina is low therefore iron aluminate phase formation is less and it is still lesser for high temperature of sintering.

Figure 2 shows XRD pattern of specimens (a) 10AFe900(2), (b) 10AFel000(2), and (c) 10AFel100(2). Specimen 10AFe900(2) shows the formation of Fe, Al_2O_3 , and FeAl_2O_4 phases, respectively. Similar to specimen 10AFe900(2) the other two specimens, that is, 10AFel000(2) and 10AFel100(2), also showed the presence of Fe, Al_2O_3 , and FeAl_2O_4 phases. The iron aluminate phase is formed due to the reactive sintering between the iron and alumina particles. More amount of Al_2O_3 and less amount of FeAl_2O_4 phase were found in the specimen 10AFe900(2) whereas a large amount of FeAl_2O_4 and small amount of Al_2O_3 phase was found in the specimen 10AFel100(2). It can be concluded from the above discussion that as the sintering temperature increases the iron aluminate phase formation also increases.

Figure 3 shows XRD pattern of specimens (a) 20AFe900(2), (b) 20AFel000(2), and (c) 20AFel100(2). Specimen 20AFe900(2) showed the presence of iron (Fe), aluminum oxide (Al_2O_3) and iron aluminate (FeAl_2O_4) phases. Similarly specimens 20AFel000(2) and 20AFel100(2) also showed presence of Fe, Al_2O_3 , and FeAl_2O_4 phases. Similar to the previous specimens these specimens also showed the presence of iron aluminate phase which took place as a result of reactive sintering phenomenon between iron and alumina particles. It is also found that the amount of iron phase decreased and consequently the amount of iron aluminate phase increased as we increase the sintering temperature. This change can be attributed by the fact that upon increasing the sintering temperature the rate of reaction between the iron and alumina particles increases thereby increasing the iron aluminate phase formation [15].

Figure 4 shows XRD patterns of the specimens (a) 30AFe900(2), (b) 30AFel000(2), and (c) 30AFel100(2), respectively. XRD pattern of 30AFe900(2) shows peaks of iron and aluminum oxide, respectively. Specimen 30AFel000(2) and 30AFel100(2) shows presence of iron, aluminum oxide, and iron aluminate. It can be seen from the XRD results that as we increase the Al_2O_3 content as well as the sintering temperature the amount of the iron aluminate phase increases significantly. For lower percentage of reinforcement the reaction between iron and aluminum oxide particle is complete leading to small amount of iron aluminate phase. But for high percentage of Al_2O_3 (i.e., 30%) formation of iron aluminate phase was maximum in the specimen along with some traces of aluminum oxide. It is clear from XRD patterns that as we increase the percentage of alumina the intensity of peaks

FIGURE 5: Density versus % Al_2O_3 plots for the various specimens.

due to Al_2O_3 increases and so does the iron aluminate phase formation.

3.2. Density. Figure 5(a) shows the plot between density versus % Al_2O_3 for the specimens sintered at 900°C. Specimen 5AFe900(1) shows a high value of density (4.33 gm/cc). Specimens 10AFe900(1), 20AFe900(1), and 30AFe900(1) show a continuous decrease in the density values. The density for the specimens 10AFe900(1), 20AFe900(1), and 30AFe900(1) was found to be 3.94 gm/cc, 3.61 gm/cc, and 3.08 gm/cc, respectively. Similarly, specimen 5AFe900(2) showed a higher density (4.80 gm/cc) in comparison with the specimen 5AFe900(1). On increasing the percent of alumina (from 10–30%), that is, for specimens 10AFe900(2), 20AFe900(2), and 30AFe900(2), the density values were found to be 4.07 gm/cc, 3.64 gm/cc, and 3.03 gm/cc, respectively. Density of the specimen 5AFe900(3) was found to be equal to that of 5AFe900(2) but higher than that of the specimen 5AFe900(1). Finally specimen 30AFe900(3) showed the lowest density among all the three specimens, that is, 5AFe900(3), 10AFe900(3), and 20AFe900(3), respectively.

