Journal of the Korean Crystal Growth and Crystal Technology
Vol. 24, No. 4 (2014) 158-163
http://dx.doi.org/10.6111/JKCGCT.2014.24.4.158

p-ISSN 1225-1429
e-ISSN 2234-5078

Fabrication of mineral fiber via melt spinning method from blast furnace slag

Xiao-Song Wang*,** and Bo-Young Hur*,†

*Engineering Research Institute, Division of Nano and Advanced Materials Engineering, Gyeongsang National University, Jinju 660-701, Korea

**Program for the Training of Graduate Students in Regional Innovation, Division of Nano and Advanced Materials Engineering, Gyeongsang National University, Jinju 660-701, Korea

(Received July 15, 2014)
(Revised July 28, 2014)
(Accepted August 1, 2014)

Abstract Mineral fiber, or be called mineral wool when it assembles in large amounts, is a kind of wide applied man-made material with excellent thermal and acoustic insulation properties. In this work, mineral fiber was produced via melt spinning method by using iron blast furnace slag as raw material. Two critical experimental parameters for fabrication were investigated: melt pouring temperature and rotating speed of spinning wheels. The mineral fiber produced under the condition of melt pouring temperature 1500°C and spinning speed 4000 rpm, showed the smoother surface and most quality, while the others had rough surfaces or with heavy shots. In general, mineral fibers with the size in the range of 12~49 μm in diameter and 8~130 mm in length can be fabricated by this method, and the production rate is more than 34 wt.%, which could be up to 57 wt.% at maximum.

Key words Blast furnace slag, Slag recycling, Melt spinning, Mineral fiber, Rapid solidification

1. Introduction

Mineral wool is a general name for various inorganic insulation materials and composited of fibers. It is usually divided into different subgroups according to the raw material from which they are made: glass wool, rock wool, and slag wool. Glass wool is made from practically the same materials as those used to manufacture other glass products, in which the principal materials are silica sand, lime and soda ash. Rock wool is made out of natural rock, such as siliceous limestone or calcareous shale. Slag wool is usually made from blast furnace slag with or without the addition of natural rock, like limestone to temper the charge [1, 2]. Mineral wool is widely used in various fields, especially building construction, owing to its offering of environmental friendly characteristics and excellent performances, such as outstanding thermal insulation, remarkable fire resistance, excellent sound absorption, and mold, fungi and bacteria resistance [3, 4].

There were several fabrication methods for mineral fiber, like in-rotating water spinning method, Taylor method, melt extraction method, and melt spinning method, with a wide variation of quality and quantity of the final products [5-8]. Among various fabrication techniques, melt spinning was the commonly applied one. In this technique, mineral fiber is usually produced from slag or solid rock that is heated up to a molten state at a temperature of 1300°C to 1650°C in a cupola or heating furnace. After fully melting and becoming a highly viscous fluid, a melt jet of molten slag or rock is ejected from a nozzle and impinges onto a fiberization device, usually a group of spinning rotating wheels revolving at high speed. As the melt is discharged from the melt spinning rotating wheels, thin layers are formed from the melt droplet, finally rapidly solidify and develop into fibers as continuous thin woolly strands. In general, a single fiber is some dozens of microns in diameter and a few tens of centimeters in length. Theoretically, a long fiber with small diameter seems most desirable. The smaller the fiber, the greater will be the percentage of dead air space for insulation. The longer the fiber, the better will the wool hold together and retain its shape when put in place.

During fabrication process, some melt may not be drawn out into fiber after rapid solidification, what forms the so-called "shot" which occurs in mineral wool as globular beads of glassy texture. The shot particles vary in size from several microns dimension up to diameters

†Corresponding author
Tel: +82-55-772-1661
Fax: +82-55-753-2270
E-mail: hurby@gnu.ac.kr

of one-third of a centimeter, and their presence in mineral wool reduces its value for insulation purposes. Since the shot is inevitable, one aim of this study is to minimize its quantity and size by optimizing two critical experimental parameters, melt pouring temperature and spinning speed of rotating wheels, and then to find the fabrication condition for mineral fiber with the best quality.

