Available online at www.sciencedirect.com

ScienceDirect

Journal of Magnesium and Alloys 6 (2018) 245–254

www.elsevier.com/locate/jma

Introduction to magnesium alloy processing technology and development of low-cost stir casting process for magnesium alloy and its composites

Anil Kumar[a,*], Santosh Kumar[a], N.K. Mukhopadhyay[b]

[a] *Department of Mechanical Engineering, Indian Institute of Technology (BHU) Varanasi, India*
[b] *Department of Metallurgical Engineering, Indian Institute of Technology (BHU) Varanasi, India*

Received 12 December 2017; received in revised form 27 April 2018; accepted 9 May 2018
Available online 5 June 2018

Abstract

This paper presents the processing of magnesium alloys and its composite through different stir casting technologies. Design and development of stir casting technology that is suitable for processing of magnesium alloys has been done in this study. The low-cost stir casting processing of magnesium alloy and its composite with flux and without flux has been explained. The magnesium alloy and its composite have been fabricated by both the stir casting process. The micro structural characterization and mechanical properties of the developed composites has been evaluated. The optical emission spectroscopy of the developed alloy and factography of the developed alloy as well as composite was also examined.
© 2018 Published by Elsevier B.V. on behalf of Chongqing University.
This is an open access article under CC BY-NC-ND license. (http://creativecommons.org/licenses/by-nc-nd/4.0/)
Peer review under responsibility of Chongqing University

Keywords: Metal matrix composite; Magnesium alloys; Stir casting; Composite.

1. Introduction

Design and development of lightweight and energy efficient material are one of the major challenges for the 21st-century designer. Magnesium has the potential to replace steel, aluminum alloy, and plastic-based materials. Initially, due to the high price, there were limited applications of magnesium alloy. But recently, the interest in magnesium alloys has increased because of gradually decreasing cost of magnesium alloys. Magnesium alloys has better solidification characteristics over other cast metals such as copper and aluminum alloys [1]. Casting is one of the dominant manufacturing processes for the magnesium-alloy components representing 98% of structural application of magnesium [2]. Fabrication of magnesium alloy and its composite is the great challenge for engineers and scientist because of the high affinity of magnesium towards oxygen. There are various synthesis techniques developed for the casting of magnesium-based alloys and composites. Gravity sand and permanent mold processes are used to produce high-performance aerospace and defense components [3]. Melting and casting of magnesium alloys in the vacuum-assisted inert atmosphere is one of the best suitable and environment-friendly processes.

1.1. Melting and melt protection

Molten magnesium does not react with iron like molten aluminum, which has a very high affinity with iron; therefore, magnesium-alloys can be melted and held in a crucible made of steel. If the magnesium alloy contains aluminum as an alloying element then it may react with the ferrous crucible, so to avoid this paste of boron nitride is used to provide a coating on steel crucible. The use of metallic crucibles allows the crucible to be supported from the top by means of a flange, leaving the space below the crucible [3]. Fig. 1 shows the metallic crucible with boron nitride paste inside.

* Corresponding author.
E-mail address: anilkumar.rs.mec11@iitbhu.ac.in (A. Kumar).

https://doi.org/10.1016/j.jma.2018.05.006
2213-9567/© 2018 Published by Elsevier B.V. on behalf of Chongqing University.
This is an open access article under CC BY-NC-ND license. (http://creativecommons.org/licenses/by-nc-nd/4.0/)

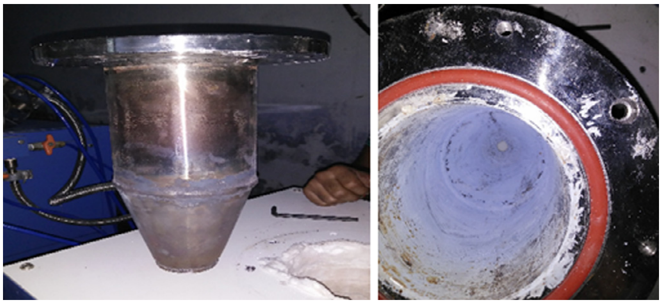

Fig. 1. Metallic crucible with flange.

Molten magnesium is prone to oxidation and burn, unless due care is taken to protect its surface against oxidation Aluminium alloy forms a continuous impermeable oxide on the molten bath that restricts further oxidation but in case of magnesium alloys, they form a loose permeable oxide coating on the molten metal surface. This loose oxide coating allows oxygen to pass through and support burning. Protection of the molten alloy using either a flux or a protective gas cover excluding the oxygen is required. There are basically two methods for melt protection of magnesium alloys as described in next two subsections.

1.2. Flux protection process

Protection of molten magnesium with the help of flux was used before the development of gaseous protection. A small quantity of flux (20% KCl, 50% $MgCl_2$, 15% MgO, 15% CaF_2 wt%) is placed at the bottom of the crucible and preheated to dull red hot [4]. Some more amount of flux is slightly sprinkled during melting, holding and casting [3]. After the invention of the fluxless process (protective gas and inert gas environment) for magnesium melting and casting, application of flux protection process has been limited to gravity casting methods or some special casting with high melting point [3].

1.3. Flux less protection process

With the addition of flux, there was possibility in magnesium alloy to lose their ductility. Therefore, a fluxless process using SF6 has been developed by the researchers in 1970s. A process with the vacuum-assisted inert atmosphere for melting, holding and casting of magnesium alloy and its composite has been developed.

1) *Protection using SF_6*: Development of Flux less melting using air/SF_6, air/CO_2/SF_6 or CO_2/SF_6 as the protective gas mixture was a great invention in melting, holding and casting of magnesium alloys [5,6]. SF_6 is one of the extremely effective oxidation inhibitors for magnesium alloys. The formation of MF_2 during oxidation of magnesium tend to block the pore in the natural oxide MgO and make it more protective [7]

$$2Mg(l) + O_2(g) \rightarrow 2MgO(s)$$

$$2Mg(l) + O_2(g) + SF_6(g) \rightarrow 2MgF_2(s) + SO_2F_2(g)$$

$$2MgO(s) + SF_6(g) \rightarrow 2MgF_2 + SO_2F_2$$

The fluxless production process of magnesium by using SF_6 (nontoxic) as a protective environment is accepted by all the leading manufacturer of the ingot producer and die casting sections of the foundry industry. In the flux-less process, the chance inclusion due to flux is eliminated.

However, SF_6 has very high global warming potential around 24,000 times more than of CO_2, because of very long retention in the atmosphere (3200 years), which means that emission of 1 kg SF_6 is equivalent to 26.5 MT of CO_2 [7]

2) *Protection using inert atmosphere*: A process with the vacuum-assisted inert atmosphere for melting, holding and casting of magnesium alloy and its composite has been developed to cater the disadvantage of using SF_6, which has high global warming potential. The safest way to protect magnesium alloy melt is creation of vacuum followed by impingement of inert gas in a controlled amount. This study is focused on the stir casting process by using vacuum pump followed by impingement of controlled atmosphere of argon gas.

