Effects of Molding Conditions on the Electromagnetic Interference Performance of Conductive ABS Parts

Shia-Chung Chen,[1] Rean-Der Chien,[2] Ping-Hwei Lee,[1] Jeng-Sheng Huang[1]

[1]*Mechanical Engineering Department, Chung Yuan University, Chung-Li, Taiwan 32023, Republic of China*
[2]*Mechanical Engineering Department, Nanya Institute of Technology, Chung-Li, Taiwan 32024, Republic of China*

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ABSTRACT: Polymers filled with conducting fibers to prevent electromagnetic interference (EMI) performance have recently received great attention due to the requirements of 3C (computer, communication, and consumer electronics) products. In the present article, the effect of fiber content and processing parameters, including melt temperature, mold temperature, and injection velocity, on the electromagnetic interference shielding effectiveness (SE) in injection molded ABS polymer composites filled with conductive stainless steel fiber (SSF) was investigated. The influence of fiber orientation and distribution resulting from fiber content and molding conditions on EMI performance was also examined. It was found from measured results that fiber content plays a significant role in influencing part EMI SE performance. SE value can reach the highest values of approximately 40 dB and 60 dB at 1000 MHz frequency for fiber content 7 wt % and 14 wt %, respectively, under the best choice of molding conditions. Higher melt and mold temperature would increase shielding effectiveness due to a more uniform and random fiber orientation. However, higher injection velocity leading to highly-orientated and less uniform distribution of fiber reduces shielding effectiveness. Among all molding parameters, melt temperature affects SE performance most significantly. Its influence slightly decreases as fiber content increases. Injection speed plays a secondary importance in affecting SE values, and its influence increases as fiber content increases. Upon examination of fiber distribution via optical microscope and subsequent image analysis, it was found that the fiber becomes more densely and random distributed toward the last melt-filled region, whereas fiber exhibits less concentration around the middle way of the flow path. This can be attributed to the combined effects of fountain flow, frozen layer thickness, and gapwise melt front velocity. The results indicate that molding conditions, instead of fiber content alone, are very important on the SE performance for injection molded SSF filled ABS composites. © 2005 Wiley Periodicals, Inc. J Appl Polym Sci 98: 1072–1080, 2005

Key words: conductive stainless steel fiber filled ABS; electromagnetic interference (EMI); fiber orientation/distribution; molding conditions; shielding effectiveness (SE)

INTRODUCTION

Going along with high technology development, many electronic, electrical machinery, and information/communication products carrying electromagnetic waves become more popularly used in daily life. However, it has become an inevitable problem due to high-density electromagnetic waves generated from the devices. Particularly, among many of the 3C (computer, communication, and consumer electronics) products, cell phones may induce higher strength of electromagnetic waves than other home electric appliances due to the high working frequencies and more complicated function in communication. This may result in jeopardizing body health very seriously if there is long-term exposure in such high-density electromagnetic waves surroundings. In addition, the electromagnetic interference (EMI) pickup by electronic components may also raise serious problems, such as noise enhancement and malfunction of electronic instruments. Therefore, how to prevent and/or reduce electromagnetic interference has become an important issue for all electronics-related industries.

To prevent electromagnetic interference, one may utilize the design of internal electric circuits or external electromagnetic shielding. In general, the most effective method is to use the housing directly as an obstacle to detain electromagnetic interference from the interior or exterior of the product itself. Using the metal as an outer casing is the best choice; however, it has the shortcoming of heavy weight and may meet difficult processing issues if the product exhibits a complicated shape. Compared with metals, plastics housings provide the advantage of lower weight, lower cost, higher strength-to-weight ratio, and relatively easy processing. However, most plastics like ABS, nylon, and PC are inherently transparent to electromagnetic radiation, providing no shielding against electromagnetic interference. To solve this problem, painting with conducting paints and electroplating with metal layers are two commonly used methods for

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Correspondence to: R. D. Chien (allie819@ms27.hinet.net).

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TABLE I
Classification of Shielding Effectiveness Level

Quality of shielding	Level of shielding effectiveness
Poor	0 ≈ 10 dB
Fair	10 ≈ 30 dB
Average	30 ≈ 60 dB
Above average	60 ≈ 90 dB
Excellent	90 ≈ 120 dB
Exceptional	> 120 dB

the plastics industry. The additional operation increases part cost significantly. Both methods also meet the challenge of environmental protection regulation. One of the alternative methods is to modify the engineering of plastics by adding filler materials of metal-like properties, such as carbon fiber, stainless steel fiber, or metal-coated fiber, into polymers to provide the required shielding effectiveness. These fibers are electrically conductive[1–6] and may form a three-dimensional network and result in EM shielding properties for plastics. This is why polymers filled with conducting fibers have recently received great attention in their potential of preventing EMI performance.