2. Experimental Material and Procedure

Iron blast furnace slag coming from POSCO was used as raw material. The as received slag was rapidly quenched by water cooling and crushed by a mill to granulate slag size less than 1 cm. Chemical composition of blast furnace slag varies with the iron ore and process of iron production, but commonly includes: CaO, SiO_2, Al_2O_3, MgO, iron (FeO or Fe_2O_3), MnO, S, and so forth. The concentration of slag constituents was presented in Table 1, including the typical slag [9] and the as received slag. Fig. 1 showed the digital camera photograph and SEM image with EDS result of the blast furnace slag.

Schematic diagram of fabrication apparatus is illustrated in Fig. 2. A graphite crucible with SiC coating was used as slag container. There was a nozzle in the crucible bottom center, occupying by a graphite stopper

Table 1
Chemical composition of typical and the as received blast furnace slag

Constituent	Typical		As received	
	Average	Range	Average	Range
CaO	39	34-43	43	42-44
SiO_2	36	27-38	35	34-36
Al_2O_3	10	7-12	14	14-16
MgO	12	7-15	5	3-5
FeO or Fe_2O_3	0.5	0.2-1.6	0.3	0.2-0.4
MnO	0.44	0.15-0.76	<1	<1
S	1.4	1.0-1.9	<1	<1
TiO_2	——	——	0.6	0.5-0.7
P_2O_5	——	——	<1	<1
$K_2O + Na_2O$	——	——	~0.8	~0.8

Unit: wt.%

until melt pouring. The crucible filling with slag was heated in a super Kanthal furnace, using argon as protection gas. The heating rate of the furnace was 15°C/min. A thermo-couple was installed to measure inside the furnace temperature.

In melt spinning system, four unified stainless steel spinning wheels with 200 mm diameter was adjusted at designed positions, where could let the slag melt flow in a suitable track to form better fiber [7]. The rotating wheels speed could be controlled in the range of 3000~5000 rpm, or circumferential speed varied in the range of 31.42~52.36 m/s by changing the voltage on motor

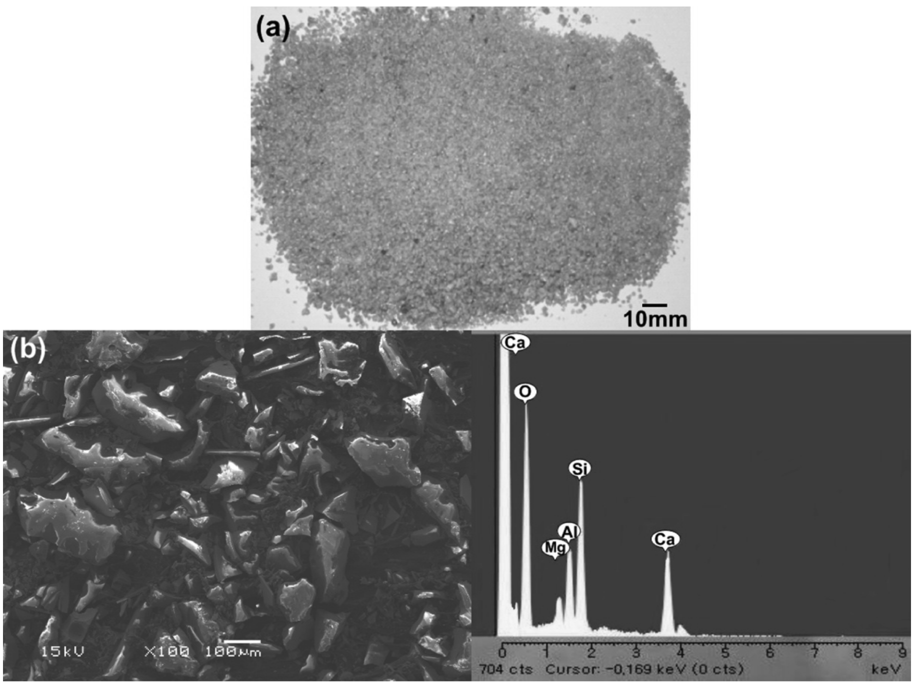

Fig. 1. Digital camera photograph (a) and SEM image with EDS result (b) of as received blast furnace slag.