On account of safety, prevention of accident and accidental precaution the weight of the vehicle has been increased by approximately 20% since last two decades. As the weight of a vehicle increases, the fuel consumption also increases in the same proportion of the weight of the vehicle. So there is huge pressure on the design engineer to search newer lightweight material.

Using magnesium alloys is one of the solutions for reducing the weight of the vehicle and most importantly it is recyclable. Some polymer material may also be used as low-weight material, but the cost of polymer material is very high and their thermal properties are highly negotiable. For designing and casting of magnesium alloy based metal matrix composite, there are several variables on the basis of which a new composite can be manufactured. The most important variables are:

- Selection of processing methods.
- Selection of magnesium alloys.
- Selection of reinforcement by characteristics.
- Selection of reinforcement by size.
- Variation of the volume fraction of reinforcement.

The liquid metal casting is one of the best and economical processing method for processing magnesium alloys and its composites. Depending on the use and application, most suitable alloy can be selected from available series of alloy or a new alloy may be created by adding a different alloying element in base magnesium. The reinforcements are also available in different types and sizes. The size and volume fraction of reinforcement plays an important role in the processing of metal matrix composites.

2. Literature review

The pure Magnesium has limited applications because of its reactivity and corrosion in open atmosphere. But magnesium alloy and its composite has wide applications because of its superior and lightweight properties. Magnesium is the third most-commonly used structural-metal, after steel and aluminum. By using magnesium alloys, there is huge weight saving. Magnesium alloys can save weight by 70% and 30 % if it is used in place of steel and aluminum alloys, respectively. Magnesium and its alloys has many outstanding properties relative to other engineering material such as low density, high strength, great damping capacity, and excellent fluidity for casting, good elastic shielding effect, non-magnetic, satisfactory heat conduction, and low-heat capacity, negative electrochemical potential, recyclable and nontoxic. These properties make magnesium and its alloys more attractive to many industries particularly in automotive and aerospace industries, where the strength to weight ratio is a critical issue [8]. Magnesium offers significant opportunities for lightweight applications in automotive, aerospace, power-tools, medical, and 3C (computer, communication, and consumer products) industries.

Magnesium casting is widely used by many well recognized automotive companies including G.M., Ford, Volkswagen and Toyota [9–16]. The major automotive magnesium application include instrument-panel beam, steering component, transfer case, door and radiator support. On addition of hard reinforcement, the yield strength of the materials decreases but the yield strength increases as the percentage of SiC particulate increases [17].

Historically, magnesium was used by German military aircraft in world war-I and extensively in world war-II [18]. The United States Air Force also used a large amount of Magnesium in long-range bombers B-36 and B-52 [25]. Magnesium was also used by Soviet aircraft industry: TU-95 plane had 1550 Kg and TU-134 plane had 780 Kg of magnesium component at a different location of airplane [19]. Unfortunately, the use of magnesium in modern aviations has drastically reduced due to perceived hazards with magnesium parts.

Today's use of the proper alloying element in magnesium alloy, the corrosion resistant of magnesium has improved remarkably [20]. Magnesium is not used in a structural application by major aircraft manufacturers such as Airbus, Boeing, and Embraer [19], but it is mostly used in helicopter industry such as cast gearboxes and some other non-structural components.

Historically, magnesium has been used as a piston in the racing engine for 'Indy 500' in 1921 B Dow Chemical [18] in the United States. In 1925, Germany used magnesium piston and there were more than 4 million of them in operation by 1937 [21]. Sand cast crankcase was another early application of magnesium as an automotive material by Chevrolair in 1931 [22]. Crankcase and its housing also produced by high pressure die casting in Germany [23].

The increasing environment and legislative pressure on automotive industry to produce lighter, high performance and better fuel efficient vehicle resulted in the use of magnesium and its alloys. Leading automobile makers such as Audi, Daimler Chrysler (Mercedes-Benz), Toyota, Ford, BMW, Jaguar, Volkswagen, Fiat, Hyundai and Kia Motors Corporation have used magnesium-based materials in their automobile parts.

The lightweight magnesium is widely used in electronic devices for lightweight as well as heat transfer properties. The density, fracture toughness, elastic modulus and compressive strength of magnesium are similar to the human bone; due to this, magnesium can be used as an implant in the human body.

Magnesium and its alloys are mainly processed either through solid (powder metallurgy) or liquid phase. The liquid phase processing is more beneficial than solid phase processing. This is due to high-processing cost of the solid phase, limitations on thickness, lower ductility, and fracture toughness, and required tedious handling of fine powders. The liquid phase processing can be classified into the sand casting, high pressure and gravity die casting, squeeze casting, semisolid metal (SSM) casting, stir casing, spray forming and melt infiltration method, in-situ synthesis is examples of liquid phase processes. Stir casting is more appropriate liquid processing method [24–26].

Stir casting is one of the most economical processes for the production of metal matrix composite due to its simplicity, flexibility and less processing cost [28]. Stir casting process is suitable for casting of magnesium alloy as well as magnesium alloy composites. The addition of particle into the matrix is done by different proprietary methods. The mixing of particles into the molten metal was performed with the help of stirrer. The main issue related to stir castings is an agglomeration of the reinforced particle, settling or floating of reinforcing particle and reaction between reinforcing phase and matrix materials. To avoid these problems mixing of reinforcing particle can be done in a semi-solid condition of the metallic matrix.

3. Experiments

A low-cost stir casting process has been developed in production lab of Mechanical Engineering department at IIT BHU Varanasi. The schematic diagram of fabricated set-up with different components is shown in Fig. 2.

The fabrication of the actual set-up has been done as per the details available in the schematic diagram. The maximum rage of furnace temperature was 1000 °C and maximum stirrer speed was 600 RPM. The furnace has a rectangular shape with round opening. Two stepped semi-cylindrical round ceramics bricks were used to cover the opening of the furnace. The speed of stirrer rod was controlled by a speed controller. The actual snaps of set-up are as shown in Fig. 3.