The conducting property of composites can be changed from insulating to conducting over a narrow range of filler concentrations. Gurland and coworkers[7] investigated the variation of plastics' electrical conductivity with added conductive filler concentration. It was found that the electric conductivity exhibits a linear variation with the concentration of filler until the concentration reaches some critical value, then the linear relationship becomes unclear.[8] This critical concentration depends primarily on the filler's electrical characteristics. Davenport[9] also reported that conductivity increases with increasing aspect ratio of fiber because a conductive path can be generated more easily under the condition of larger aspect ratio. The aspect ratio is defined as the magnitude ratio of the maximum and minimum dimension of the filler material. When the filler material was fiber, the ratio is the value of length divided by diameter. In addition, higher aspect ratio can also result in greater mechanical strength. Among different conducting fibers, Chen and colleagues[10] pointed out that the EM shielding effectiveness of injection molded composites with stainless steel fiber is higher than those added with graphite fiber coated with a layer of nickel if both have the same filler weight percentage. More recently, Chiu[11] studied the shielding effectiveness performance for two types of polymer composites (carbon fiber filled liquid crystal polymers and nylon, respectively) manufactured by two kinds of gate locations and samples (of circular disc and rectangular plate), which were injection molded. It was found that liquid crystal polymers (LCP) provide better SE than nylon parts. Additionally, previous works[1–6] also indicate that the carbon fiber is electrically conductive, and the planar layer structure of carbon atoms makes graphite a good electrical conductor. High graphite contents or high ordering structure of carbon fibers inside the thermoplastic results in high electrical conductivity and high SE. However, the cost of carbon fibers is several times higher than that of plastics, and this hinders industrial application. Meanwhile, with increasing fiber content, the fluidity of the composite diminishes in the processing and the chance of fiber breakage will be increased, leading to reduction of electromagnetic interference shielding. Cheng and coworkers[5] pointed out that composites with continuous carbon fibers show better EMI SE than those with discontinuous carbon fibers because continuous carbon fibers provide better EM reflection, the dominant mechanism of EMI shielding.

As previously described,[1–11] the aspect ratio, orientation, dispersion, and concentration of the added conductive fibers can affect the conductivity and the EM shielding of the polymer composites. But from the

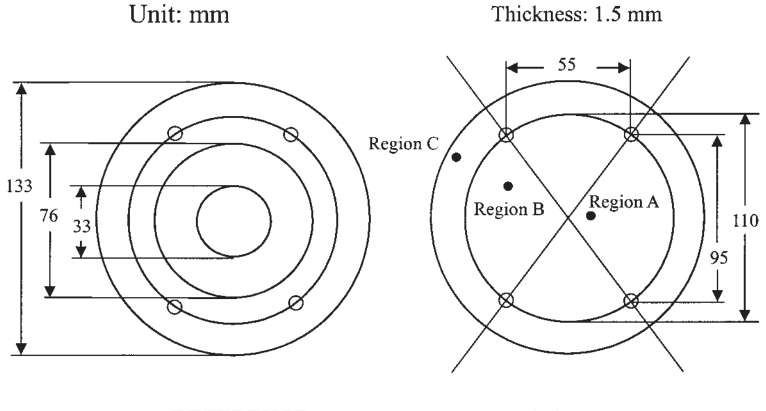

Figure 1 Shape and dimensions of EMI SE test specimen.

viewpoint of the part manufacturer, it is also very important to have molding guidelines concerning the quantitative dependence of shielding effectiveness on the parameters of the molding process. The work of Chiu,[11] although providing an initial step regarding gate design's influence on shielding effectiveness, lacks correlation of SE to molding parameters. In the present article, EMI shielding effectiveness of injection molded ABS filled with different content of long stainless steel fiber and molded under different molding parameters was addressed. The effect of stainless steel fiber content and molding parameters, including melt temperature, mold temperature, and injection velocity, on the shielding effectiveness performance are analyzed and correlated. The influence of fiber orientation and distribution from molding conditions was also evaluated. Hopefully, the results can provide a detailed understanding in choosing optimized molding conditions for injection molded SSF-filled ABS polymer composite parts to achieve the best shielding effectiveness performance.

EXPERIMENTAL

Shielding effectiveness (SE) value is an important parameter that measures the shielding of a device from EMI. The less the EM wave that passes through the sample, the higher the associated SE value designated in decibel (dB). Shielding theory was identified by three modes in which a material can shield EM radiation: (1) reflected from the material's surface, (2) absorption of the EM energy, and (3) multiple internal reflections of the radiation.[12] The measured SE represents the combined effectiveness of the above three modes. There are two types of measurement systems that can be used to measure the shielding effectiveness of composite samples.[1] One is a continuous conductor (coaxial) transmission-line device and the other is an aperture-in-a-box system. Plane-wave analysis[13] provides a good correlation with experimental measurements in terms of the relationship between conductivity and shielding effectiveness. Six levels of quality of shielding were specified according to the range of shielding effectiveness, as shown in Table I.