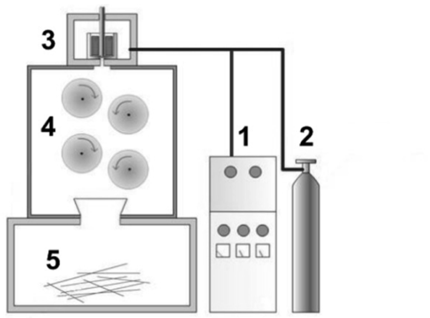

Fig. 2. Schematic diagram of mineral fiber fabrication apparatus.

power supply. The volumetric melt flow was 4.98~7.96 cm^3/s, depending on different viscosity of molten slag. For safety reason, the four spinning wheels were encircled by a stainless steel protection shield, which can prevent the melt droplet escaping from the system. In the bottom of the system, there was a collection chamber, across where airflow was blown to transport mineral fibers onto a perforated mesh.

The slag began to melt when the temperatures exceeds 1300°C, and with the higher the temperature inside the furnace, the lower the slag melt's viscosity (Fig. 3, [10]). In this study, the melt pouring temperatures were changed from 1300°C to 1550°C. Holding the melt for 5 minutes at desired pouring temperature, then pulling up the stopper, so as to let the melt flow down as a jet, and fall onto melt spinning wheels revolving at high speed. The melt was elongated to long fibers, which could be collected mechanically and layered.

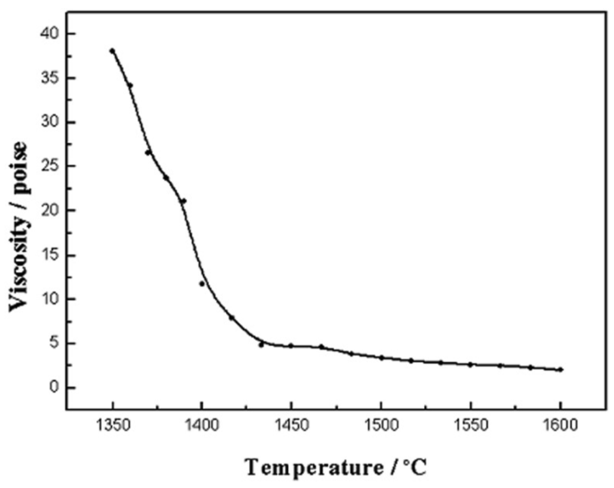

Fig. 3. Viscosity of blast furnace slag melts, adopted from [10].

The microstructure and chemical composition of the mineral fibers were observed and analyzed with Optical metallurgical Microscope (OM, Nikon Epiphot), Scanning Electron Microscope (SEM, Jeol JSM-5600) with X-ray Energy Dispersive Spectroscopy (EDS, Oxford Inca Energy 200), respectively. Diameters of fiber samples were measured by the OM attached to computer using digital imaging processing software (i-solution, iMTechnology), and lengths were examined by a vernier caliper.

3. Results and Discussion

Mineral fiber assembling on the perforated mesh from collection chamber was shown in Fig. 4. The diameter was in the range of 12~49 μm and the length was in the range of 8~130 mm. Over 60 wt.% of the fiber has the diameter between 15 μm and 35 μm, and the length from 20 mm to 60 mm. Density of the fiber is 2.6 g/cm^3, measured by Archimedes principle.

