The Role of Wettability in Liquid-Assisted Processing of Ceramic-Reinforced Iron-Based Metal Matrix Composites

Ł. Szymański[1,2*], J. Sobczak[1], N. Sobczak[3], K. Peddeti[4], E. Olejnik[1,5], A. Bigos[3], K. Żak[1], S. Sobula[1], K. Biegun[5], B. Karakkunnummal[6]
1. Faculty of Foundry Engineering, AGH University of Krakow, 23 Reymonta St., 30-059 Krakow, Poland
2. FLSmidth Mining Technology GmbH, 12 Schleebergstrasse, 59320 Ennigerloh, Germany
3. Institute of Metallurgy and Materials Science, Polish Academy of Sciences, 25 Reymonta St., 30-059 Krakow, Poland
4. FLSmidth Inc., 1100 American Parkway, Allentown, PA, 18109, USA
5. Innerco sp. z o.o., 17 Władysława Siwka St., 31-588 Krakow, Poland
6. FLSmidth Private Limited, 34 Egatoor, Kalembakkam, Old Mahabalipuram Road, 603103 Chennai, Tamil Nadu, India
*Corresponding address: e-mail: lukaszszymanski14@gmail.com

Abstract： The high-temperature wettability tests were conducted for various types of ceramics commonly used as reinforcements in fabrication of metal matrix composites (MMCs) by liquid-assisted processes. Significant differences during wettability tests in the course of kinetic curves were identified with regards to ex-situ and in-situ techniques used in manufacturing process of MMCs. Two different types of MMC castings were manufactured, i.e. reinforced by TiC particles (in-situ) and preforms made from oxide ceramics (ex-situ). Compared to monolithic alloys, the presence of the ceramic phases (TiC, Al2O3, ZrO2) in the both cases significantly improved its hardness (at least two-fold increase) and wear resistance (weight loss decrease at the level from 30 to 300%).

Keywords: MMC, wettability, ceramic, wear resistance

1 Introduction

Literature data indicate that the wear resistance of commercial monolithic iron alloys can be significantly increased by introducing hard ceramic particles into the metal matrix [1]. The most common ceramic reinforcements for iron alloys are oxides and carbides, including Al_2O_3, ZrO_2, B_4C, WC, and TiC [2]. Independently on manufacturing process of metal matrix composites (MMCs), their utility properties are conditioned by obtaining the relevant bonding at the reinforcing phase/matrix interface. For liquid-assisted processes, the wettability between a molten metal matrix and a reinforcement is a key factor affecting interface structure and properties that are responsible for high quality and reliability of final MMC products [3,4]. This work aims at experimental study of wetting behavior of molten cast iron in contact with different ceramic reinforcements followed by the trials to manufacture castings made from either cast steel or cast iron, both locally reinforced with TiC particles and oxide preforms.

2 Experimental procedure

In this study, a sessile drop method combined with non-contact heating of an alloy/substrate couple to the test temperature was adopted for the real-time observation of wetting and infiltration phenomena taking place between molten cast iron and (Ti + C_{gr}) substrate. The detailed experimental procedure has been presented in the previous work of authors [4]. On the contrary, wettability of ceramic oxides by molten high chromium cast iron was investigated by contact heating procedure.

For the *in-situ* production of TiC/Fe composite layers on the surface of castings an aqueous solution with the addition of TiC-forming (Ti + C_{gr}) mixture was used. Next, it was deposited in the cavities of the sand molds as a reactive coating in a contact with molten cast steel or cast iron. Because after pouring, the high temperature of molten alloy initiated the synthesis reaction of TiC.

The second type of composite castings, reinforced by ceramic preforms of a porous spatial structure made from ZrO_2 and Al_2O_3 powders, were produced by pressure-less infiltration. The manufactured composite castings were subjected to microstructure characterization (LM, SEM/EDS) as well as measurements of hardness (Vickers test) and wear resistance (ball on disc test, Miller test and cavitation erosion in slurry).

3 Result and discussion

High-temperature wettability test

The wetting kinetic curve for molten cast iron on reactive (Ti + C_{gr}) substrate is shown in Fig. 1a. The course of the wetting process can be divided into four stages. Stage I corresponds to non-wetting behavior with the contact angle values of $\theta > 90^o$. A threshold value of $\theta = 90^o$ is reached in only 1.5 s and subsequent continuous decrease in the contact angle value up to 72^o (Stage II – wetting) and 18^o (Stage III – good wetting). In the last stage (Stage IV), θ approached zero as a result of the complete wetting and infiltration of the molten alloy into the substrate. Such behavior is characteristic of spontaneous reactive wetting in the systems with the very fast kinetics of the synthesis reaction. Fig. 1b shows the top-view image of substrate surface after the wettability test. The presence of the three zones could be observed: Zone I (complete infiltration area), Zone II (partial infiltration area), and Zone III (limited infiltration area). In contrast, oxide ceramics showed with the same alloy non-wetting behavior and a lack of permanent bonding between them (the drops broke away from substrates after cooling process).