An 80-ton Victor injection molding machine equipped with an accumulator capable of delivering a maximum screw speed of 136 mm/s (flow rate 138 cm^3/s) and providing maximum injection pressure of 170 MPa was used for these experiments. A circular disc specimen molded by center gate with 133 mm in diameter and 1.5 mm thickness was prepared experimentally according to ASTM D4935–89 specification for EMI measurement, as depicted in Figure 1. A schematic of mold gate dimension and geometry is shown in Figure 2. Transparent POLYLAC PA-758 ABS resin from CHI MEI company,[14] filled with two different weight percent (7 and 14% by weight, respectively) stainless steel fibers (with length 4 mm and diameter 11μm) were utilized as the molding materials. To investigate the influence of processing conditions on EMI shielding performances of the molded parts, initial molding conditions for melt temperature, mold temperature, and injection velocity were chosen to be 230°C, 50°C, and 68 mm/s (or flow rate was 69 cm^3/s), respectively, after several trials. These processing parameters were varied with three different levels individually to investigate the effect of their variations on the parts' EMI shielding effectiveness. Molding conditions for various stainless steel fiber contents are listed in Table II. Five samples were molded under the same molding conditions and used for each EMI shielding testing. The averaged values from these measurements were used for analyses and correlation. A technique (Fig. 3) based on the ASTM D4935[15] method was applied to measure the SE of

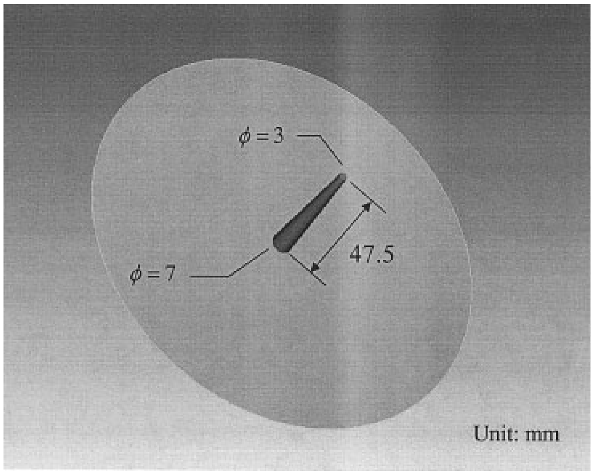

Figure 2 Schematic of mold gate dimensions and geometry.

TABLE II
Experimental Molding Conditions

Stainless steel fiber content	7 %			14 %		
Molding level	I	II	III	I	II	III
(1) Melt temp. (°C)	210	230	250	210	230	250
(2) Mold temp. (°C)	40	50	60	40	50	60
(3) Injection vel. (mm/sec)	40.8	68	95.2	40.8	68	95.2

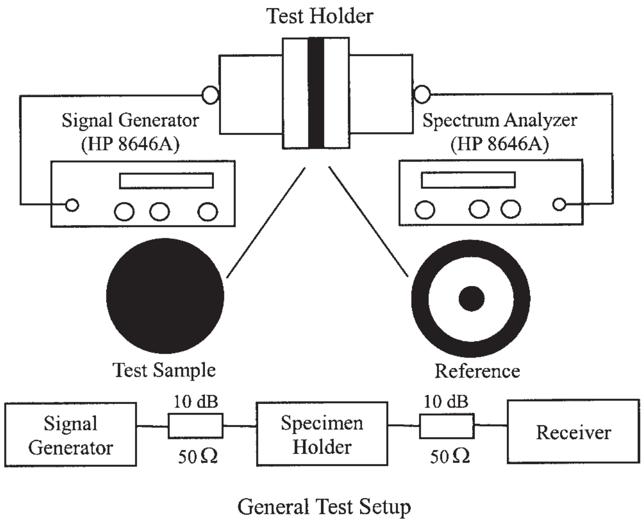

Figure 3 Schematic apparatus of EMI SE test.

electrical conductive stainless fibers filled ABS composite. The EMI shielding effectiveness test in our study was conducted on an HP 4396B internet/spectrum/resistive analytical apparatus,[16] whose measurement range was 100 kHz ~ 1.8 GHz. In our study, measurements were carried out at a chosen frequency range between 300MHz and 1500MHz (i.e., 300, 500, 1000, and 1500MHz, respectively). The measured SE value corresponds to the fiber distribution/orientation within region B (Fig. 1) because of the geometry of the reference specimen, shown in Figure 3.

In addition, to investigate the effect of SSF orientation induced during the mold filling process on EMI shielding effectiveness, an optical microscope was used to observe the specimen surface at three different positions, as shown in Figure 1. At the same time, scanner and analysis using an image analysis program developed by Borland C++Builder5 (the value of gray ranges between 0 ~ 255, with pure white 255 and pure black 0) is applied to the image of black opaque SSF embedded in transparent ABS. Then, the percentage of the black image area was calculated by the pixel of gray value less than 100 to compare the effect of fiber orientation on shielding EMI performance. The more random the distribution and the higher content of fiber, the associated image will have less gray value.

