Optimization of injection molding process of polypropylene with aluminum metallic pigments

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ABSTRACT: The coloring of plastics is essential in parts design and in the promotion of new products. As such, metallic pigments are used to color plastics aiming to replace the appearance of metals. However, the metallic look in plastics by the addition of metallic pigments prone the visual appearance of weld lines and flow lines. These defects are caused by the anisotropic character of flake like metallic pigments when there is the meeting of two flow fronts or there are melt flow disturbances caused when holes or castles are present in the part. There are some solutions to overcome this problem, but there are also numerous variables that constrain the elimination of these defects. Therefore, the coloration of plastics should be taken into account in part design. The number of gates, its position and type, abrupt changes in wall thickness and improper wall angles influence the melt flow, which in turn allows these defects. The effect of the amount, size and shape of the metallic particles in the appearance of weld lines and flow lines has been studied. Larger size of metallic particle and spherical/rounded particles attenuate these defects. However, the solution may consist in optimizing the injection process and in the appropriate selection of metallic particles or otherwise can even be necessary changing the mold design. This work aims at studying the influence of the physical characteristics of the metallic pigments (size and shape of the particles) on the aesthetic appearance of defects and on the optimization of the processing conditions to minimize the defects caused by the use of metallic particles. The part geometry used is a two gated box. Morphological analysis and optical characteristics of the part are analyzed in this work.

1 INTRODUCTION

In recent years emerged the interest in the industry to replace metal products by light weight and low cost products with the same appearance and performance. One solution is the addition of metallic pigments in polymeric matrices, which gives the metallic look to plastics, with no further post processing finishing of the part like paining or metallization.

Pigments are available in the market with different supply forms, such as powder, pastes and pellets and also with different shapes like irregular shape (flakes), lenticular, glitter and spherical (Charvat 2003). They all provide a different metallic appearance to the parts arising from the ways they scatter the light. The type, shape, size and concentration of pigments (Edenbaum 1996) affects the metallic look of plastic parts. Pigments composed by particles in the form of flakes tend to reflect the entire incident light due to the high surface area (Harris 1999; Martins et al. 2012; Santos et al. 2013). However, at the edges the light is diffused, contributing to the reduction of the metallic effect when the size of the flake pigments is reduced. Also spherical/rounded shaped pigments have low light reflection because only a very small area (single point) reflects light, decreasing the metallic effect (Charvat 2003). As a result, parts made of spherical aluminum pigments appear gray with a scattered sparkling effect, whereas with irregular-shaped pigment (flakes) display a very grayish silver effect (Charvat 2003; Martins et al. 2012; Santos et al. 2013).

The pigment type and particle size defines the amount of pigment necessary to added to the polymeric matrix. Typically, 0.01-1 wt% is the amount required for a pigment with a size of 5-30 µm, 0.5-2 wt% for a pigment with 30-60 µm and 2-5 wt% for a pigment with a size greater than 70 µm (Charvat 2003). Larger particles causes a greater amount of reflected light, thus a better metallic effect (Martins et al. 2012; Santos et al. 2013). In smaller particles there is a lower amount of reflected light, causing a decrease in brightness and in the metallic effect (Edenbaum 1996).

Although the metallic pigments have numerous advantages in the production of parts with metallic effect, such as the elimination of post-processing techniques, the reduction of costs and production times, there use is still a challenge for the industry. Undesired defects such as dark flow lines and weld lines occur in injection molding when two flow fronts collide due to inhomogeneous orientation and anisotropy of particles (Wheeler 1999; Park et al. 2012; Santos et al. 2013).

There are some studies performed about the possible solutions to attenuate the defects caused by the use of metallic pigments. Optimization of the processing conditions may be one of the solutions used to reduce the visual appearance of dark weld lines. A high speed injection creates disturbances in the flow, which can reduce the visibility of the flow lines (Charvat 2003, Kerr 2006). A high melt and mold temperature prolong the flow, increasing disorientation and improving the appearance of the parts (Park et al. 2012). Furthermore, the high temperature prevents the orientation of particles frozen near the wall in the perpendicular direction to the plane of the surface because the polymer solidification takes place more slowly allowing the particles to reorient in parallel to the plane of the surface before they become frozen-in in the perpendicular direction (Park et al. 2012). Besides the melt and mold temperature, high back pressure reduces the appearance of the weld line due to the increased dispersion of the particles (Kerr 2006).