Besides the main product, non-fibrous shot also appeared and interlaced with mineral fiber. Some shot was formed due to the melt droplet solidify before being drawn out into fiber, and some originated from the melt droplet escaped from the cross airflow, and then accumulated and solidified together. As mentioned above, it was unavoidable byproduct in fiber fabrication, totally 43~66 wt.% in the result under various fabrication conditions. Among which, the mineral fiber produced at melt pouring temperature 1500°C achieved the highest average production rate of 46 wt.%, and up to 57 wt.% at

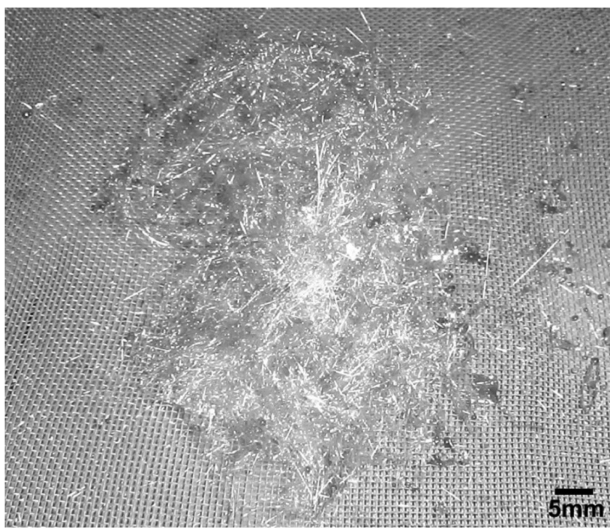

Fig. 4. Mineral fiber on the perforated mesh from collection chamber.

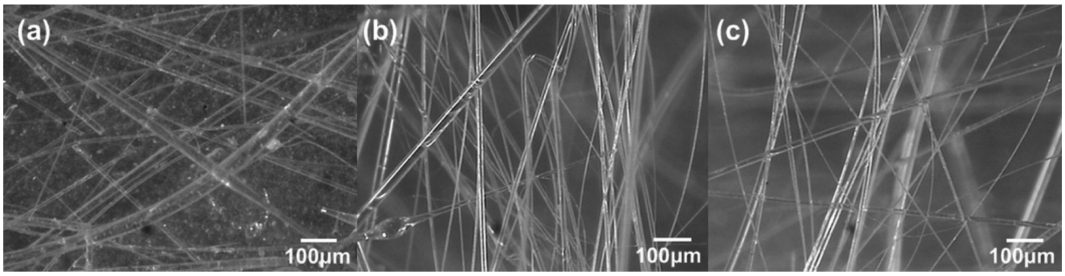

Fig. 5. Optical microstructure of mineral fibers produced at melt pouring temperature 1400°C with different melt spinning speed: (a) 3500 rpm, (b) 4000 rpm and (c) 4500 rpm; × 100.

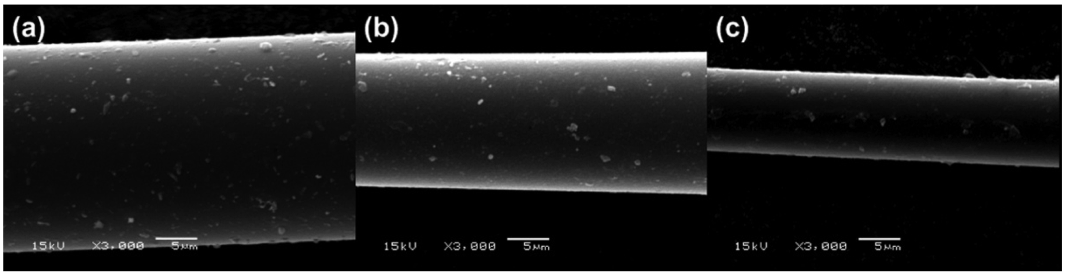

Fig. 6. SEM images of a single mineral fiber produced at melt pouring temperature 1400°C with different melt spinning speed: (a) 3500 rpm, (b) 4000 rpm and (c) 4500 rpm; × 3000.

