

## A study of size and frictional effects on the evolution of melting Part II: Twin screw extruder

D.S. Kim<sup>†</sup>, B.K. Lee, H.S. Kim\*, J.W. Lee\*\* and C.G. Gogos\*\*\*

*Machinery R&D Center, LG Cable Ltd. 555, Hogye-dong, Dongan-gu, Anyang-shi, Kyungki-do, 431-080, Korea*

*\*Applied Rheology Center, Department of Chemical Engineering, Dankook University San 8,  
Hannam-Dong, Yongsan-Gu, Seoul, 140-714, Korea*

*\*\*Applied Rheology Center, Department of Chemical Engineering,  
Sogang University 1 Shinsu-Dong, Seoul, 121-742, Korea*

*\*\*\*Polymer Processing Institute, GITC Building, Suite 3901  
New Jersey Institute of Technology, Newark, NJ 07102-1982, USA*

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### Abstract

Effects of particulate size and frictional characteristics were examined on the melting behavior of PP (polypropylene) in a twin screw extruder. Powder and pellet types of PP were used and each component was blended with PE (polyethylene) wax and clay, respectively. It was observed that small size particulates, i.e. powder systems exhibit accelerated melting behavior; and it was also found that the abrasive additive acts as an effective agent for fast melting of PP powder. Retardation of melting due to the reduced friction was observed in both types of PP, contrary to the result found in a batch mixer. The tendency observed in variation of torque and exit temperature was explained in terms of frictional effect and length of compacted region formed during evolution of melting.

**Keywords :** melting behavior, PP, friction, lubricant, abrasive additive, particulate size, twin screw extruder

### 1. Introduction

Recently, the melting of the solid feed is become one of the major task in compounding of polymeric materials. It is generally agreed that the melting process is often the most important in determination of the maximum output rate with acceptable quality of extrudate, and understanding melting phenomenon would help in optimizing energy consumption and screw design. For these reasons, melting in single screw extruder has been extensively investigated (Tadmor and Klein, 1985) and a number of studies presented the mechanism of melting occurred in the kneading section of twin screw extruder. For example, Tadmor and Gogos (1979) indicated that in the mix melting process which occurs in the first kneading elements of a twin screw extruder, inter-particle friction heating is more advantageous and efficient than simple heat conduction from barrel walls. Todd (1992) investigated the melting mechanism in the kneading blocks of a 2 in. ( $L/D = 10$ ), intermeshing co-rotating APV(Baker Perkins) twin screw extruder. Experiments were conducted using flexible PVC(polyvinylchloro-

ride) in powder or pellet form with addition of colored master batch of SAN(styrene-co-acrylonitrile) and ABS (acrylonitrile-butadiene-styrene). Todd concluded that melting in kneading block paddles arises primarily from energy dissipated by inter-particle friction. He also attributed the mechanism to the forced periodic deformation flow of the compacted solid bed due to the compression/expansion sequence in a kneading block geometry. In most compounding operations of polymeric materials, the components are fed into the machine as solid pellets, spheres or powder. During this process, a large amount of energy input is consumed to transform the solid feed into melt. Curry (1995) investigated the melting mechanism of SAN, LDPE (low density polyethylene), and PP(polypropylene) through carcass analysis using a split barrel, 40 mm twin screw extruder (ZSK40, W & P). The author identified the progression toward melting as follows; (i) loose particulates, (ii) joined structures, (iii) compressed masses, (iv) fluid poor aggregates, and finally (v) homogeneous melt. For all materials, melt initiation started at positions where the material was closely packed. From the analysis of the samples in cross section, Curry noticed that the samples did not indicate that melting takes place through catastrophic and global destruction of the solid bed rather than

<sup>†</sup>Corresponding author: dskim@ofmail.mach.lg.co.kr  
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the draining mechanism typically encountered in single screw extruders. More recently, Essegir *et al.* (1996) studied the melting mechanisms of single component polymers in kneading blocks of a twin screw extruder through carcass analysis as an attempt to gather the information necessary for the development of heuristic models. Although various types of materials having different particulate sizes and thermo-mechanical properties were studied in their research, there are still less understanding of effects of the particulate size and addition of additives on melting in a twin screw extruder. Therefore, in this study, it is intended to examine two main aspects: (i) effect of particulate size and (ii) addition of lubricant or abrasive additive on the evolution of melting in a twin screw extruder.