Figure 5(b) shows the density versus % Al_2O_3 plot for the specimens sintered at 1000°C. Specimen 5AFel000(1) shows density value of 4.78 gm/cc. Specimen 10AFel000(1) shows the density value of 3.93 gm/cc, specimen 20AFel000(1)

FIGURE 6: SEM images at 250x of (a) Fe powder and (b) Al_2O_3 powder.

shows the density value of 3.58 gm/cc, and specimen 30AFel000(1) shows density value of 3.06 gm/cc. On increasing the sintering time to 2 hours at the same sintering temperature, specimen 5AFel000(2) shows the density value of 4.88 gm/cc, which is higher than that of the density of specimen 5AFel000(1). 10AFel000(2) shows the density value of 4.25 gm/cc and 20AFel000(2) shows density value of 3.79 gm/cc. Similarly specimen 30AFel000(2) shows the density value of 3.16 gm/cc. After 2 hours of time interval the specimens were sintered for a time interval of 3 h at 1000°C . Specimen 5AFel000(3) showed density value of 4.96 gm/cc. Specimens 10AFel000(3), 20AFel000(3), and 30AFel000(3) showed density value of 4.50 gm/cc, 3.89 gm/cc, and 3.25 gm/cc, respectively.

Figure 5(c) shows density versus % Al_2O_3 plot for the specimens sintered at 1100°C . Specimen 5AFel100(1) shows the density value of 4.81 gm/cc. Subsequently specimens 10AFel100(1), 20AFel100(1), and 30AFel100(1) show the density values of 4.47 gm/cc, 3.87 gm/cc, and 3.18 gm/cc, respectively. The specimen when sintered for 2 hours yields the specimens 5AFel100(2), 10AFel100(2), 20AFel100(2), and 30AFel100(2). Density of these specimens was found to be 4.90 gm/cc, 4.60 gm/cc, 3.93 gm/cc, and 3.24 gm/cc, respectively. This shows that as we increase the amount of % Al_2O_3 the density values decrease significantly. Among the specimens sintered for 3 hours, specimen 5AFel100(3) shows the density value of 5.07 gm/cc and specimens 10AFel100(3), 20AFel100(3), and 30AFel100(3) show the density values of 4.98 gm/cc, 3.96 gm/cc, and 3.29 gm/cc.

The overall variation in the density values with the variation in % Al_2O_3 , sintering temperature, and time can be understood in the following manner. Within the compositional range the density value increases with the increase in the sintering temperature as well as with the sintering time. Outside the compositional range, that is, for 10%, 20%, and 30% of the reinforcement of aluminum oxide, the density values decrease continuously. This decrease in the density values can be attributed to the increase in the volume fraction

of the iron aluminate phase formation. The theoretical density of iron aluminate phase as calculated using the cell software was found to be 4.23 gm/cm^3 . Iron aluminate phase is brittle in nature and thus the density value decreases with increase in the aluminum oxide percentage.

3.3. Scanning Electron Microscopy. Figure 6(a) shows the SEM image of Fe powder at 250x which shows the homogeneous sized particle of constituent phase. The particle size of the iron particle lies in the range of 50–55 microns. Figure 6(b) shows the SEM image of Al_2O_3 powder which also shows the homogeneous sized particle of constituent phase. It can be observed that the particle size of Al_2O_3 lies in the range of 100–150 microns, respectively. Therefore, it can be concluded that the particle size of the powder taken from electron micrographs is in close proximity with that of the manufacturer's specification.

Figures 7, 8, and 9 show the SEM of specimens 10AFel900(1), 10AFel900(2), and 10AFel100(1) at (a) 5000x and (b) 20000x magnification, respectively. The microstructures are provided in such a sequence in order to study the effect of composition, sintering temperature, and the sintering time, respectively. Figures 7(a), 8(a), and 9(a) show highly dense phase composite structure containing negligible amount of porosity. These microstructures show grains of Fe, Al_2O_3 , and FeAl_2O_4 . The dark black grains are of iron and white ones are of aluminum oxide. Remaining grey coloured grains are of iron aluminate. Figures 7(b), 8(b), and 9(b) show electron micrographs of the same specimens at 20,000x magnification. This microstructure shows the micron and nanometer size grains of iron aluminate phase. The particle size lies in the range of 14–135 nm, respectively.