In the existing set-up having DC motor with spur gear arrangement (as shown in Fig. 4), there was no provision for up and down agitation of stirrer rod. To provide vertical agitation of stirring rod, another stirrer motor is used for holding stirrer

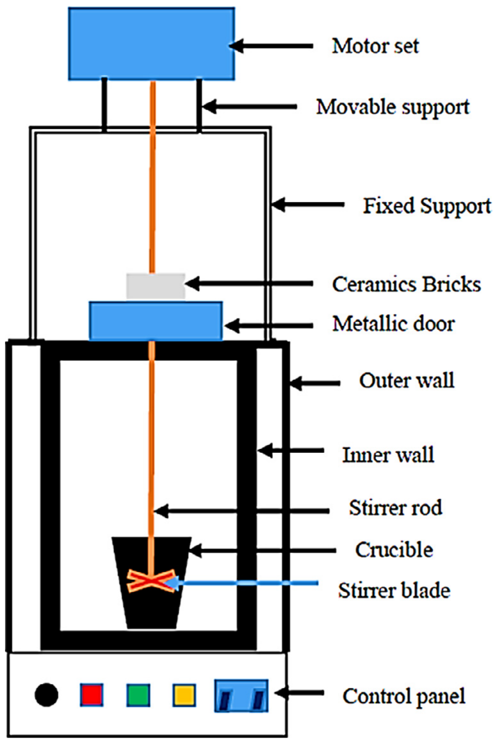

Fig. 2. Schematic diagram of stir casting set-up.

Fig. 3. Set-up of stir casting.

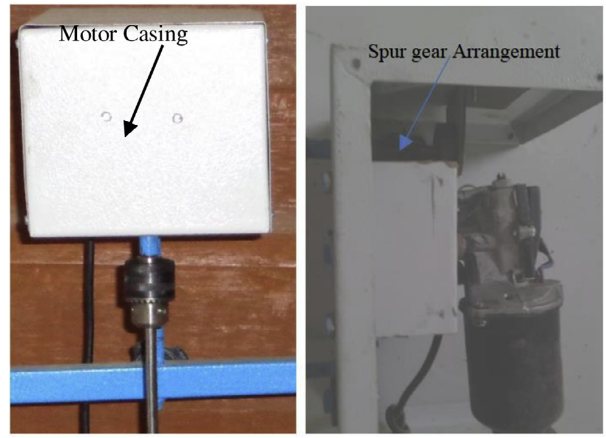

Fig. 4. Motor casing and gear arrangement of the stirrer.

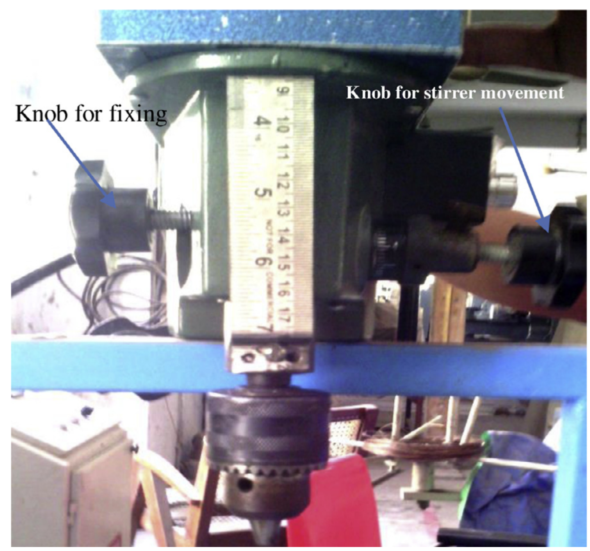

Fig. 5. Modified arrangement of the stirrer.

rod. This modified stirrer motor having vertical movement arrangement from 1 mm to 60 mm, is shown in Fig. 5.

The second stir casting process has been developed at KNIT Sultanpur with the support of VB ceramics, the component used in the furnace is supplied by VB ceramics, but the argon gas with pressure controller was purchased in local Sultanpur market. The schematic diagram of vacuum-assisted stir casting is shown in Fig. 6.

The set-up is fabricated by using some electronic and mechanical controlling device. The vacuum pump is used to create a vacuum inside the metallic crucible as well as die holder to avoid oxidation of the molten metal. The inert gas impinged inside the crucible as well as die holder area. The pressure inside the crucible is just above the atmospheric pressure to avoid entrapment of oxygen inside the molten metals. The pneumatic valve is used to control the opening and closing of the crucible hole. The air compressor is used to supply compressed air to the pneumatic valve for opening and closing of the valve so that pouring can be performed after uniform mixing of reinforced particle and matrix elements. The

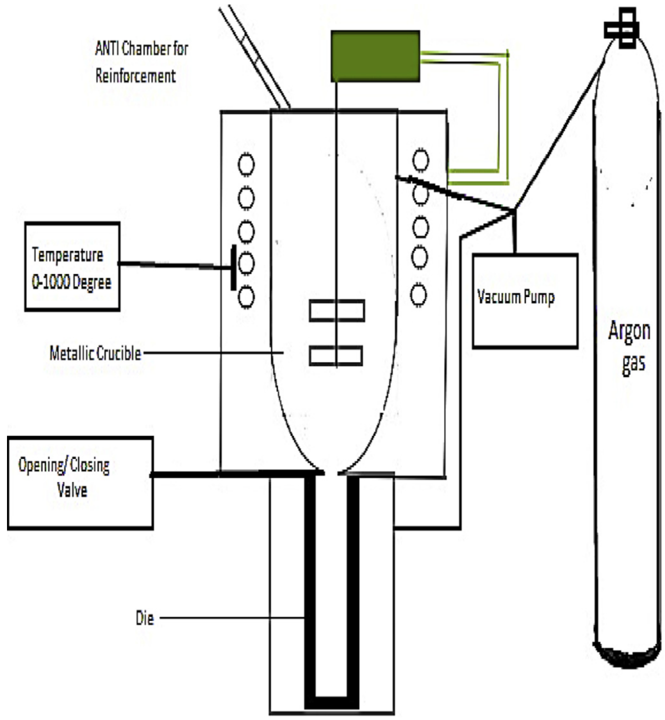

Fig. 6. Schematic diagram of vacuum assisted stir casting set-up.

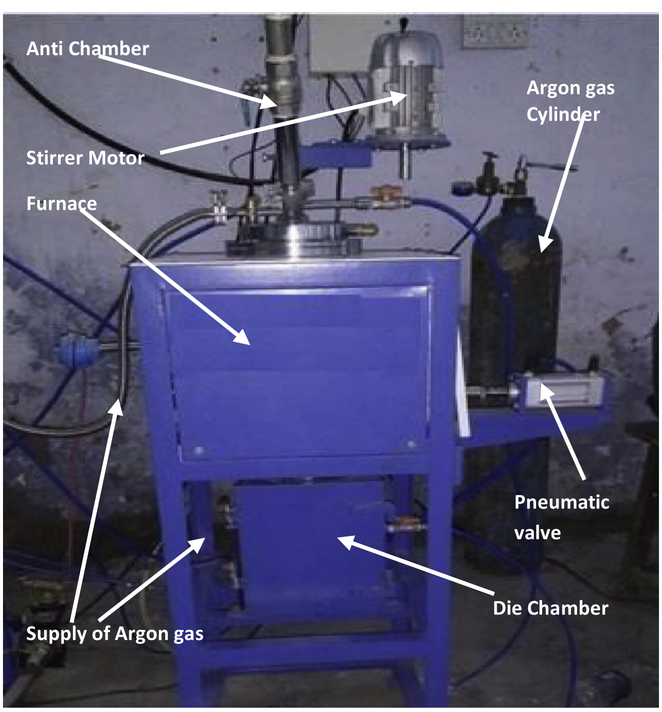

Fig. 7. Actual set-up vacuum assisted stir casting.

anti-chamber with double knob has been used for holding of reinforcement. After successful melting of materials, the reinforcement is released from anti-chamber and stirrer motor was also fixed in stirrer rod for stirring. The vacuum assisted stir casting set-up is shown in Fig. 7.