## 2. Experimental

### 2.1. Materials

The materials used in this study are all commercially available polymers and their details are summarized in Table 1. The PP6501 is a free flowing powder with particle sizes ranging from 20 to 400  $\mu\text{m}$ . The majority of the particles are of 200 to 300  $\mu\text{m}$  in size. For stabilization purpose, 0.5% of Irganox 1010 powder and 0.25% of Irganox B225 have been added. The friction coefficients between barrel surface and polymer for various types of PP were measured as a function of pressure discharge following a procedure proposed by Lee (Kim *et al.*, 1999). The friction coefficient of PP6501 was found to be  $\sim 0.34$ . PP6523 is a stabilized grade in the form of disk-shaped pellet with 3 mm of diameter and 2 mm of height. The friction coefficient of PP6523 was found to be  $\sim 0.25$ . PE wax has micro-palletized form which is in spherical shape with 1mm of diameter. Compared to PP, PE wax has a very low melting point in the range of 55-60°C and exhibit a constant viscosity of  $4.0 \times 10^{-3} \text{ Pa} \cdot \text{s}$  at 175°C. The clay used

in this study is calcined kaolin, which is a very fine powder with average size of 1.4  $\mu\text{m}$ .

### 2.2. Twin Screw Extrusion

Several blend experiments were carried out on the 30 mm (length to diameter ratio,  $L/D = 11.4$ ) Twin Screw Mixing Element Evaluator (TSMEE, W & P) at controlled feeding rate of 11.35 kg/hr using an Acrison loss-in-weight feeder. As described elsewhere (Gogos *et al.*, 1994), the advantage of this type of extruder is that barrel can be opened for carcass examination. The extruder was run at 250 rpm and at a barrel temperature of 180°C. The TSMEE was configured with a series of individual conveying elements and kneading paddles arranged in a forwarding array, followed by a reverse element whose purpose is to fill the forwarding element. The schematic diagram of the screw configuration is given Fig. 1, where the numerical numbers denote various  $L/D$ 's. For each run, after steady state operation for a sufficient period of time, process variables were recorded, and the barrel was quickly cooled with tap water circulation as soon as the machine and feeder were stopped. The barrel was then opened for carcass examination at room temperature. Samples were taken along the screw length, beginning with the solid particles at the feed zone to the fully homogenized melt region.

## 3. Results and Discussion

### 3.1. Melting of PP powder

#### 3.1.1. Pure PP powder

The sequence of images illustrating the various stages leading to melting of pure PP powder is shown in Fig. 2. Samples taken along with the conveying and kneading sections until screw position of  $L/D = 6.5$  have shown the presence of free flowing powder, indicating there is little to

Table 1. Materials used in this study

Material	Designation	Maker	Form	T <sub>g</sub> (°C)	T <sub>m</sub> (°C)
Polypropylene	PP 6501	Montell	Powder	-20	165-175
	PP 6523	Montell	Pellet	-20	165-175
Polyethylene wax	PE wax	Frank Ross	Micro-pellet	N/A	55-60
Clay (Translink)	Clay	Engelhard	Powder	N/A	N/A

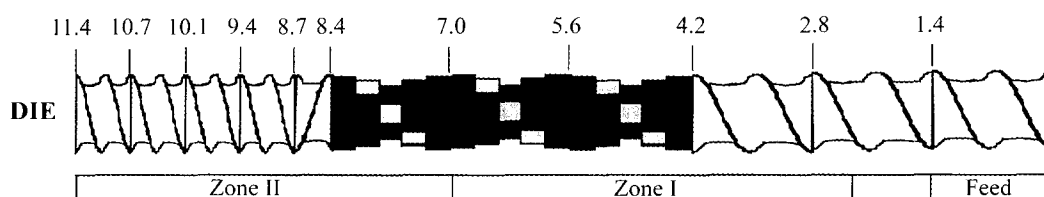


Fig. 1. Schematic diagram of screw configuration used in this study.