Figures 10, 11, and 12 show SEM of the specimens 20AFel900(2), 20AFel1000(2), and 20AFel100(2) specimens, respectively. Figures 10(a), 11(a), and 12(a) show the scanning electron micrographs at 5000x. The micrographs show the presence of the particles of micron, submicron, and some nanosize range particles of iron aluminate. Since this

FIGURE 7: SEM of 10AFe900(1) at (a) 5000x and (b) 20000x.

FIGURE 8: SEM of 10AFe900(2) at (a) 5000x and (b) 20000x.

FIGURE 9: SEM of 10AFel100(1) at (a) 5000x and (b) 20000x.

FIGURE 10: SEM of 20AlFe900(2) at (a) 5000x and (b) 20000x.

FIGURE 11: SEM of 20AlFe1000(2) at (a) 5000x and (b) 20000x.

FIGURE 12: SEM of 20AlFe1100(2) at (a) 5000x and (b) 20000x.

FIGURE 13: Hardness versus % Al₂O₃ for the specimens sintered at 900°C.

composition contains 20% aluminum oxide therefore formation of FeAl₂O₄ was more as compared to the specimens containing 10% of aluminum oxide reinforcement. Therefore, in the present micrographs mostly the iron aluminate particles are present. Figures 10(b), 11(b), and 12(b) show the micrographs of the same specimens at 20000x. All the three specimens show nanosize particles of iron aluminate phase in the range 70 to 100 nm.

3.4. Hardness. Figure 13 shows the variation of hardness with content of Al₂O₃ plot for the specimens sintered at 900°C. Initially the hardness number for the specimen 5AFe900(1) was found to be 53 HRH. Specimen 10AFe900(1) showed a slight increase in the hardness as compared to the specimen 5AFe900(1). Its hardness number was found to be 55 HRH. Hardness of the specimen 20AFe900(1) is less than that of the specimens 5AFe900(1) and 10AFe900(1). Hardness number of the specimen 20AFe900(1) was found to be 23 HRH. Among specimens sintered at 900°C for 2 hours, specimen 5AFe900(2) showed hardness value of 50 HRH which is less than the hardness number of specimen 5AFe900(1). 10AFe900(2) showed a decrease in the hardness number in comparison to specimen 5AFe900(2). 20AFe900(2) also showed a lower hardness number. The value of hardness number for the specimen 10AFe900(2) and 20AFe900(2) was found to be 42 HRH and 17 HRH, respectively. The specimen 5AFe900(3) shows a hardness number of 40, specimen 10AFe900(3) shows a hardness number almost the same as specimen 5AFe900(3), and the specimen 20AFe900(3) shows a higher hardness number.

Figure 14 shows hardness versus % Al₂O₃ reinforcement plot for the specimens sintered at 1000°C. Specimen 5AFel000(1) shows a hardness number of 45. The hardness number of the specimen 10AFel000(1) reduces a little bit in comparison to the specimen 5AFel000(1). Specimen

FIGURE 14: Hardness versus % Al₂O₃ for the specimens sintered at 1000°C.

20AFel000(1) shows a higher hardness number in comparison to the specimens 5AFel000(1) and 10AFel000(1). Among the specimen sintered for a time interval of 2 hour at 1000°C, specimen 5AFel000(2) shows hardness number the same as that of 5AFel000(1). The hardness number of specimen 10AFel000(2) is also the same as the hardness number of the specimen 10AFel000(1) and finally specimen 20AFel000(2) has highest hardness number. Specimen 5AFel000(3) showed less hardness in comparison to the specimens 5AFel000(1) and 5AFel000(2). On the other hand specimen 10AFel000(3) showed higher hardness in comparison to the specimen 10AFel000(1) and 10AFel000(2), respectively. Specimen 20AFel000(3) showed highest hardness number and it was found to be same as that of specimen 20AFel000(2).