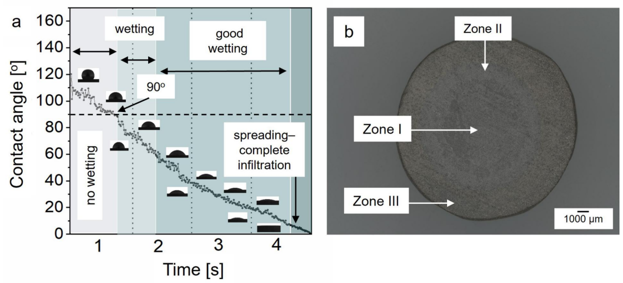

Fig. 1. a) wetting kinetics recorded in the sessile drop test of molten cast iron on (Ti + Cgr) substrate; b) LM micrograph showing the top-view of the substrate after its interaction with molten cast iron drop

Manufacturing process of composite castings

The microstructure of the TiC/Fe-type composite layer *in-situ* formed in locally reinforced cast steel casting is shown in Fig. 2a. The SEM/EDS analysis indicated its non-uniform structure and thickness varying from 1.0 to 2.0 mm. The maximum hardness values within this layer were above 1000HV1 which is more than a double increase as compared to the monolithic alloy. Similar to the sessile drop sample of the same system, the transition area was formed between the TiC-reinforced layer and the base alloy showing a lack of discontinuities and a good bonding between them related to the phenomenon of the reactive infiltration of the casting coating by liquid metal and high exothermic reaction synthesis of TiC carbide. Wear resistance tests showed significant decrease in the weight loss of composite samples ranged from 2 to 3.5 times as compared to the reference samples. On the contrary, the Fe-based MMCs reinforced with TiC exhibited lower resistance to cavitation erosion than monolithic materials.

The illustrative microstructure of composite zone reinforced by a ceramic preform is presented in Fig. 2b. The observations evidenced that the open porosity of preforms was fully infiltrated by molten Fe-based alloys while the occasional occurrence of discontinuities was related to the closed porosity formed in the preforms themselves during their fabrication. The chemical analysis (EDS) of the composite produced with high-Cr alloys and the ZrO_2 reinforcement showed the presence of complex Cr-rich oxide within the ceramic/matrix transition area. These results point to the positive role of Cr, which promoted a physicochemical interaction between the matrix and the reinforcement despite the lack of wetting found in the sessile drop tests. The hardness measurements indicated that the presence of the ceramic phase caused a two-fold increase in the hardness and around a 250 HV0.1 more increase for the cast steel and high chromium cast iron respectively, while their wear resistance was increased up to 20%.

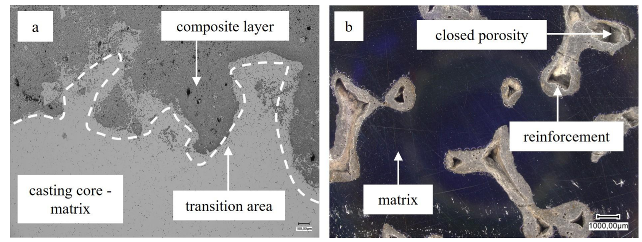

Fig. 2. a) SEM image of composite layer of steel casting *in situ* reinforced by TiC; b) LM image showing the microstructure of composite zone reinforced by ceramic preform

4 Conclusion

The mechanism of *in-situ* synthesis of TiC in ferrous alloys was explained based on high-temperature wettability test. Two types of composite castings were produced by *in-situ* and *ex-situ* methods. The use of reactive coatings is an effective method for *in situ* production of composite layers reinforced with TiC particles on the surface of ferrous castings while introduction of porous ceramic preforms allowed to produce MMC zones in Fe-based castings. The usage of ceramic preforms as well as TiC particles significantly increased the hardness and wear resistance, as compared to monolithic cast steel, and cast iron.

5 Acknowledgments

Scientific work financed by The National Centre for Research and Development of Poland within Project No. LIDER/49/0200/L-11/19/NCBR/2020.

References

[1] Luo ZC, Ning JP, Wang J, et al. Microstructure and wear properties of TiC-strengthened high-manganese steel matrix composites fabricated by hypereutectic solidification[J]. Wear, 2019, (202970): 432-433.

[2] Szymanski L, Sobczak J, Peddeti K, et al. Production of metal matrix composites reinforced by TiC by reactive infiltration of cast iron into Ti + C preforms[J]. Ceram. Int. 2024 (50): 17452-17464.

[3] Chao L, Jun W Y, Ke Q, et al. The research status of the wetting of metal/ceramic in the high temperature self-lubricating materials[J]. Int. J. Mater. Sci. Appl., 2016, 5(2): 108-112.

[4] Sobczak N, Singh M, Ashtana R. High-temperature wettability measurements in metal/ceramic system – some methodologies issues[J]. Curr. Opin. Solid. State Mater. Sci., 2005 (9): 241-253.