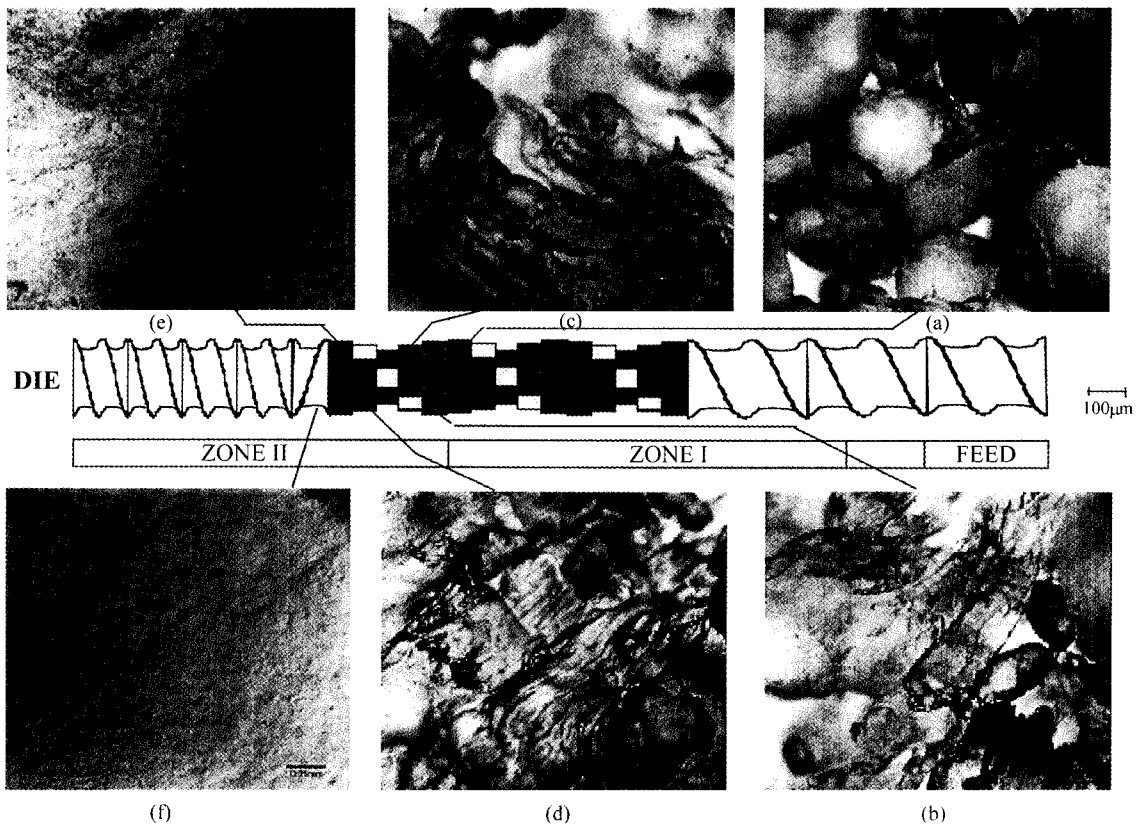


Fig. 2. Evolution of melting on pure PP powder.

no interparticle friction. Up to this region, powders are brought in contact with hot barrel and screw surface by tumbling of solid particulates, which leads to the formation of melt film on the barrel side. At screw position of  $L/D = 7$  (Fig. 2(a)), evidence of mild compaction and deformation of particles is found, which is associated with the tumbling in previous stages and interparticle friction. Here, pressure is built up and particles begin to compact into a solid plug. The next image (Fig. 2(b),  $L/D = 7.3$ ) shows the initiation of melt formation. The structure has been compacted further and particles begin to bond. Energy dissipation in this section is dominated by frictional heating (Esseghir and Yu, 1996), and sufficient heat dissipation can be generated to a point where small particles can be brought up to the melting point. More compaction is observed in Fig. 2(c) ( $L/D = 7.6$ ) where intensive deformation of particles is facilitated by shearing and compression. As melting progresses, the molten material engulfs individual or groups of solid particles and a melt pool is formed as described in Fig. 2(d) ( $L/D = 8.1$ ). Heat dissipation for further melting of the remaining solid particles would now mainly come from viscous energy dissipation (VED) in the molten phase. The heat generated by VED mechanism is consumed by a conduction process to melt the remaining solid as well as to induce the further rise of the melt temperature. Fig. 2(e) and Fig. 2(f) show

homogeneous melt structure in the entire bed.