The present work focus on the study of the influence of shape and size of metallic particles on the aesthetic properties of a two gated boxed part made of PP, as well as, on the optimization of injection molding parameters to reduce the appearance of dark weld lines at the surface of the part.

2 EXPERIMENTAL

2.1 *Raw materials*

The polymeric matrix used in this work was Polypropylene copolymer powder from ICORENE with a specific gravity of 0.9 g/cm^3 and a melt flow index of 13 g/10min (190 ºC, 2.16 kg). Four metallic pigments of different shapes and dimensions were used, namely: (i) sparkle silvet 880-30 of 27 microns (Al 27); (ii) 21075 aluminum pigment of 75 microns (Al 75); (iii) aluminum powder of 50 microns (Al 50) and (iv) grit aluminum of 200 microns (Al 200). The particles of Al 27 and Al 75 have an irregular shape (corn flake), while the Al 50 and Al 200 have a rounded shape. In brackets it is given the name used along the text to identify each particle.

The compounding material was obtained by dry mixing of PP and metallic pigments in a rotary drum at the percentage of Al of 2 % by weight.

2.2 *Injection molding*

The test geometry used is a two gated box depicted in Figure 1 with the purpose of studying the weld line formed in the part. The pigmented parts were processed by injection molding on a Ferromatik Milacron K85, using the following processing conditions: mold temperature of 40 ºC, melt temperature of 220 ºC and injection speed of 30 mm/s.

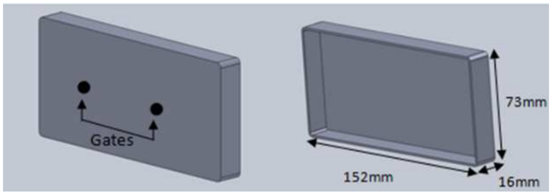

Figure 17. Part geometry: dimensions and gate position of a two gated box.

Upon evaluation of the metallic look of the produced parts, a single compound (PP/metallic pigment) was used to optimize the processing conditions in order to reduce/eliminates the appearance of dark line formed at the weld. The following variables were used: melt temperature (T_{inj}=190-220-250 ºC), mold temperature (T_{mol}=25-40-55-70 ºC) and injection speed (V_{inj}=30-60-90 mm/s). A total of 36 different processing conditions were obtained with the combination of the variables used.

2.3 *Characterization techniques*

2.3.1 *Aesthetical properties*

The aesthetical properties evaluated were the gloss and the light reflectance curves of the parts.

The gloss was measured using a device BYK-Gardner micro-TRI-Gloss according to the ASTM D23-85 standard. An illumination angle of 60 º was defined. The measurement was performed in the same position on five boxes for each composite to ensure the repeatability of the tests.

The light reflectance was measured using a spectrophotometer Shimadzu UV-240 1PC interfaced with a software UV-Probe, in the wavelength range of visible light between 380-780 nm.

2.3.2 *Morphological analysis*

The microstructure of the parts was analyzed using a microscope Olympus BH-2 couple with a digital camera Leica DFC 280. The samples were cut using the microtome Leitz 1401. Thin slices of 15 µm were obtained and placed between a slide and a glass slide with Canada balm.

SEM micrographs of cryofractured surfaces were obtained using an Ultra-high resolution Field Emission Gun Scanning Electron Microscopy (FEG-SEM), NOVA 200 Nano SEM, FEI Company. The samples were sputter coated with gold and fixed on a support with carbon tape adhesive.

3 RESULTS AND DISCUSSION

3.1 *Characteristics of metallic pigments*

Figure 2 depicts the supply form of the pigments used. Al 27 and Al 75 pigments are provided in the form of pellets, whereas Al 50 and Al 200 are provided as powder. The most suitable supply form to handle the pigments, to compound and process plastics products are in pellet form. Pigments in powder, are more difficult to incorporate and disperse in plastics and more prone to break during processing (Charvat 2003).

Figure 2. Supply form of the metallic pigments.

Figure 3 shows the SEM micrographs of metallic pigments in its initial state. Both Al 27 and Al 75 are an agglomerate of particles with irregular shape looking like a flake. Al 50 and Al 200 are individual rounded like shaped particles and contrary to the other pigments they are not agglomerated.