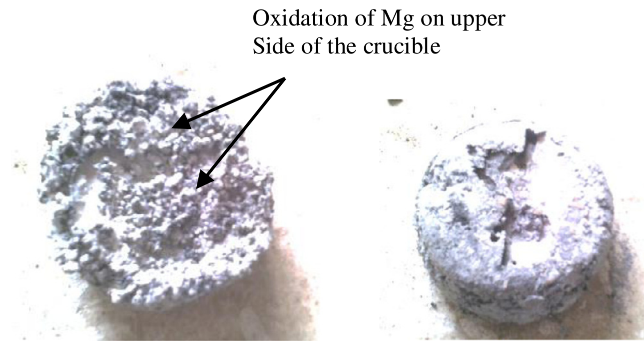

Fig. 8. Casted product of Mg using flux.

The stirrer speed is also controlled by varying current supply. The metallic crucible is protected by boron nitride paste to prevent reaction of aluminum with the metallic crucible. The sealing of furnace door and bottom was done by silicon washer. Chilled water is used to circulate in the head of the crucible to prevent damage of silicon washer. The die cavity is also sealed to avoid oxidation of magnesium in the die area. The die is made of cast iron in two parts for providing easy removal of the casted product. The stirrer motor can be placed at any position from 0° to 90°. This will facilitate the positioning and clamping of stirrer motor as per requiremnt. The casting of magnesium alloy based metal matrix composite has been successfully casted at IIT BHU, Varanasi and also at KNIT Sultanpur.

3.1. The casting of Mg alloy at IIT BHU Varanasi

The casting of magnesium alloy was performed at IIT BHU Varanasi by adding flux because there was no any vacuum or inert atmosphere available at the time of the casting. Due to highly oxidative nature of magnesium, and non availability of proper flux, about 15% of the magnesium has been oxidized into MgO and the remaining magnesium alloy was defect free and very hard in nature. The image of magnesium alloy casting at IIT BHU Varanasi is shown in Fig. 8.

3.2. The casting of Mg alloy and composite at KNIT Sultanpur

Die casting of magnesium alloy and magnesium alloy based metal matrix composite has been performed. The average size of SiC particles are 40 microns. The following steps are involved in the casting of Metal matrix composite.

Step 1. Cleaning of metallic (Inconel) crucible.
Step 2. Coating of the inner wall of the crucible with boron Nitride paste.
Step 3. Placement of Crucible and die at the proper place.
Step 4. Loading of Material (Mg alloy) in crucible and reinforcement in Anti Chamber.
Step 5. Creation of vacuum in a crucible, die, and Anti-chamber.
Step 6. The opening of Argon gas valve.

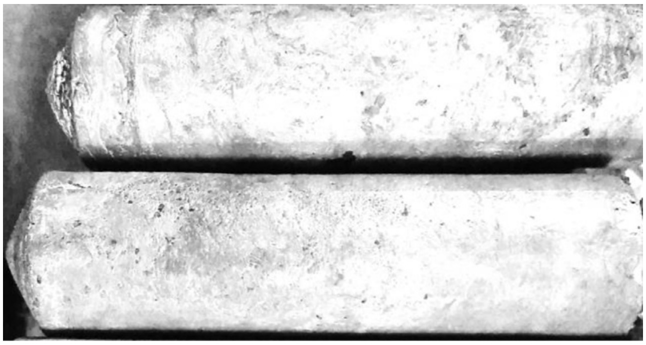

Fig. 9. Sample of the casted product.

Step 7. Repeat steps 5 and 6 three times for complete removal of oxygen.

Step 8. Close the pneumatic valve by the close switch and Switch on the furnace.

Step 9. Ensure metal melts fully, allow stirrer to rotate for 30 min.

Step 10. Turn on pouring by an open switch.

Step 11. Turn off furnace switch.

Step 12. After 5 min, close the Argon gas purging.

Step 13. After 30 min, open the die cavity and release die bolt and take the sample.

The sample, which is obtained by casting was solid cylindrical, defect-free and porosity free. The diameter of the circular sample is 39 mm and length is 200 mm. The snaps of the casted sample are shown in Fig. 9.

4. Results and discussions

4.1. Microstructure of composite

Microstructural study plays a very important role for estimating the quality of the liquid metal processing technique