### 3.1.2. Effect of Lubricant on Melting of PP powder

When a lubricant is added into the system, melting is expected to occur with less interparticle friction; consequently melting is delayed as described in our previous paper on batch experiment (Kim *et al.*, 1999). The sequence of images shown in Fig. 3 illustrate the various steps leading to melting of PP powder with PE wax as a lubricant. Through the conveying section to screw position of  $L/D = 5.9$ , carcass sampling has shown presence of free flowing powder and the similar results were obtained for polypropylene powder without additive. At screw position of  $L/D = 6.2$ , the agglomeration of particles was observed because earlier melted PE wax wets the surface of particles and rapidly fills the void volume between particles so that the particles are stick together and form an agglomerate. An important fact is that the agglomerated state is different from the state of compaction in which pressure is built up and particulates begin to compact into a solid bed caused by down stream obstruction caused by the reverse element. By constructing the agglomerated structure, heat dissipation by tumbling may be more effective than that of pure PP powder within the same  $L/D$  because wetted PP particles by melted PE wax has better surface contact between particles and barrel. In addition such agglomerated structure would indicate increased torque, as will be presented

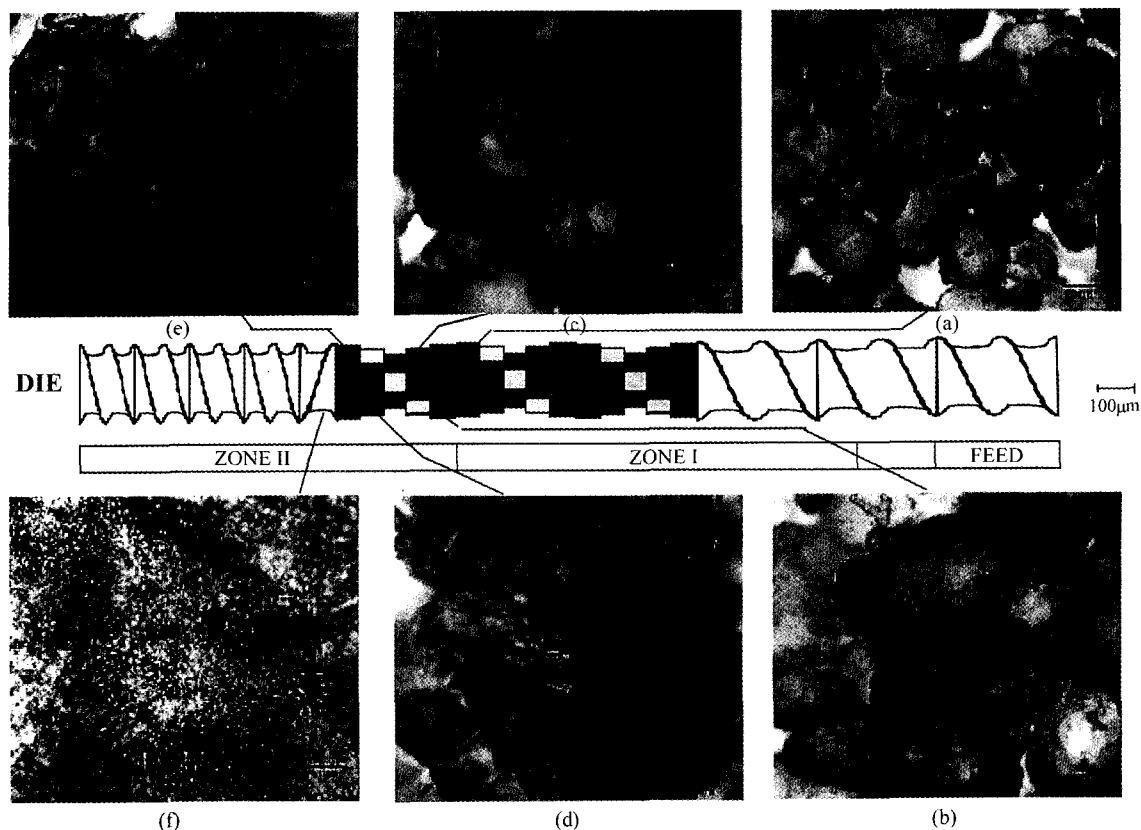


Fig. 3. Effect of lubricant addition on melting of PP powder.

detail in the later section.

Fig. 3(a) shows few deformed particles with mild compaction. Further compaction is observed in Fig. 3(b) where the initiation of melt is illustrated. The structure here has been compacted further and particles begin to bond. In Fig. 3(c) and Fig. 3(d), more deformation is observed, however still several solid particles are seen in the melt pool. Extensive delay of melting is evident here, as compared to the case of pure PP powder, since shearing between particles and/or between the particles and the barrel wall is limited by the presence of the lubricant. Obviously, this is due to the fact that the lower viscosity generates less heat by VED to melt the remaining solid particles in a molten pool, resulting in retardation of melting. The evidence of this lubrication effect is observed through Fig. 3(c) to Fig. 3(f). This figures show that some highly deformed particles are still in the non-homogeneous molten surround.