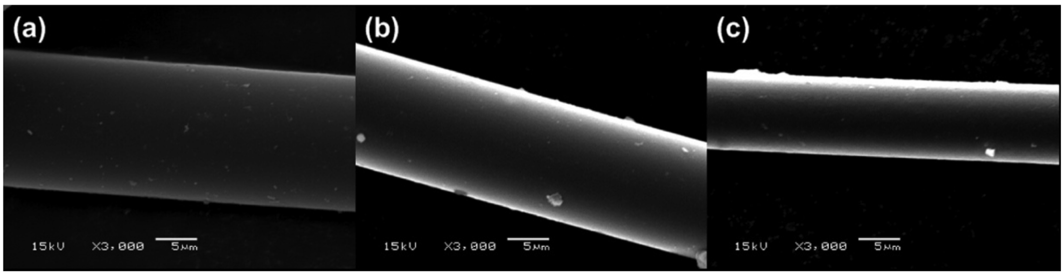

Fig. 7. SEM images of a single mineral fiber produced at melt spinning speed 4000 rpm with different melt pouring temperature: (a) 1450°C, (b) 1500°C and (c) 1550°C; × 3000.

maximum.

Fig. 5 showed the optical microstructure of mineral fibers produced at melt pouring temperature 1400°C with different melt spinning speed of (a) 3500 rpm, (b) 4000 rpm and (c) 4500 rpm. As well as the SEM microscopic views of a single fiber under the same fabrication condition were shown in Fig. 6. It can be seen from the two figures that the fiber diameter decreases with increasing melt spinning speed. From the SEM images, some rough particles on the fibers' surface can be clearly observed, and the fiber produced at melt spinning speed 4000 rpm had a smoother surface. The reason for particles exist on fiber's surface probably was due to the difference of cooling rate in forming process of mineral fiber, which is determined by melt spinning speed. According to previous research, in the case of low melt spinning speed, the cooling rate of mineral fiber was much less than that at high speed [11] and this would result in different forming speed of thin film layers on mineral fiber surface, then made particles appear in some positions after rapid solidification.

Fig. 7 showed the SEM microscopic view of a single mineral fiber produced at melt spinning speed 4000 rpm with different melt pouring temperature of (a) 1450°C, (b) 1500°C and (c) 1550°C. It was apparent that at constant melt spinning speed, the lower melt pouring temperature promoted a thicker fiber, owing to its relatively higher viscosity. According to Poiseuille's law, the flow velocity of fluid is inversely proportional to its viscosity. This could be confirmed by experimentally measured viscosity of blast furnace slag melt in Fig. 3. The viscosity value of molten slag at 1400°C, 11.8 poise was about three times larger than that value at 1450°C, and 1500°C. This resulted in that at low melt pouring tem-