RESULTS AND DISCUSSION

Variation in EMI shielding effectiveness with measured frequency at different SSF content (of 7 and 14% wt %) under a specified molding condition (melt temperature 210°C, mold temperature 40°C, and injection velocity 40.8 mm/s) can be found in Figure 4. Basically, the ratio of standard deviation and average value ranges between about 4 and 10%. On examining the SE data, it is apparent that the higher the fiber content, the higher the shielding effectiveness. The measured EMI shielding effectiveness of 14% conductive SSF filled ABS composites was over 40dB, at the measured frequency range (i.e., it is in the range of the average level, according to Table I). So, when the weight percentages of SSF filled ABS is attained up to 14%, the part can obtain the average quality of shielding. Meanwhile, from the data of this Figure, the average values of SE are approximately 22dB and 44dB (the ratios are 1 : 2) for fiber content of 7 and 14%, respectively. It can be seen that there is a tendency that the shielding effectiveness is proportional to the fiber content, similar to the observed result of Gurland and coworkers.[7] Generally speaking, the shielding effectiveness increases with increasing fiber content. However, higher fiber content will increase melt viscosity and reduce the moldability and the associated molding window.[17]

The effect of various melt temperatures (210°C, 230°C, and 250°C) on the shielding effectiveness of molded parts filled with fiber content 7 and 14% are shown in Figures 5 and 6, respectively, over the frequency range of 300 to 1500 MHz. It can be noted that the SE increases with increasing melt temperature. Melt temperature plays a significant influence in determining SE, especially in the case of lower SSF content (7% wt %). The reasons can be attributed to that at higher melt temperature, the required molding pressure and shear stress are reduced, leading to a lower level of orientated fiber distribution. Besides, high melt temperature can assist the relaxation of orientated molecules and fiber to a more random state. This is why the corresponding SE values are higher. The effect of mold temperature on the SE performance is illustrated in Figures 7 and 8, respectively. On exam-

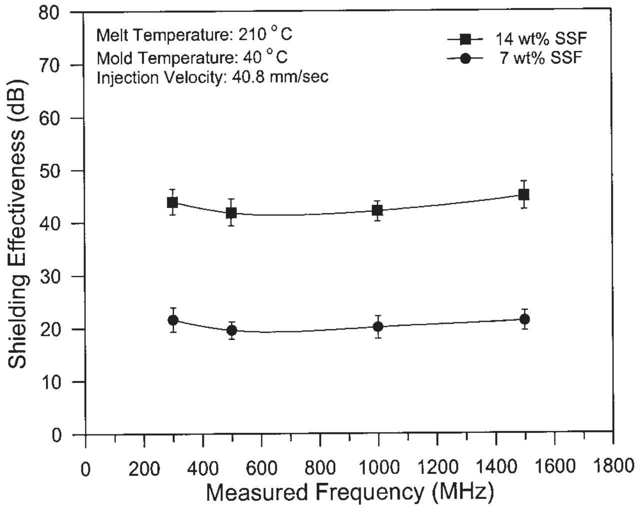

Figure 4 Variation in EMI shielding effectiveness with measured frequency at different SSF contents under some specified molding condition.

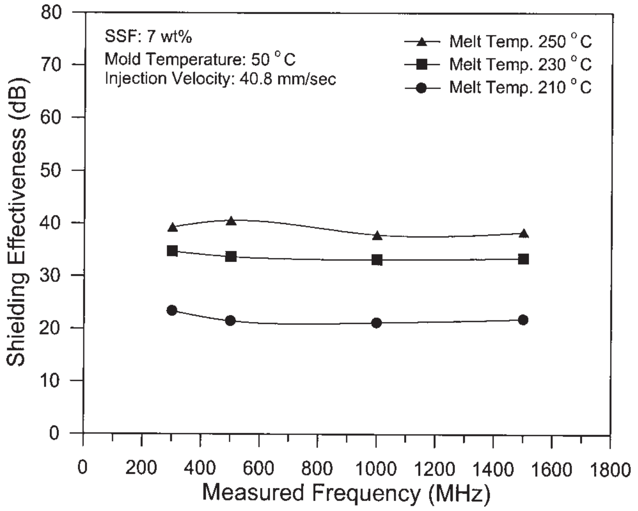

Figure 5 Effect of melt temperature on the shielding effectiveness for SSF 7% filled ABS composite.

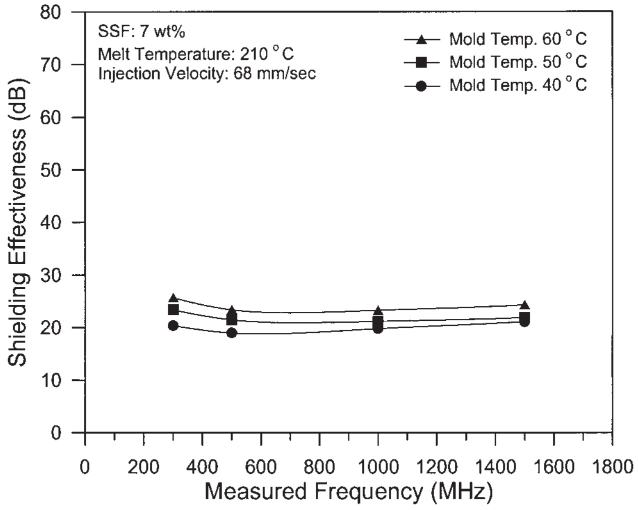

Figure 7 Effect of mold temperature on the shielding effectiveness for SSF 7% filled ABS composite.

ining the SE value, it can be seen that the value increases with increasing mold temperature, but less significantly than the influence of melt temperature.