**3.1.3. Effect of Abrasive Additive**

By adding clay as an abrasive additive, melting occurs under the influence of a larger interparticle friction accompanied with high frictional heat, more mechanical energy and higher viscous energy dissipation; melting rate is higher than the case of pure PP powder. Since clay has a very small particle size (1 to 2 µm), compared to the size of the powder (200 to 300 µm), the void volume between the powder particles may be partially filled by adding 2%

of clay. This leads to better surface contact and generates higher friction between PP particles or between PP particles and the barrel wall.

Fig. 4(a)(L/D = 7) reflects the influence of such environment in which the frictional heat is more dissipated than in the pure PP experiment. The higher dense compaction has been observed to support this phenomenon. Fig. 4(b) shows that the higher deformed particles by energy dissipation of high compression and shearing are found, although still less deformed particles are shown. Comparing this state to Fig. 2(b) or Fig. 3(b), the melting rate for PP/clay is apparently faster. Fig. 4(c) shows that the highly deformed particles are engulfed in the molten surrounding, and further melting would be caused by VED from this section.

**3.2. Melting of PP Pellets**

**3.2.1. Pure PP pellets**

Here melting occurs with less or no interparticle friction, but earlier deformation of pellets plays major role in melting PP pellets. The sequence of various steps for the entire process is illustrated in Fig. 5. Until screw position of L/D = 4.8 (Fig. 5(a)), little to no deformation has occurred in pellet and 80% or more free pellets are presented in this area. Evidence of shearing, the forming of a very thin film on the barrel side, is clearly found when the barrel tem-

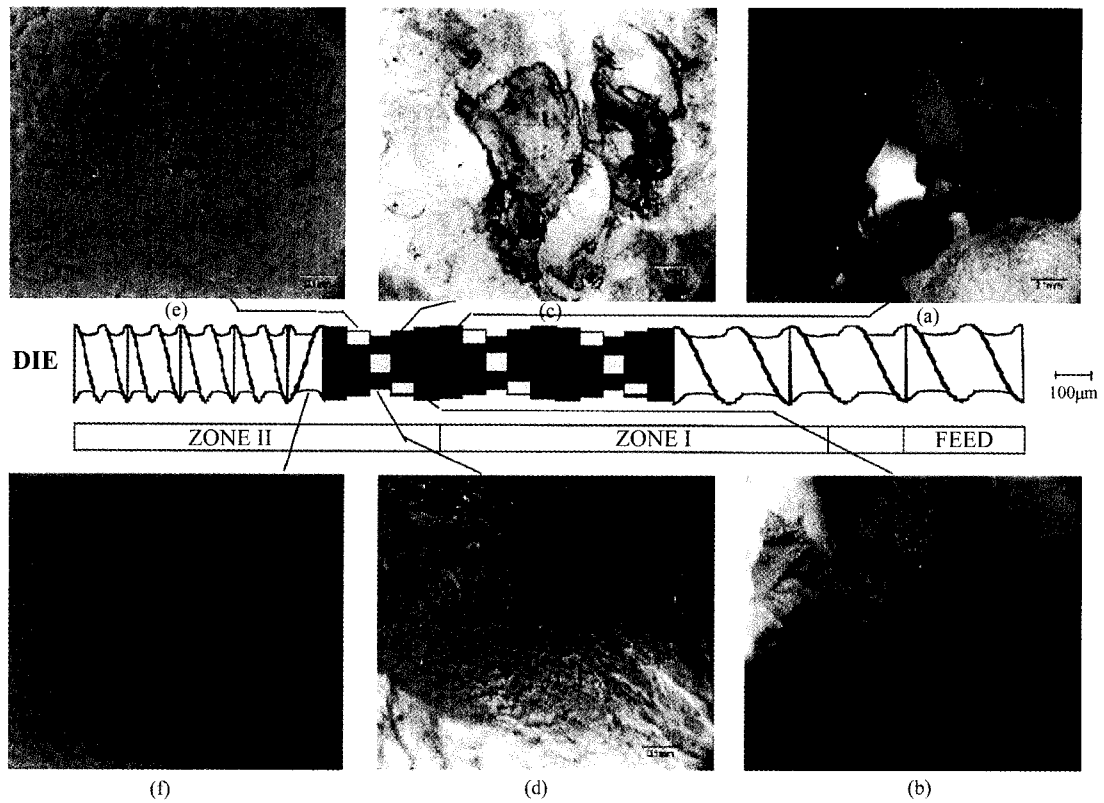


Fig. 4. Effect of clay addition on melting of PP powder.