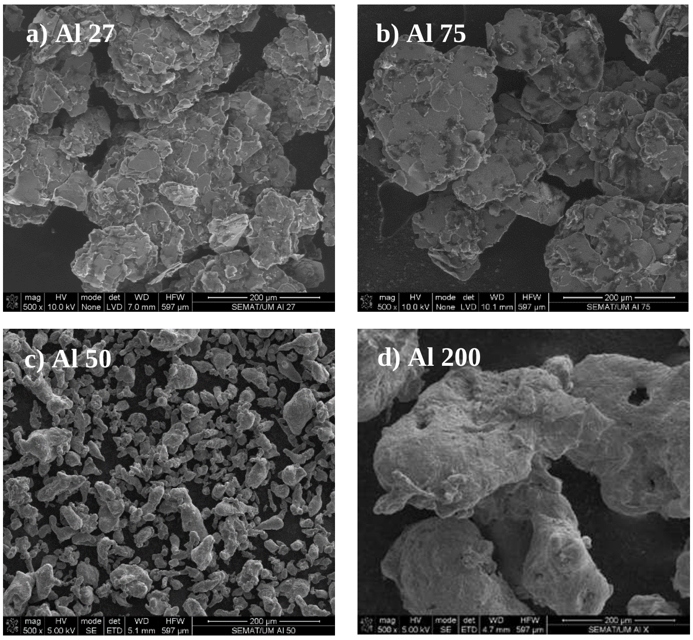

Figure 3. SEM micrographs of different Aluminum metallic pigments: a) and b) are flakes and c) and d) are rounded.

3.2 *Metallic look of injection molded parts*

The metallic look given to PP by metallic pigments is shown in Figure 4. Different metallic effects are obtained: PP/Al 27 has a metallic look of pure metal, like brushed aluminum or polished steel; PP/Al 50 looks similar to the lead, with a dark gray color; PP/Al 75 has a traditional metallic effect conferred to plastics by other techniques, such as painting and metallization; finally, PP/Al 200 displays a transparent gray tone, with visible metal particles spread on the part. This is the only case that does not present a good metallic look; all of them present a uniform metal like color of the part.

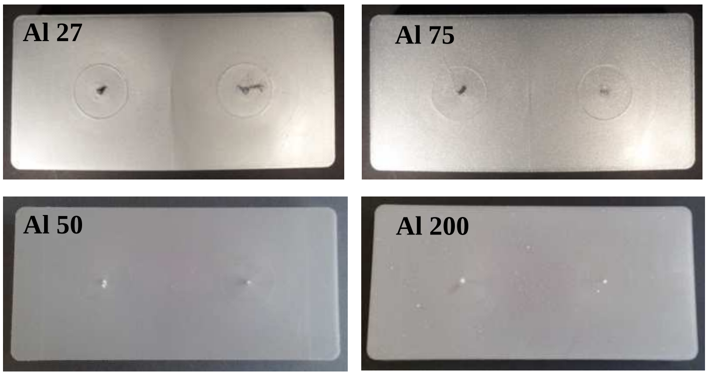

Figure 4. Pictures of the injection molded part showing the effect of type of metallic pigment on the appearance of the part.

Pigments with rounded shape tend to be darker in color since only a small area on the particle reflects light, as compared to the flake like pigments. However they are the only ones that do not present the visual appearance of the weld formed by the meeting of the two flow fronts in the central region of the box. Spherical/rounded pigments are proven to minimized weld/flow lines due to the fact that this type of pigments do not have a preferential orientation (Charvat 2003; Kerr 2006). This fact is proven when the morphology of the parts is analyzed.

3.3 *Morphological analysis of the part*

Figure 5 depicts the optical microscopy images of sections taken from the weld region of the parts. In general there is a good distribution of the metallic pigments on the polymeric matrix. The only exception is the Al 200 due to its large size. On the weld region (pointed with an arrow in the figure) where there is the meeting of the flow fronts, flake like metallic pigments, such as PP/Al 27 and PP/Al 75, shows an accumulation of particles that are randomly orientated in that region. The rapid solidification of the melt in contact with the mold does not allow the reorientation of the particles in the weld zone, so the particles remain perpendicular to the plane of the surface, causes the appearance of a dark line (Kobayashi 2011, Park et al. 2012) due to the diffusion of light through the edge of the particles.