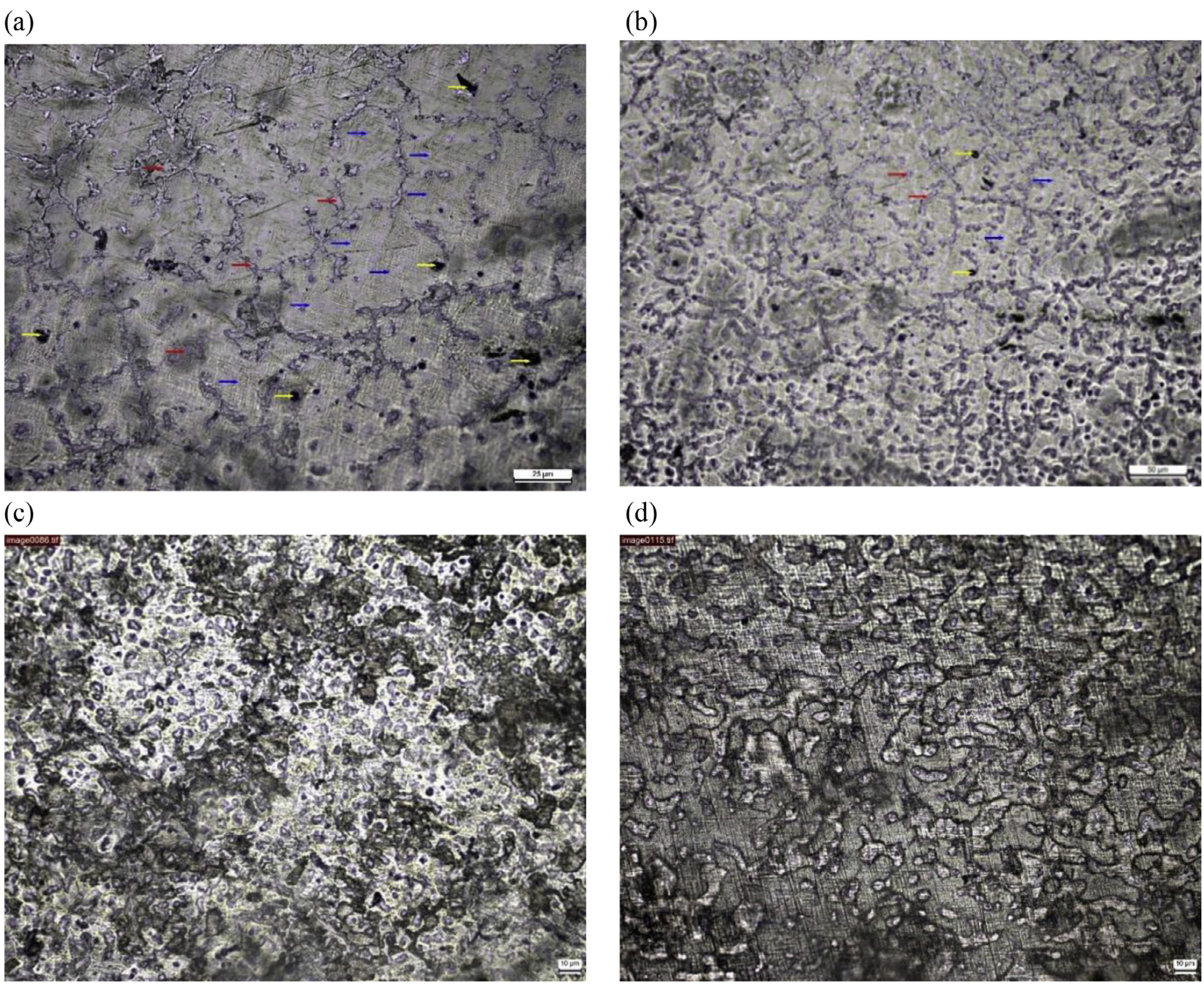

Fig. 10. Optical micrograph (a) 3% SiC in AZ91 (b) 6% SiC in AZ91 (c) 9% SiC in AZ91 (d) 12% SiC in AZ91 (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.).

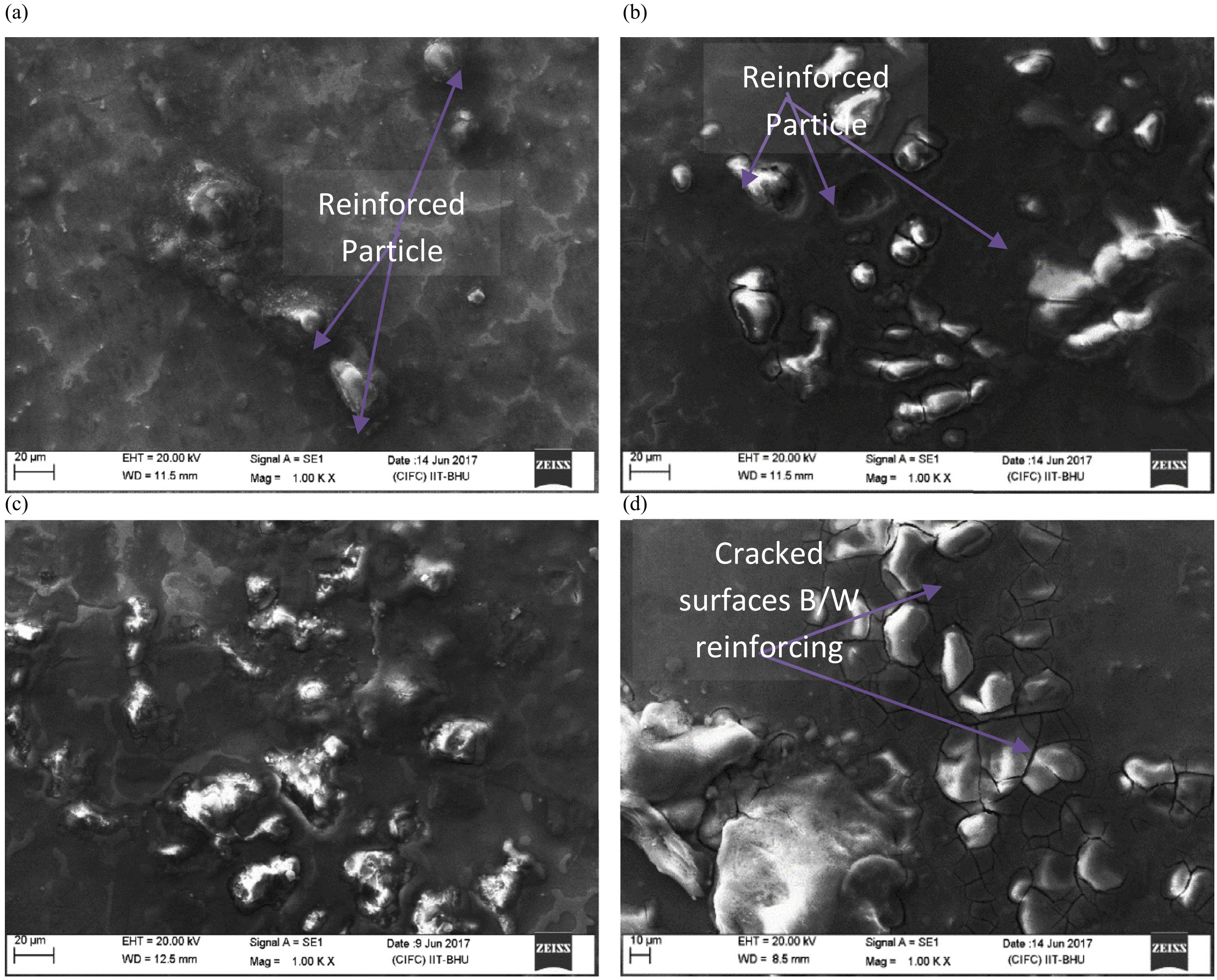

Fig. 11. Scanning electron micrograph (a) 3% SiC in AZ91(b) 6% SiC in AZ91(c) 9% SiC in AZ91 (d) 12% SiC in AZ91.

[27]. The optical, as well as scanning electron micrograph of the magnesium alloy (i.e. AZ91) composite reinforced with SiC particulate, has been obtained with help of ZEISS optical and ZEISS FE SEM. The distribution of particle within the composite was found as fairly uniform throughout the sample. As the percentage of reinforcing particle increases, the grain boundary refined and the SiC particle also entered in a hard secondary phase of the alloys. During the process of solidification of the composite, most of the particle were segregated in the intergranular regions of the other growing grains.