Figure 15 shows the hardness versus % Al₂O₃ plot for the specimens sintered at 1100°C. Specimen 5AFel100(1) showed low hardness being 38 HRH. Specimen 10AFel100(1) showed hardness number almost equal to specimen 5AFel100(1). Specimen 20AFel100(1) showed a higher hardness (72 HRH) in comparison to specimens 5AFel100(1) and 10AFel100(1). Specimen 5AFel100(2) showed a higher hardness in comparison to specimen 5AFel100(1); 10AFel100(2) also shows an increase in the hardness number of the specimen. Its hardness number was found to be 54 HRH. The hardness number of the specimen 20AFel100(2) was found to be 77 HRH. On increasing the sintering time for 3 hours, specimens 5AFel100(3), 10AFel100(3) and 20AFel100(3) showed hardness number of 44 HRH, 42 HRH, and 79 HRH, respectively. It is quite interesting to note that the hardness value of cast iron specimen was found to be 18 HRH which illustrates that the hardness number of the formed nanocomposites was much higher in comparison to the cast iron specimen.

Variation in the hardness number of the specimens with respect to the sintering temperature and time can

FIGURE 15: Hardness versus % Al_2O_3 for the specimens sintered at 1100°C .

be explained on the basis of the nature and type of the sintering in the composite for respective sintering time. Two types of sintering behavior are observed in the present nanocomposite system: (i) solid state sintering between iron particles and (ii) reactive sintering between iron and aluminum oxide particles associated with the formation of iron aluminate. With first kind of sintering there will be no change in the fraction of ceramic reinforcement in the composite and metallic characteristics are enhanced due to densification resulting in the decrease in hardness number, whereas with second kind of reactive sintering content of aluminate phase, that is, ceramic phase, increases resulting in an increase in the hardness number. For lower sintering temperature, reactive sintering rate is smaller than the solid state sintering amongst Fe particles and hardness number decreases correspondingly with increasing sintering time. With increasing sintering temperature, reactive sintering rate increases due to formation of ceramic FeAl_2O_4 nanoparticles resulting in an increase in hardness number of the specimen with increasing sintering temperature. Further the variation of the hardness number with % Al_2O_3 can be explained as follows: for the sintering of the specimen done at 900°C for 1 h and 2 h of time interval, the hardness value first increases up to 10 wt% of Al_2O_3 and then it decreases for 20 wt%. For 3 h of time interval at 900°C the hardness increases with the content of reinforcement. It is due to the reason that at this temperature and time interval optimum amount of iron aluminate phase formation has taken place. The hardness values for the specimen sintered at 1000°C and 1100°C for different time intervals showed a continuous increase in the hardness values up to 20% of Al_2O_3 reinforcement. The hardness for the 30% reinforced Al_2O_3 could not be found due to brittleness of the specimen.

4. Conclusions

A systematic study on sintering and hardness behavior of Fe- Al_2O_3 Metal Matrix Nanocomposites (MMNC) prepared by Powder Metallurgy has been reported in this paper. The experimental results have been discussed critically and the following important conclusions have been drawn.

- (i) Reactive sintering phenomena between iron and alumina leads to the formation of iron aluminate phase.
- (ii) SEM shows the formation of highly dense phase structure with the presence of nano dispersion of iron aluminate phase.
- (iii) Density increases with the sintering temperature as well as with the sintering time which is due to the formation of iron aluminate phase.
- (iv) Hardness value reduces for sintering carried out at 900°C for 1 and 2 hours, whereas for rest of the cases it increases significantly.
- (v) It was found from the investigations that the ductility is maintained in the specimens up to 10% of the aluminum oxide dispersion after which the specimens become brittle in nature which is due to the increase in the formation of iron aluminate phase.