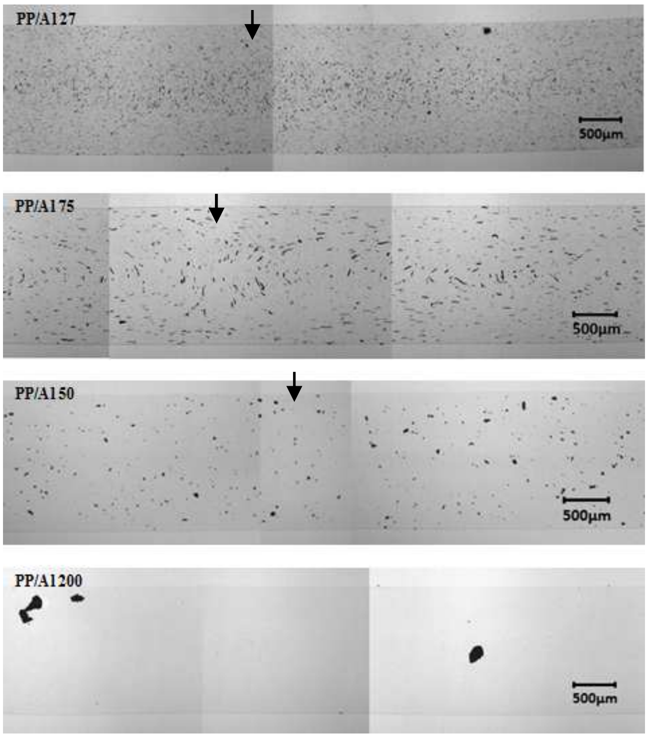

Figure 5. Optical microscopy images of PP/metallic pigments at the weld region of the part.

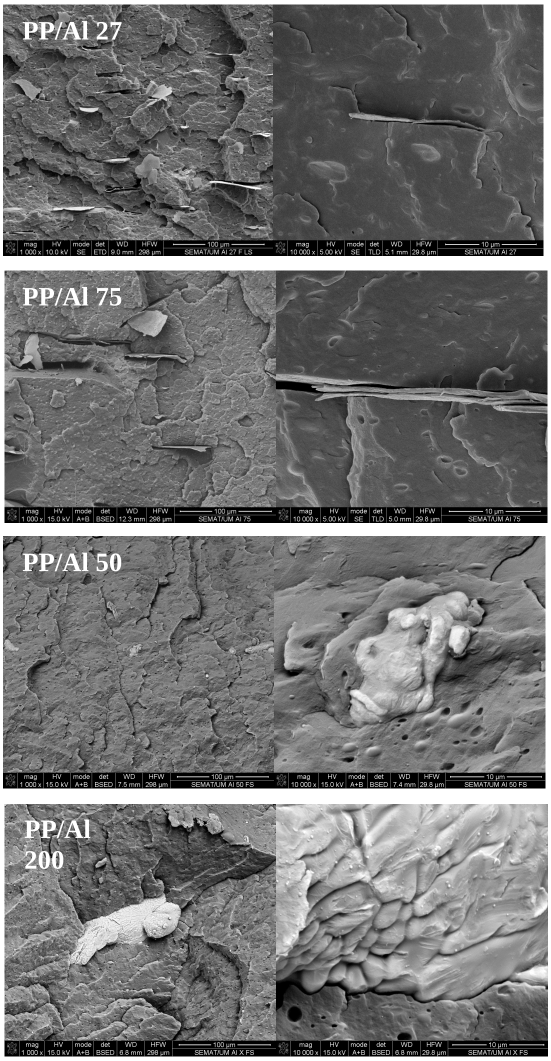

Figure 6. SEM micrographs of PP/metallic pigments.

PP/Al 50, consisting of rounded like pigments, shows no accumulation of particles in that region. Moreover they do not have a preferential orientation. For that reason there is no appearance of weld line at the surface of the part. The weld line still exists but is not visible.