Fig. 10 shows the optical microstructure of AZ91/SiC composites, which contains 3%, 6%, 9% and 12% by volume of SiC as a reinforcement. The blue arrows represent the primary phase α, red arrows show the secondary phase β and yellow arrow show the porosity. Fig. 11 shows the SEM micrograph of SiC particle reinforced AZ91 magnesium alloy at different percentage of SiC (i.e. 3%, 6%, 9% and 12% by volume). The FE SEM micrograph shows the fairly uniform distribution of SiC particle in AZ91 metal matrix composite. The arrow marks clearly show the distribution of reinforced particle and micro-fractured surfaces at a higher resolution.

4.2. Ultimate tensile properties

The ultimate tensile strength of magnesium alloy (AZ91) was found to be 187.67 MPa, which is higher than SiC particulate reinforced composite. The UTS of the 3% composite was lower than UTS of the magnesium alloy as shown in Fig. 12 and the UTS increases as the percentage of reinforcement increases. However, UTS of 12% by volume SiC reinforced composite is higher than unreinforced alloy. The difference of UTS in AZ91/SiC composite is due to its processing technique, which is stir casting. For the as-cast AZ91 composite, UTS is usually lower than that of as-cast AZ91. Because of the addition of any secondary hard phase particle reduces tensile strength. Under the tensile load, strong internal stress lead to the formation of cracks in secondary phase and particle coated with secondary phase. Both SiC particle and secondary phases are very brittle, so the interface be-

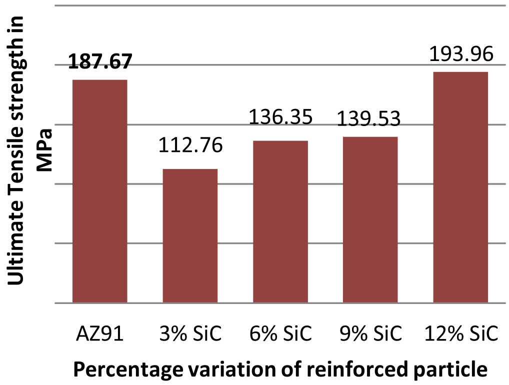

Fig. 12. Ultimate tensile strength with different percentage of SiC.

Table 1
The composition of magnesium as received from supplier.

1	2	3	4	5
Mg	Al	Si	Zn	Fe
99.600	0.129	0.073	0.045	0.032
6	7	8	9	10
Ag	Pb	Ca	Mn	Sn
0.031	0.018	0.017	0.014	0.010

Table 2
The composition of AZ91 magnesium alloy developed at KNIT Sultanpur.

1	2	3	4	5
Mg	Al	Zn	Mn	Si
88.467	10.240	1.017	0.089	0.086
6	7	8	9	10
Cu	Pb	Fe	Sn	P
0.026	0.020	0.020	0.017	0.007

tween SiC particle and large secondary phase cannot bear the large strain. However, as the volume fraction of SiC particle increases, the large secondary phases at SiC particle surfaces reduced significantly and the size of secondary phase was also refined. This leads to the increase in the strength and elongation as the volume fraction of SiC particle increases. The variation in UTS with variation in particle content are shown in Fig. 12. The highest value of UTS at 12% by volume of SiC particle.

4.3. Optical Emission Spectroscopy

The Optical Emission Spectroscopy (*OES*) analysis has been performed to know the quantitative *analysis* of the pure magnesium and magnesium alloy, which was developed at KNIT Sultanpur by adding the appropriate amount of alloying element. Tables 1 and 2 show the elemental composition up to 10 elements of the pure magnesium as received and magnesium alloy developed by stir casting set-up.

4.4. Fracture behavior

The fracture behaviors of the magnesium matrix are found as a combination of brittle and ductile like features in the cases of AZ91/SiC composites. The dimple size in the fractured surface decreases as the percentage of SiC increases.

Fractured surface morphology of the composite also reveals that small size dimple, cracks, shrinkage porosity and cleavage fracture increase with an increase in volume fraction of the reinforcement. Figs. 13–15 show the facto-graph of the AZ91, and Figs. 16–19 show the facto-graph of the SiC particle reinforced composite by stir casting routes. The cracks between surfaces are observed at a high magnification of the facto-graph image.

From Figs. 13–19, it can be concluded that on addition of SiC particulate, the materials seem to be slightly ductile in

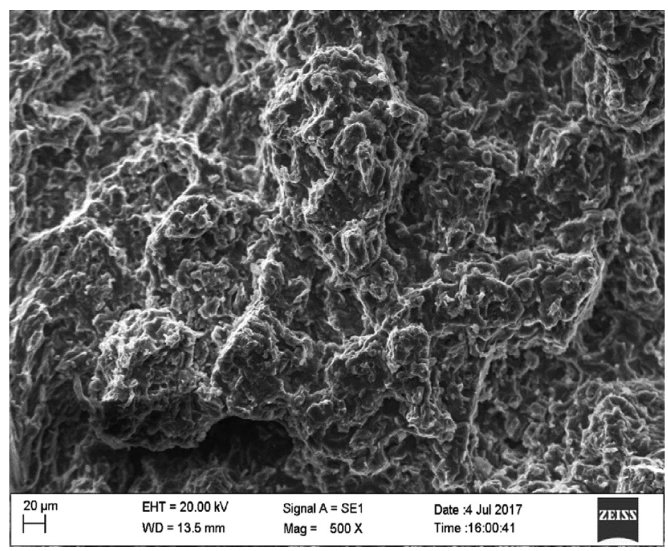

Fig. 13. Facto-graph of AZ91 at magnification 500×.

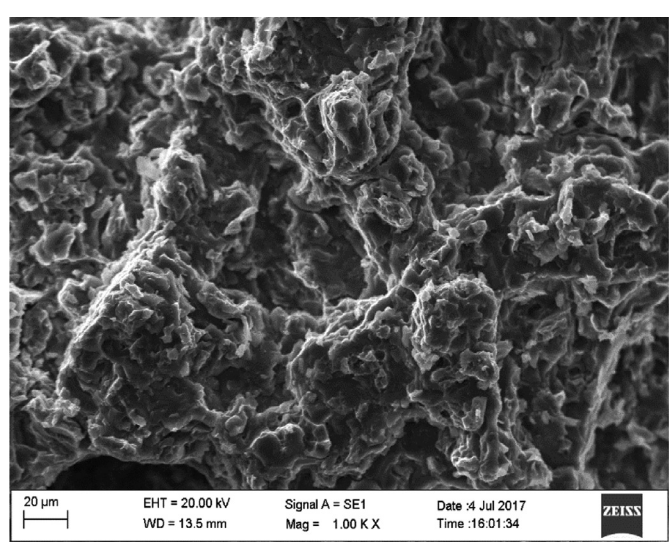

Fig. 14. Facto-graph of AZ91 at magnification 1000×.