Figures 9 and 10 show the influence of the SE value from injection velocity for specimens molded with different fiber content. From these Figures, it is apparent that when injection velocity increases, the SE value of the molded part decreases for all different fiber contents. The influence seems to become greater as fiber content increases. A higher injection speed will result in a high degree of fiber orientation, and the associated SE value decreases. At high fiber content, the long fiber may have a greater chance of breakage. At the same time, the greater mutual interaction makes fibers not easy to relax to a random state. This is why a high injection speed exhibits a greater influence on SE value at high fiber content. The results can be clearly verified by the observation of optical microscopes and the associated analysis of images. The pixel values analyzed by the image program using VB (Visual Basic) for 7% SSF filled conductive polymer composite specimens under three different injection velocities (melt temperature 250°C and mold temperature 40°C) are shown in Figures 11(a), (b), and (c), respectively. From the pixel value one can infer the percentage of shielding effective area, given in Table III. From the analyzed images, one can see the influence of injection speed on the fiber orientation and the associated shielding effectiveness. In general, melt temperature shows the most significant influence on SE value, particularly at lower fiber content. Injection

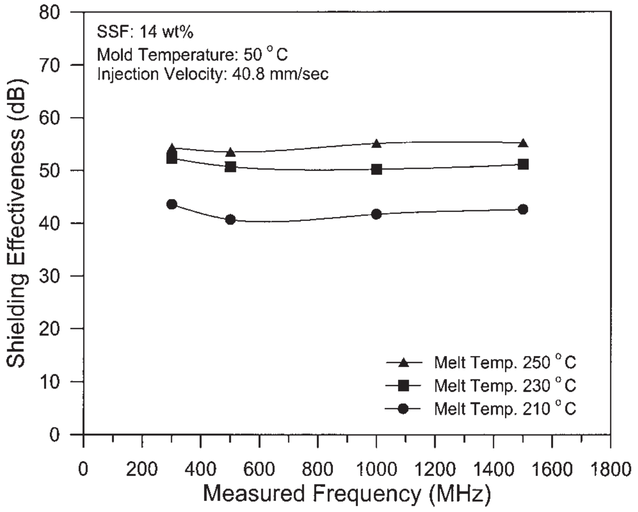

Figure 6 Effect of melt temperature on the shielding effectiveness for SSF 14% filled ABS composite.

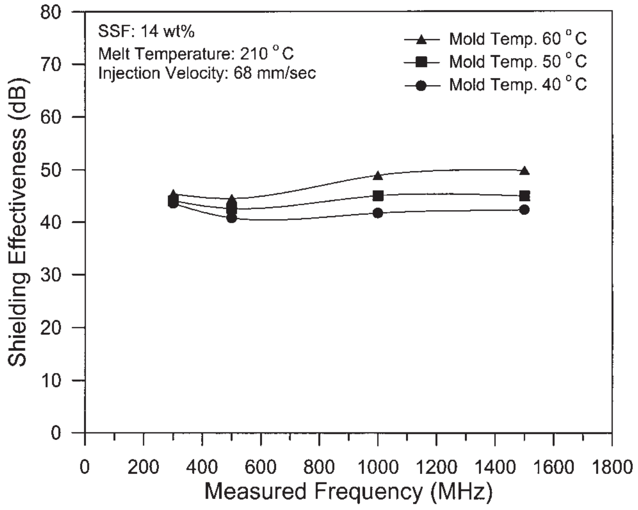

Figure 8 Effect of mold temperature on the shielding effectiveness for SSF 14% filled ABS composite.

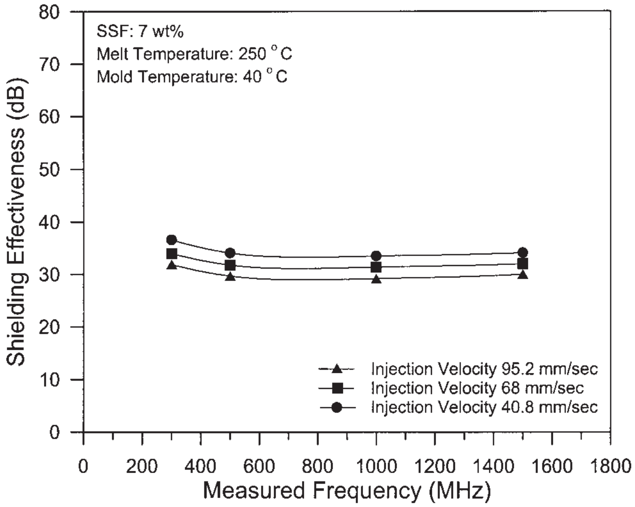

Figure 9 The correlation of SE value with measured frequency for SSF 7% filled ABS composite under different injection velocities.

speed exhibits a secondary influence, whereas mold temperature provides the most insignificant effect.