Note that the different concentration of pigments observed in the part is related to the size of the particles and its density. PP/Al 27 have greater concentration of particles in the sample than PP/Al 75 with the same content of pigment. This is due to the smaller particle size of the PP/Al 27 which leads to an increase of particles compared to the PP/Al 75.

Figure 6 show SEM images of cryofractured surfaces of the parts. The particles are well dispersed on the matrix, but its adhesion is poor, especially for flake particles like Al 27 and Al 75. The particles that are round in shape are encrusted on the matrix; therefore its adhesion seems to be better than for the flakes.

3.4 *Optical properties of the part*

The gloss of the parts is related with the way light is reflected by the sample, being influenced by the characteristics of the surface of the part. Figure 7 shows the gloss of the parts produced with different metallic pigments. Parts made of PP show 44 % of gloss; there is no significant change for parts with flake pigments as PP/Al 27 and PP/Al 75. The most significant change is observed for rounded pigments like PP/Al 50 with gloss at 36 % and PP/Al 200 that approaches 40 % (in this case, perhaps due to the fact that the part is similar to PP).

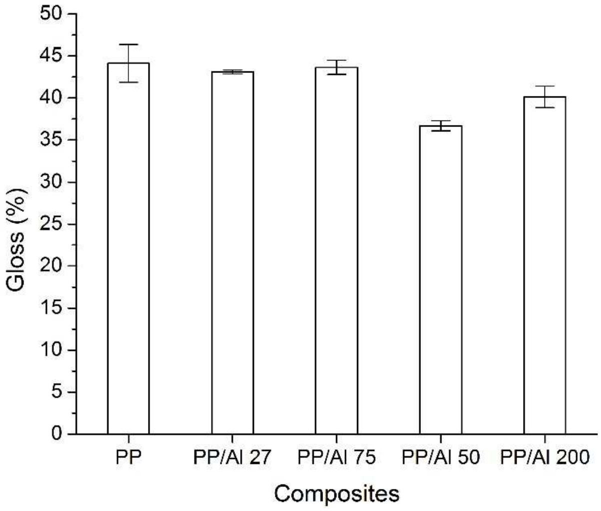

Figure 7. Gloss of PP/metallic pigments parts.

Figure 8 depicts the reflectance curves obtained for each part. PP/Al 27 and PP/Al 75 have a similar reflectance curve, being slightly lower for PP/Al 27 comparatively to PP/Al 75. The reflectance is above 40% for the range of visible light; it is typical of a gray color. PP/Al 200 shows the same shape of reflectance curve as PP, at lower reflectance level, because PP/Al 200 displays a transparent light grayish color. Finally, PP/Al 50 has the lowest reflectance value of about 15 %, explained by the dark color of the part.

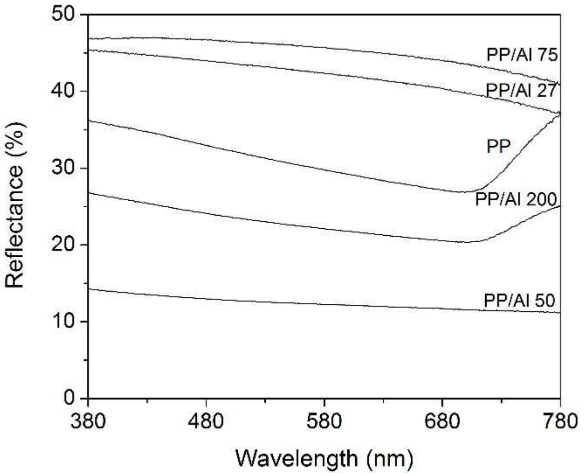

Figure 8. Reflectance curves of PP/metallic pigments parts.

3.5 *Optimization of injection molding process*

Parts of PP with flack like metallic pigments have the most appealing effect; however they are the ones showing the most pronounced weld line appearing at the surface of the part. The size of the pigments also plays a role, enhancing the weld line when the size increases. For that reason, PP/Al 75 was selected to carry on a detailed study about the optimization of the processing conditions envisaging the reduction or elimination of the weld line effect.

To optimize the injection moulding process the mold temperature (T_{mol}=25-40-55-70 ºC), the melt temperature (T_{inj}=190-220-250 ºC) and the injection speed (V_{inj}=30-60-90 mm/s) were varied. The variation of injection speed has no significant influence on the appearance of the weld line. Therefore the results are presented only for an intermediate injection speed of 60 mm/s.