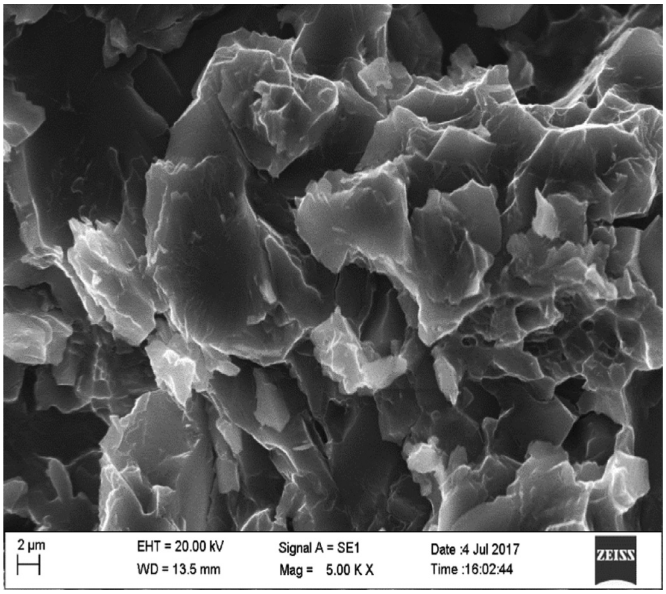

Fig. 15. Facto-graph of AZ91 at magnification 5000×.

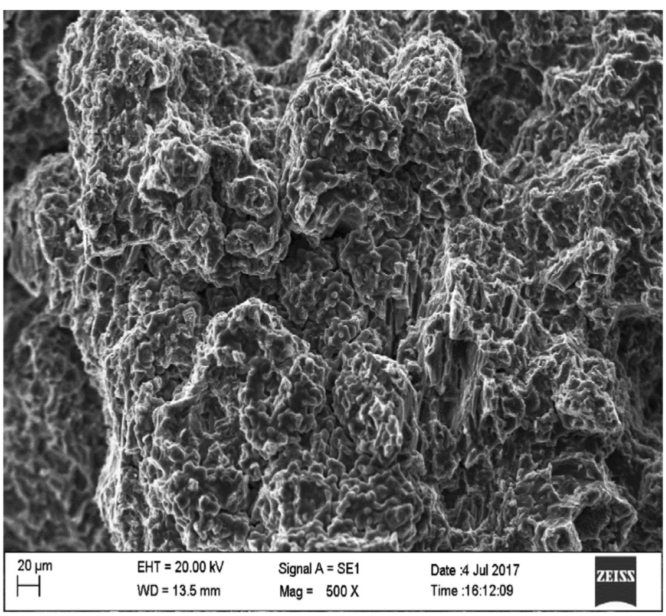

Fig. 16. Facto-graph of AZ91 at magnification 500×.

nature. The reinforced particles were also clearly seen from these Figs.

5. Conclusions

The following conclusion can be drawn from the fabrication and experimental experience of stir casting set-up developed at IIT BHU, Varanasi, and KNIT Sultanpur.

A. The casting of magnesium with composite is not suitable with addition of flux during casting.
B. The vacuum assisted stir casting is one of the most suitable process for magnesium and its composite.

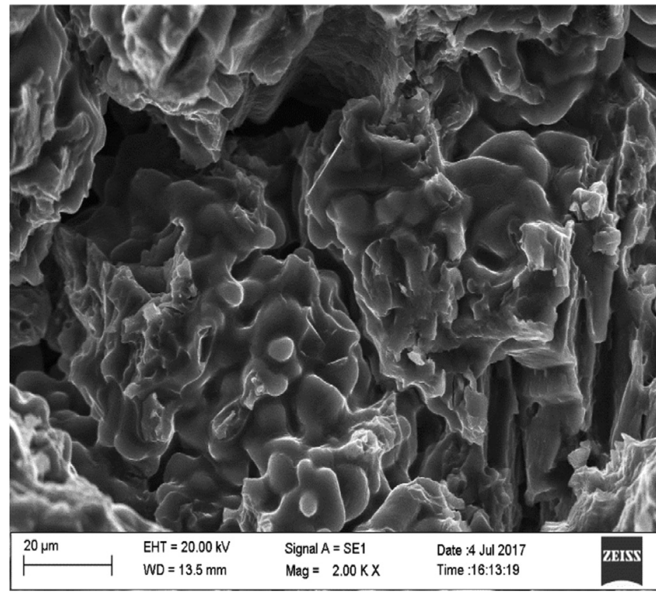

Fig. 17. Facto-graph of AZ91 at magnification 2000×.

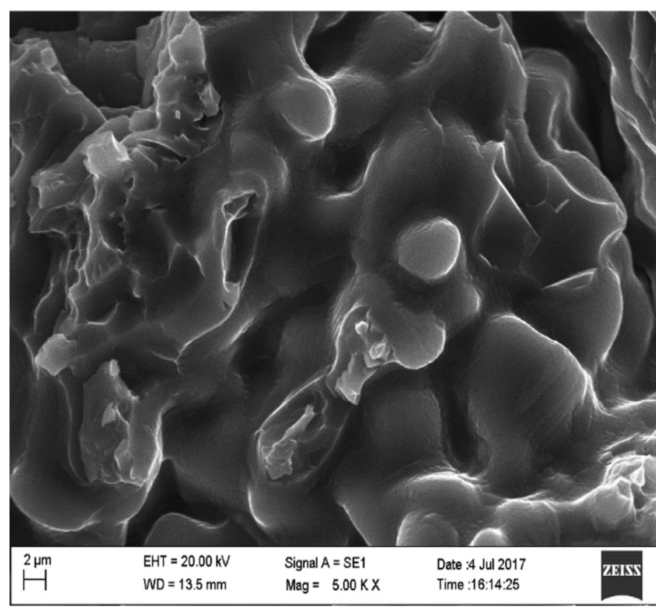

Fig. 18. Facto-graph of AZ91 at magnification 2000×.

C. The ductility of the all the composite (i.e. with varying the percentage of SiC in AZ91) is lower than the ductility of the magnesium alloy.
D. The casted product from stir casting set-up developed at KNIT Sultanpur was defect free and porosity free as well as the distribution of alloying elements and the reinforced particle was also uniform.
E. The ultimate tensile strength increases as the percentage of SiC particle reinforcement increases in AZ91 magnesium alloy.