It is expected that the results of these investigations will be useful in developing technology for producing better quality MMNC products at competitive rates.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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References

- [1] D. B. Miracle, "Metal matrix composites—from science to technological significance," *Composites Science and Technology*, vol. 65, no. 15-16, pp. 2526–2540, 2005.
- [2] P. K. Liaw, D. K. Hsu, N. Yu, N. Miriyala, V. Saini, and H. Jeong, "Investigation of metal and ceramic-matrix composites moduli: experiment and theory," *Acta Materialia*, vol. 44, no. 5, pp. 2101–2113, 1996.
- [3] J. M. Torralba, C. E. Da Costa, and F. Velasco, "P/M aluminum matrix composites: an overview," *Journal of Materials Processing Technology*, vol. 133, no. 1-2, pp. 203–206, 2003.
- [4] S. Gorsse, J. P. Chaminade, and Y. Le Petitcorps, "In situ preparation of titanium base composites reinforced by TiB single crystals using a powder metallurgy technique," *Composites A: Applied Science and Manufacturing*, vol. 29, no. 9-10, pp. 1229–1234, 1998.

- [5] Y. G. Wei, "Particulate size effects in the particle-reinforced metal-matrix composites," *Acta Mechanica Sinica*, vol. 17, no. 1, pp. 45–58, 2001.
- [6] S. H. Chen and T. C. Wang, "Size effects in the particle-reinforced metal-matrix composites," *Acta Mechanica*, vol. 157, no. 1–4, pp. 113–127, 2002.
- [7] F. Akhtar, S. J. Askari, K. A. Shah, X. Du, and S. Guo, "Microstructure, mechanical properties, electrical conductivity and wear behavior of high volume TiC reinforced Cu-matrix composites," *Materials Characterization*, vol. 60, no. 4, pp. 327–336, 2009.
- [8] M. Rahimian, N. Ehsani, N. Parvin, and H. R. Baharvandi, "The effect of particle size, sintering temperature and sintering time on the properties of Al-Al₂O₃ composites, made by powder metallurgy," *Journal of Materials Processing Technology*, vol. 209, no. 14, pp. 5387–5393, 2009.
- [9] B. W. Chua, L. Lu, and M. O. Lai, "Influence of SiC particles on mechanical properties of Mg based composite," *Composite Structures*, vol. 47, no. 1–4, pp. 595–601, 1999.
- [10] E. Pagounis, M. Talvitie, and V. K. Lindroos, "Influence of the metal/ceramic interface on the microstructure and mechanical properties of HIPed iron-based composites," *Composites Science and Technology*, vol. 56, no. 11, pp. 1329–1337, 1996.
- [11] P. Gupta, D. Kumar, O. Parkash, and A. K. Jha, "Structural and mechanical behavior of 5% Al₂O₃ reinforced Fe metal matrix composites (MMC) produced by powder metallurgy (P/M) route," *Bulletin of Materials Science*, vol. 36, no. 5, pp. 859–868, 2013.
- [12] P. Gupta, D. Kumar, M. A. Quraishi, and O. Parkash, "Corrosion behavior of Al₂O₃ Fe metal matrix nanocomposites produced by powder metallurgy technique," *Advanced Science, Engineering and Medicine*, vol. 5, no. 4, pp. 366–370, 2013.
- [13] P. Gupta, D. Kumar, O. Parkash, and A. K. Jha, "Effect of sintering on wear characteristics of Fe-Al₂O₃ metal matrix composites," *Proceedings of the Institution of Mechanical Engineers J: Journal of Engineering Tribology*, vol. 228, no. 3, pp. 362–368, 2014.
- [14] N. Nemati, R. Khosroshahi, M. Emamy, and A. Zolriasatein, "Investigation of microstructure, hardness and wear properties of Al-4.5wt.% Cu-TiC nanocomposites produced by mechanical milling," *Materials and Design*, vol. 32, no. 7, pp. 3718–3729, 2011.
- [15] K. Konopka and A. Oziębło, "Microstructure and the fracture toughness of the Al₂O₃-Fe composites," *Materials Characterization*, vol. 46, no. 2–3, pp. 125–129, 2001.