Figure 9 show that the increase of melt temperature induces the formation of a darker line located at the central region of the part and it is attenuated on the lateral positions. At lower melt temperatures the line is much lighter and similar throughout the thickness of the sample. When looking to the morphology of the part, depicted in Figure 10, it is observed a good dispersion of the pigments on the samples. Nevertheless, the concentration of the pigments is more pronounced in the center as compared to the lateral; also it increases with the melt temperature. Therefore, the dark line at the surface of the part is attributed to the higher concentration of the particles in that region and not only to the orientation of the particles perpendicular to the surface of the sample, as observed by other authors (Park at al. 2012).

Although the weld line is less visible at 190 ºC or 220 ºC other defect are appearing such as aureole at the gate and flow lines (Figure 9 and 11).

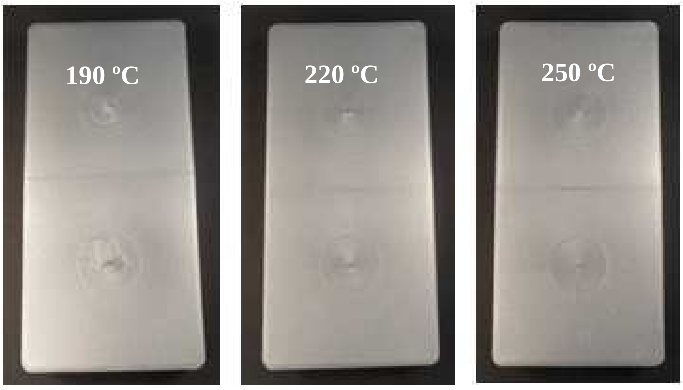

Figure 9. Pictures of the injection molded part showing the effect of melt temperature on the visual appearance of weld line (mold temperature of 55 ºC and injection speed of 60 mm/s).

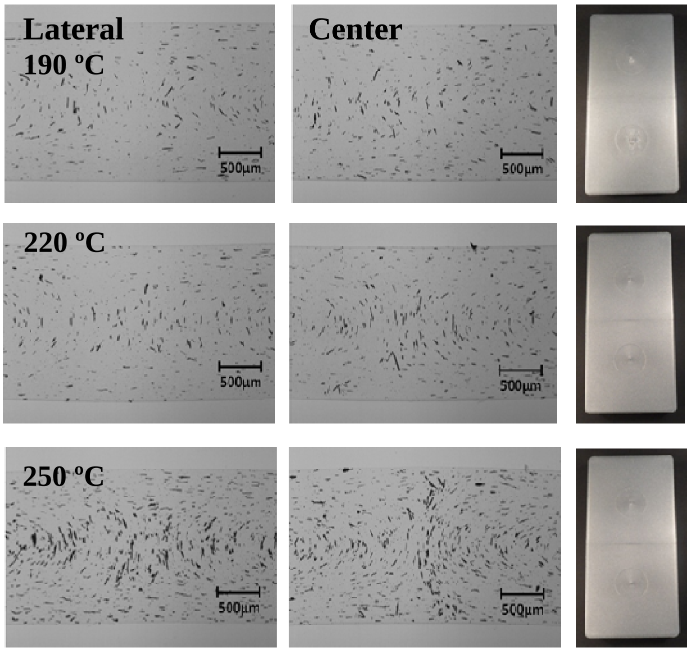

Figure10. Optical microscopy images of PP/Al 75: effect of melt temperature on the morphology of the part (mold temperature of 55 ºC and injection speed of 60 mm/s).

The effect of mold temperature is depicted in Figure 11. In this case a melt temperature of 220 ºC has been considered as reference. Figure 12 shows the morphology of the part at the center and side of the weld line.

Lower mold temperatures (25 ºC) eliminate the dark weld line; however other defect arises such as flow lines, as clearly observed in Figure 11. Once more, the lower concentration of particles and the better orientation of the particles parallel to the flow at the surface of the part are the reasons for the attenuation of the dark weld line.