Figures 12(a–c) show the fiber distribution around the gate area (region A in Fig. 1), in the middle region along the radial direction from the gate (region B in Fig. 1), and a location of last filled (region C in Fig. 1), respectively. It should be noted that the observed fiber distribution and orientation exist in the surface layer. Around region C, the fibers seem to be more dense and randomly distributed. This can be clearly understood as due to the fountain flow effect, resulting in a flip over of the melt form core to the surface, accompanied with a more random and dense distribution of fiber. Near the gate area, the frozen layer is thin due to the high shearing effect and high entrance melt temperature; the fiber is also randomly distributed, although not as highly as that of region C. In the middle region (region B), the frozen layer is thicker, resulting in more orientated fiber. In addition, prior to the completion of filling, most of the fiber in region B will be flashed over to the surface of region C, thus leading to less dense fiber distribution. The simulated frozen layer thickness from the mold filling using the @Moldflow package is illustrated in Figure 13. The frozen layer thickness increases with decreased injection speed. The thicker the frozen layer, the lower the fiber density. A similar situation happens as compared to the fiber density in samples 1 and 4. The thicker frozen layer (Fig. 14) of sample 4 results in lower density of the fiber. Finally, it is worthwhile to mention that if one selects the melt temperature to be 250°C, the mold temperature to be 60°C, and the injection velocity to be as low as 40.8 mm/s, the SE performance can reach its highest values of approximately 40 dB and 60 dB at a measured frequency of 1000 MHz for fiber content of 7 and 14%, respectively. On the contrary, the worst molding conditions may result in poor SE performance and as low as 20dB and 40 dB for fiber contents 7 and 14%, respectively. The importance of molding conditions on SE is quite obvious.

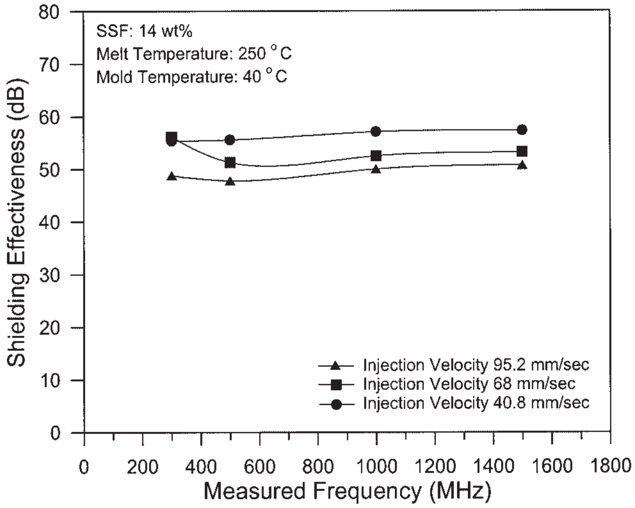

Figure 10 The correlation of SE value with measured frequency for SSF 14% filled ABS composite under different injection velocities.

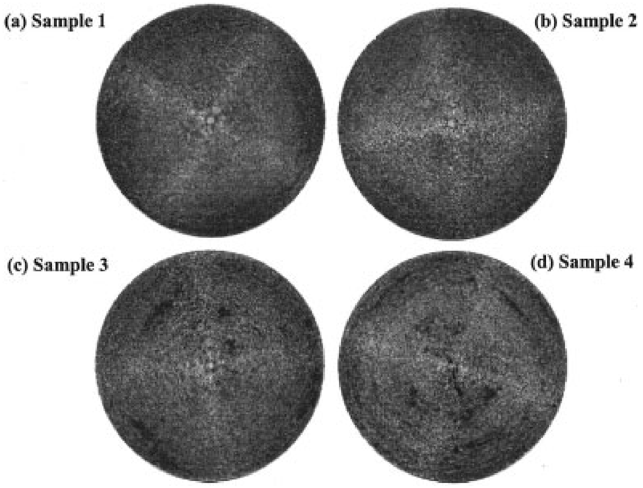

Figure 11 The image of the scanner for 7% SSF filled ABS composite under some specified molding condition.

CONCLUSIONS

In the present article, the electromagnetic shielding effectiveness of injection molded ABS filled with different contents of conductive stainless steel fiber of circular disk shape were investigated followed ASTM D4935–89 specification. The effect of fiber content and processing parameters, including melt temperature, mold temperature, and injection velocity, on the electromagnetic shielding effectiveness in conductive

TABLE III
EMI Shielding Effectiveness and Pixel Value Under Different Molding Parameters

	Melt temperature (°C)	Mold temperature (°C)	Injection velocity (mm/sec)	Pixel	Percentage of area (%)	SE (dB)
Sample 1	250	40	40.8	166724	46	37
Sample 2	250	40	68	152296	42	34.6
Sample 3	250	40	95.2	117450	33	32.7
Sample 4	230	40	40.8	97780	27	29.4

polymer composite material were measured experimentally. The influence of fiber orientation and distribution on EMI SE performance as a result of various molding conditions was also examined and discussed. Based on the measured results, the following conclusions can be made:

1. The shielding effectiveness is roughly proportional to the fiber content at a specified frequency (1000MHz) and molding conditions. The shielding effectiveness of 14% conductive SSF filled ABS polymers composites was found to be over 40dB. This indicates that when weight percentages of SSF filled ABS is over 14%, the molded composites can obtain the quality of average shielding.
2. Among all molding conditions, higher melt temperature and mold temperature would in-

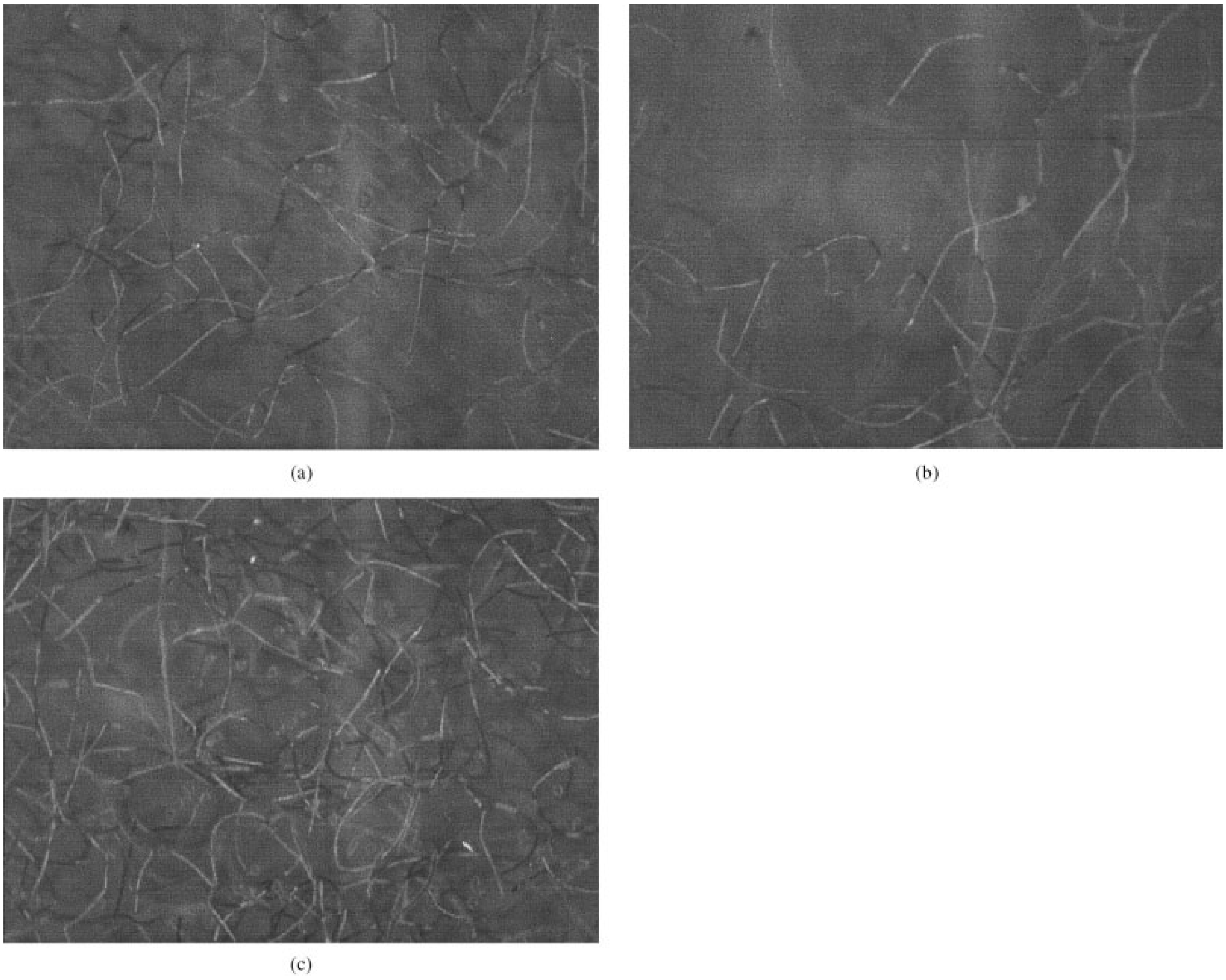

Figure 12 Metallographic photos for: (a) 7% SSF filled ABS composites around the gate area (region A in Fig. 1); (b) 7% SSF filled ABS composites in the midway region along the radial direction from the gate (region B in Fig. 1); and (c) 7% SSF filled ABS composites in the region toward the periphery of the circular specimen (region C in Fig. 1).