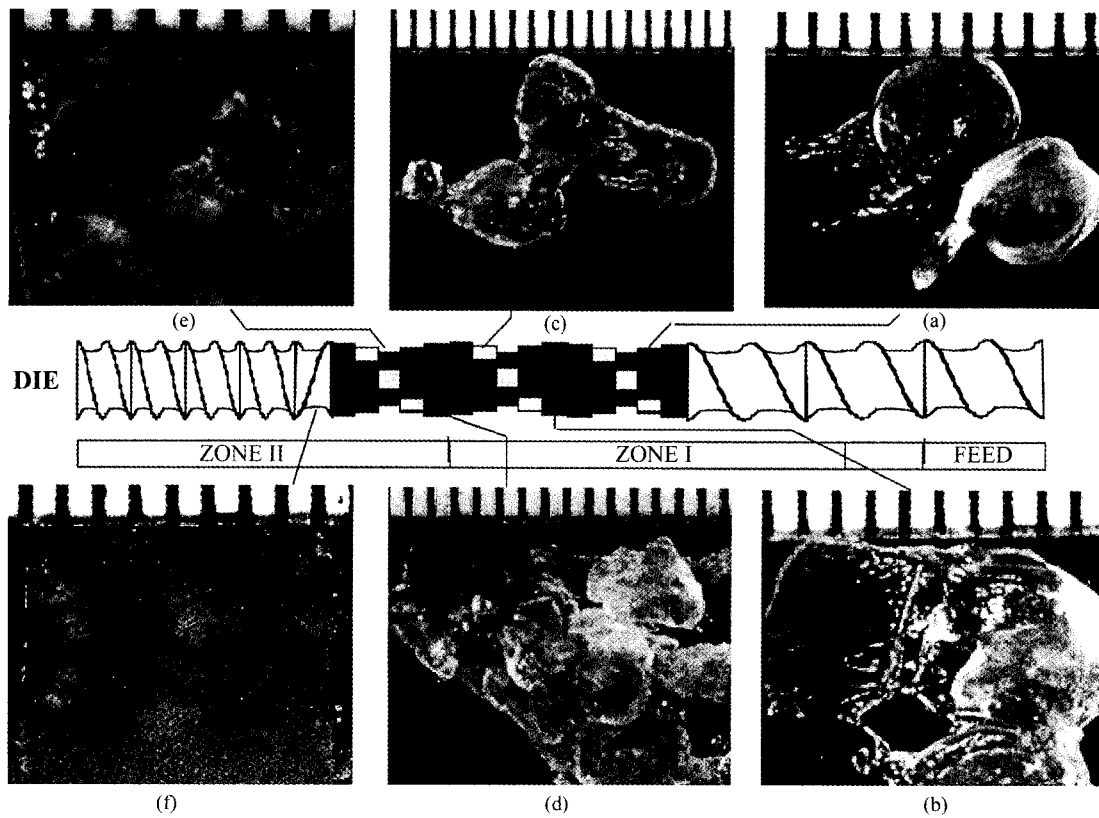


Fig. 5. Evolution of melting on PP pellet.

perature is maintained slightly above the melting temperature of PP(180°C), and when high rotor speed is maintained. By position of L/D = 5.9 (Fig. 5(b)), the extensive deformation of solid pellets is possible. Most of the pellets are deformed severely and some totally deformed pellets are found. The other two or three pellets are stuck together so that they show the evidence of flattening by compression. Thus, the deformation up to this position is attributed to compression and shearing. Energy dissipation is mainly due to the deformation of pellets and partly due to interparticle friction and tumbling in a hot environment. Fig. 5(c)(L/D = 6.7) indicates that the pellets have just started to bond together and melt fusion has begun. Most of the flattened pellets with the thickness of 0.6 mm are bonded together forming a compacted structure. Heat dissipation is dominantly due to compression at this position. By position of L/D = 7.3 (Fig. 5(d)), softening of pellets has occurred for extensive compaction. The pellets are further extensively deformed and are compacted together to form an interpenetrated structure of thin layers. The continuation of melt fusion is also taking place in this section. From L/D = 7 through L/D = 7.8 (Fig. 5(e)), the compacted plug of thin layer is being deformed at an accelerated pace by shearing. The shearing action takes place and dissipates heat in a homogeneous fashion. In the later section of this position, some highly deformed layers of material are surrounded by molten pool. Heat dissipation is mainly attributed to viscous energy dissipation in melt phase for full melt (L/D = 8.7, Fig. 5(f)).