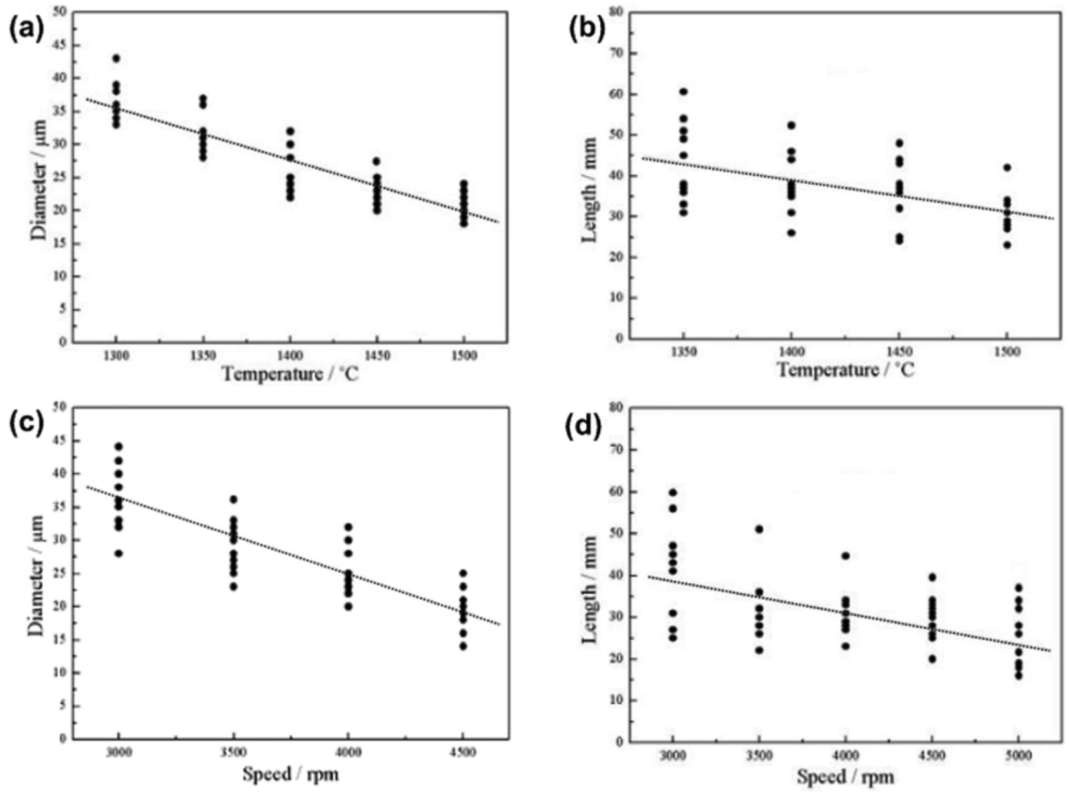

Fig. 8. The effects of fabrication parameters on diameter and length of mineral fiber. (a) and (b): Melt pouring temperature on the fiber produced at melt spinning speed 4000 rpm. (c) and (d): Melt spinning speed on the fiber produced at melt pouring temperature 1500°C.

perature, the melt was easy to form larger aggregates, and most likely transformed into thicker fibers and globular shots as stable form. When the slag melt pouring temperature was over 1500°C, the effect of viscosity became trivial because of the nearly same viscosity values.

The optimum condition for mineral fiber fabrication in our experimental result was obtained: melt spinning wheels' rotating speed 4000 rpm and melt pouring temperature 1500°C. After measuring diameters and lengths of the mineral fibers produced at various fabrication conditions, it was easy to understand the effect of melt pouring temperature on mineral fiber: the diameter and length reduce with rising melt pouring temperature from 1300°C to 1550°C. The effects of melt pouring temperature on fiber diameter and length at melt spinning speed 4000 rpm were shown in Fig. 8a and 8b, respectively. In another aspect, the similar manner was also discovered to reveal the influence of melt spinning speed on mineral

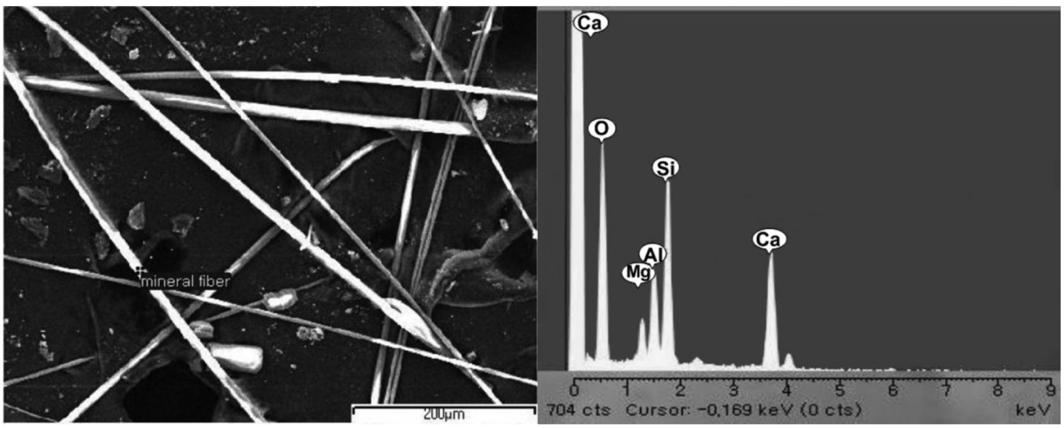

Fig. 9. SEM image with EDS result of typical mineral fiber produced at melt spinning speed 4000 rpm and melt pouring temperature 1500°C.

fiber: increasing melt spinning speed leads to decrease of diameter or length in the range from 3000 to 5000 rpm. The relationships between melt spinning speed and fiber diameter and length at melt pouring temperature 1500^{o}C were illustrated in Fig. 8c and 8d, severally. The result was in agreement with previously published data regarding the diameter variation tendency [11].