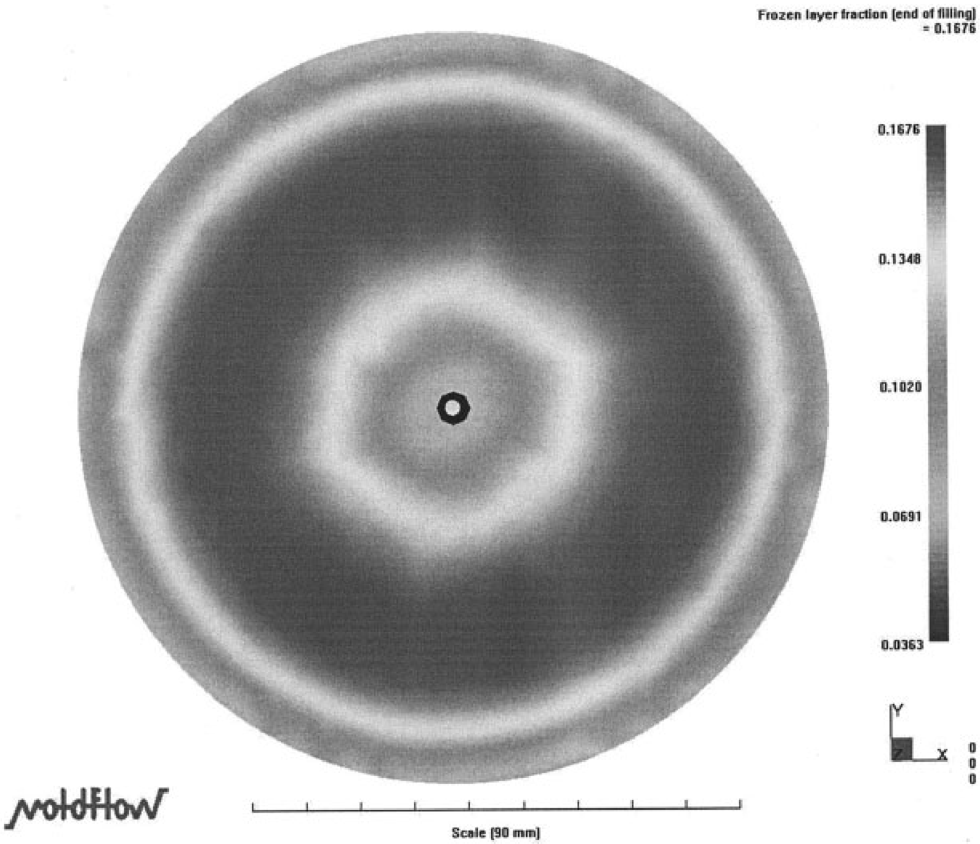

Figure 13 Frozen layer fraction distribution of the mold cavity.

crease shielding effectiveness, whereas higher injection velocity would reduce the shielding effectiveness value. Melt temperature affects SE performance most significantly, especially at low fiber content. However, its influence on SE at high SS fiber content is greatly reduced. Injection speed plays a secondary role in affecting the SE value. However, the influence of injection speed on SE increases at high fiber content.

3. Upon optical microscope examination and image analysis of fiber distribution and orientation, it was found that fiber distributed more densely and randomly in the last melt-filled region. The fountain flow effect also plays an important role in the fiber content distribution. Higher injection speed and induced shear stress will orientate the SS fiber in a direction parallel to flow direction, leading to weaker SE performance. Higher melt temperature and mold temperature not only promote the fluidity of melt but also help the SS fiber to be more randomly orientated, resulting in a higher shielding effectiveness. The nonuniform distribution and orientation of SS fiber indicates the important influence of molding conditions, instead of fiber concentration alone. Its influence may be as high as 100% when ABS is filled with a low content of SS fiber.
4. The SE value of injection molded ABS composites can reach the highest EMI SE value of approximately 40 dB and 60 dB at the frequency of 1000 MHz with fiber content of 7 and

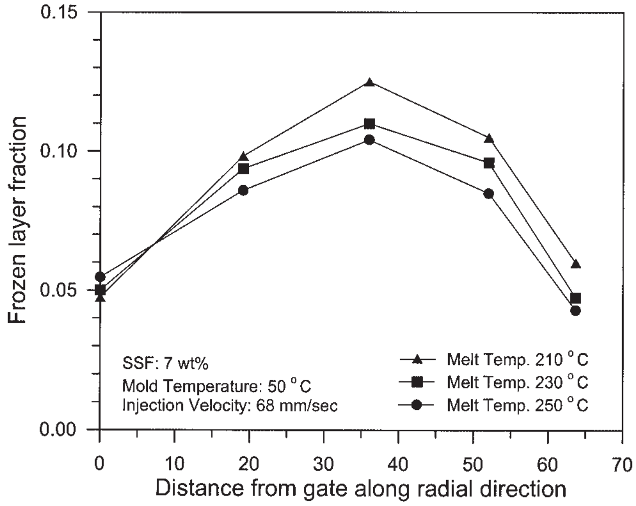

Figure 14 Frozen layer fraction distribution of the cavity along the radial direction from the gate.

14%, respectively, when the best molding condition was chosen (melt temperature 250°C, mold temperature 60°C, and injection velocity 40.8 mm/s). SE values may be as low as 20dB and 40 dB for fiber content 7 and 14%, respectively, when molded at poor conditions.

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