Analyzing the results it is concluded that higher melt or mold temperatures might not be favored for the elimination of the weld line as reported in the literature (Rawson et al. 1999; Charvat 2003; Park et al. 2012). In this case it is proven that higher temperatures promoted the movement of a larger amount of particles in the flow front that once they meet, results in a higher concentration of particles in that region causing the appearance of darker line mark that is not acceptable for the part quality.

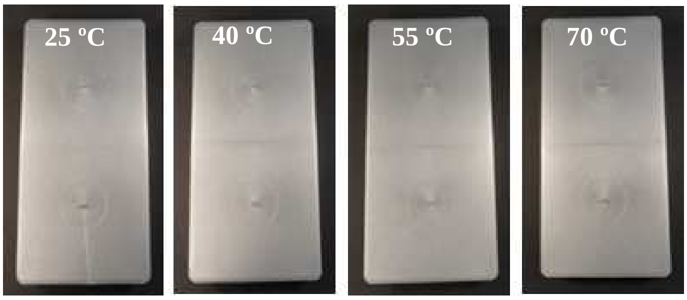

Figure 11. Pictures of the injection molded part showing the effect of mold temperature on the visual appearance of weld line (melt temperature of 220 ºC and injection speed of 60 mm/s).

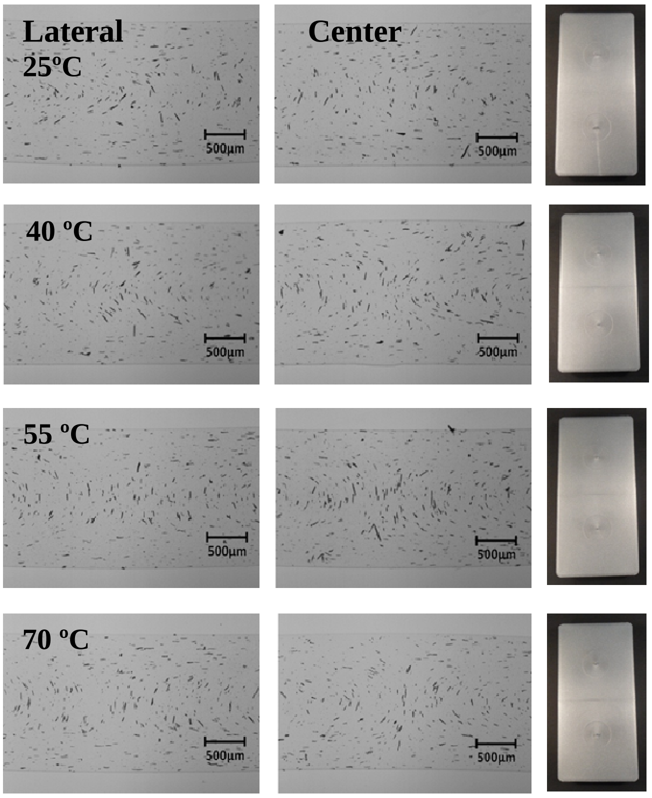

Figure12. Optical microscopy images of PP/Al 75: effect of mold temperature on the morphology of the part (mold temperature of 55 ºC and injection speed of 60 mm/s).

CONCLUSION

The addition of metallic pigments provides different metallic effects to the polymeric matrix. They can easily substitute metallization or painting, avoiding post processing operations. Flake like metallic pigments give rise to shiny surfaces with a metallic look of pure metal, like brushed aluminum or polished steel; rounded like metallic pigments of small size (approx. 50 μm) give also a metallic effect of lead. All of them are easily compounded to the polymer matrix showing a good distribution upon processing by injection molding. The processing itself is also easy. The main drawback is the defects that appear at the surface of the part when flake like metallic pigments are used in parts with more than one gate or complex geometries that fills with more than one flow front. Undesirable defects such as dark weld lines appear due to the anisotropy of the metal particles and their orientation in the polymer matrix.

Morphological analyses to the weld region made it possible to conclude that the higher concentration of pigments at that region and also the orientation of the particles perpendicular to the surface, are the cause of the dark line defining the position of the weld caused by the meeting of the two flow fronts. Optimization of the processing conditions shows that the use of low melt temperatures avoids the accumulation of particles in that region; together with moderate mold temperatures the appearance of weld line can be attenuated. Very low mold and melt temperatures, although completely eliminated the dark line gives rise to other defects like flow lines.

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