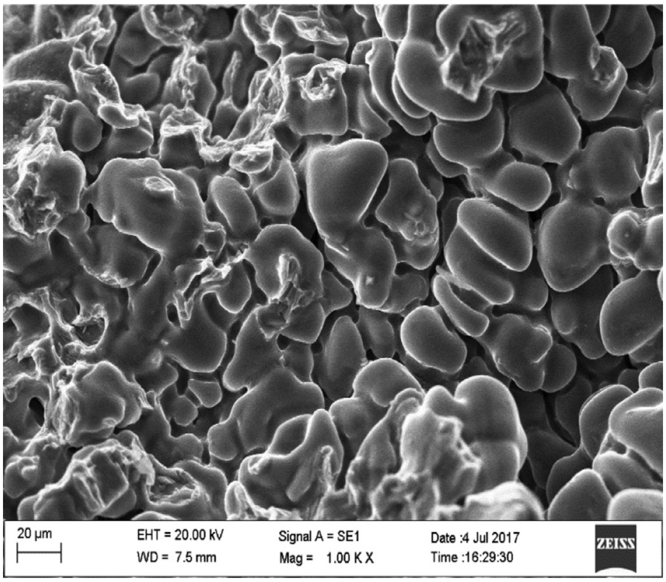

Fig. 19. Facto-graph of AZ91 at magnification 2000×.

Acknowledgment

This work is sponsored by WB TEQIP-II funds received at KNIT Sultanpur UP, India.

References

[1] A.A. Luo, K. Sadayappan, Technology for Magnesium Castings, American Foundry Society, Schaumburg, IL, 2011, pp. 29–47.

[2] M.M. Avedesian, H. Baker, Magnesium and Magnesium Alloys, ASM International, Materials Park, OH, 1999.

[3] A.A. Luo, Magnesium casting technology for structural applications, J. Magnes. Alloys 1 (2013) 2–22.

[4] Palash Poddar, V.C. Srivastava, P.K. De, K.L. Sahoo, Processing and mechanical properties of SiC reinforced cast magnesium matrix composites by stir casting process, Mater. Sci. Eng. A 460–461 (2007) 357–364.

[5] J.W. Freuling, J.D. Hanawalt, Transactions of the American Foundrymen's Society 77 (1969) 159–164.

[6] J.W. Freuling, Protective Atmospheres for Molten Magnesium. Ph.D. Dissertation, University of Michigan, Ann Arbor, MI, USA, 1970.

[7] J.F. King, Environmental challenges facing the magnesium industry-SF6 replacement, in: *Proceedings of the Sixtieth Annual World Magnesium Conference, the International Magnesium Association*, Wauconda, IL, USA, 10–16.

[8] A.S. Gnedenkov, S.L. Sinebryukhov, D.V Mashtalyar, S.V. Gnedenkov, Localized corrosion of the Mg alloys with inhibitor containing coatings: SVET and SIET studies, Corros. Sci. (2016).

[9] A.I. Taub, P.E. Krajewski, A.A. Luo, J.N. Owens, J. Metals 59 (2) (2007) 48–57.

[10] A.A. Luo, Applications: aerospace, automotive and other structural applications of magnesium, Fundamentals of Magnesium Alloy Metallurgy, Woodhead Publishing Ltd, Cambridge, UK, 2012, pp. 393–426. Chapter 8.

[11] K.U. Kainer, Magnesium-Alloys and Technologies, Wiley-VCH, Weinheim, Germany, 2003.

[12] A.A. Luo, J. Metals 54 (2) (2002) 42–48.

[13] H.-H. Becker, Status, potential & challenges for automotive *magnesium applications from the point of view of an OEM*, in: Proceedings of the Sixty-fifth Annual World Magnesium Conference, May 18–20, Warsaw, Poland, 2008.

[14] Y. Michiura, Current magnesium research & application in automotive industry in Japan, in: *Proceedings of the International Automotive Body Congress*, November 7–8, Troy, MI, USA.

[15] J.S. Balzer, P.K. Dellock, M.H. Maj, G.S. Cole, D. Reed, T. Davis, T. Lawson, G. Simonds, Structural magnesium front end support. *SAE Technical Paper* 2003-01-0185, SAE International, Warrendale, PA, 2003.

[16] M. Hoeschl, W. Wagener, J. Wolf, BMW's magnesium– aluminium composite crankcase, state-of-the-art light metal casting and manufacturing. *SAE Technical Paper* 2006-01-0069, SAE International, Warrendale, PA, 2006.

[17] A. Kumar, S. Kumar, N.K. Mukhopadhyay, Int. J. Appl. Engg. Research 12 (2017) 16087–16093.

[18] G.D. Wardlow, A changing world with different rules new opportunities for magnesium alloys, in: Proceedings of the Sixty-fourth Annual World Magnesium Conference, May 13–15th, Vancouver, BC, Canada, 2007.

[19] R.E. Brown, Future of magnesium developments in twenty-first century, in: Proceedings of the Materials Science & Technology Conference, October 5–9, Pittsburgh, PA, USA, 2008.

[20] J. Hillis, The effects of heavy metal contamination on magnesium corrosion performance. *SAE Technical Paper No. 830523*, in: *Proceedings of* SAE International, Warrendale, PA, USA, 1983.

[21] R.E. Brown, E. Lee, Magnesium usage grew rapidly in 1930–1950, in: W.J. Poole, K.U. Kainer (Eds.), Proceedings of Ninth International Conference on Magnesium Alloys and Their Applications, July 8–12, Vancouver, BC, Canada, 2012, pp. 453–460.

[22] B.R. Powell, P.E. Krajewski, A.A. Luo, Magnesium alloys, in: Materials Design and Manufacturing for Lightweight Vehicles, Woodhead Publishing Ltd, Cambridge, UK, 2010, pp. 114–168. Chapter 4.

[23] S. Schumann, H. Friedrich, The use of magnesium in cars-today and in the future, in: B. Mordike, K. Kainer (Eds.), Magnesium Alloys and Their Applications, Werkstoff-Informations, Gesellschaft, Frankfurt, Germany, 1998, pp. 3–13.

[24] D.J. Lloyd, Particle reinforced aluminium and magnesium matrix composites, Int. Mater. Rev. 39 (1) (1994) 1–23.

[25] M.M. Avedesian, H. Baker (Eds.), ASM Specialty Handbook—Magnesium and Magnesium Alloys, ASM International, Materials Park, OH, 1999.

[26] N. Chawla, K.K. Chawla, Metal Matrix Composites, Springer, New York, 2006.

[27] A. Yadav, A. Ghosh, A. Kumar, J. Mater. Process. Technol. 248 (2017) 262–274.

[28] J. Hashim, L. Looney, M.S.J. Hashmi, J. Mater. Process. Technol. 92–93 (1999) 1–7.