SEM image with EDS spectrum of typical mineral fiber produced at melt spinning speed 4000 rpm and melt pouring temperature 1500^{o}C was shown in Fig. 9. After comparing the EDS spectra of Fig. 1b and Fig. 9, there was no obvious difference between the slag and the fiber in elemental composition, indicating that the mineral fiber was quite stable at the current condition of elevated temperature production.

4. Conclusions

Fabrication of mineral fiber using iron blast furnace slag by melt spinning method was investigated. Based on the final products with different fabrication parameters, the following conclusions could be drawn from present work:

1) For the fabrication under present condition, the optimum fabrication parameter of melt spinning speed and melt pouring temperature were 4000 rpm and 1500^{o}C. The mineral fiber produced under such condition showed a smoother surface and highest production rate, 46 wt.% on average, and up to 57 wt.% at maximum; while the others had some rough surface or with heavy shot.

2) The fiber diameter and length decrease with increasing melt pouring temperature and melt spinning speed.

3) There was no obvious difference between the as received slag and the mineral fiber in chemical elemental composition.

Acknowledgements

This research was supported by the Program for the Training of Graduate Students in Regional Innovation, which was conducted by the Ministry of Commerce Industry and Energy of the Korean Government, and Engineering Research Institute, Gyeongsang National University, Korea. The authors thank for their generous assistance in this study.

References

[1] William D. Thornbury, “Mineral wool industry of the united states”, Economic Geography 14(4) (1938) 398.

[2] T. Bajcar, B. Blagojevic, B. Sirok and M. Dular, “Influence of flow properties on a structure of a mineral wool primary layer”, Exp. Therm. Fluid Sci. 32(2) (2007) 440.

[3] M.A. Sultan and G. D. Lougheed, “Results of fire resistance tests on full scale gypsum board wall assemblies”. Internal Report No. 833. (2002). Institute for Research in Construction, National Research Council Canada.

[4] H. Leslie Simmons and Harold B. Olin, “Chapter 7, thermal and moisture protection, construction: Principles, materials and methods”, 7th ed. (John Wiley & Sons. Inc., 2001).

[5] T. Masumoto, I. Ohnaka, A. Inoue and M. Hagiwara, “Production of Pd-Cu-Si amorphous wires by melt spinning method using rotating water”, Scripta Metallurgica. 15(3) (1981) 293.

[6] A. Giboult, J.Y. Aube and D. Sainte-foi, “Method of forming mineral fibers” (1992). U. S. Patent No. 5143532.

[7] F. Trdič, B. Šironk, P.R. Bullen and D.R. Philpott, “Monitoring mineral wool production using real-time machine vision”, Real-Time Imaging. 5 (1999) 125.

[8] J.S. Szabó and T. Czigány, “Static fracture and failure behavior of aligned discontinuous mineral fiber reinforced polypropylene composites”, Polymer Testing. 22 (2003) 711.

[9] U.S. Environmental Protection Agency, “Materials Characterization Paper in Support of the Final Rulemaking: Identification of Nonhazardous Secondary Materials That Are Solid Waste Blast Furnace Slag - Used as ingredient in clinker manufacture”, Sector Strategies Performance Report. Feb. (2011).

[10] Ultra Light Strength Foam Metal Laboratory, “Development of functional composite panel of metal foam with good environment”, Research Report. July (2006). Ministry of Environment, South Korea.

[11] Victor I. Tkatch, Alexander I. Limanovskii, Sergey N. Denisenko and Sergey G. Rassolov, “The effect of the melt-spinning processing parameters on the rate of cooling”, Mater. Sci. Eng., A. 323 (2002) 91.