**3.2.2. Effect of Lubricant and Clay**

The entire fashion of the evolution of melting in both cases was not much different from the case of pure PP pellets. Instead, the major distinction arose from the melting rate mainly because of the different frictional effects. As previously mentioned in the melting of pure powder, by adding PE as a lubricant, melting occurs with less interparticle friction and lower viscosity than pure PP pellets, which is associated with reduced frictional heat and VED; thus, melting is delayed. On the other hand, introduction of clay into PP pellets represented a remarkable frictional effects; deformation rate is a lot higher than that of either pure PP pellets or PP pellets/PE wax, which results in faster melting.

**3.3. Interpretation for the Data of Torque and Melt Temperature**

The data for torque and exit temperature of the system based on PP powder and pellet are presented in Fig. 6 and Fig. 7, respectively. The torque value for pure PP powder was measured to be about 23% which is lower than that of pellet form. Since the size of the powder (200~300 μm) is smaller than that of pellets, less resistance in between powder particles or powder and gaps formed from screw tips and barrel wall is experienced. Accordingly, conveying of

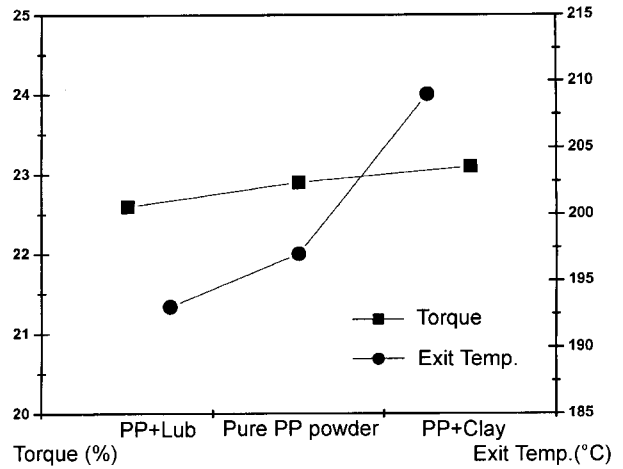


Fig. 6. Torque and exit temperature data for PP powder.

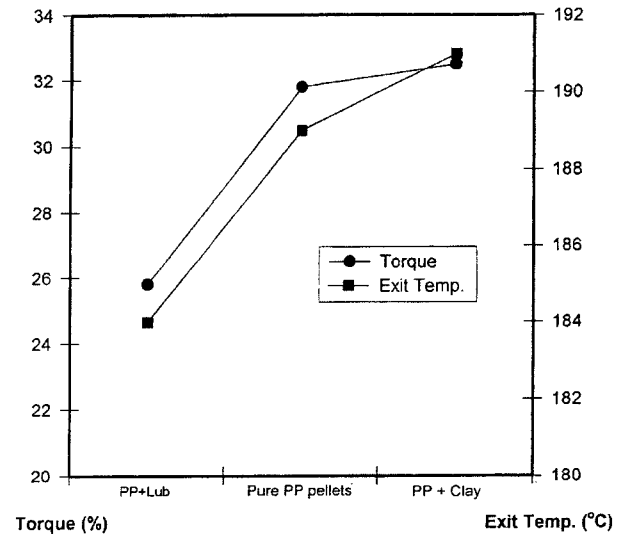


Fig. 7. Torque and exit temperature data for PP pellet.

powders is much easier than that of pellets, even though the frictional coefficient of powder is higher, leading to lower torque. Torque for PP powder/lubricant system is presented to be 22.6%, which is about the same value as for the experiment with pure powder. Two factors may be important in maintaining the torque at the same level as pure powder. First, the particle size of PE wax which is about 1.0 mm in diameter would increase the torque as explained in our previous paper (Kim *et al.*, 1999). The other factor is, as stated earlier, that torque can be increased by increasing the length of the agglomeration and compaction. Thus the torque will be increased as the density of the material increases in L/D required for melting section, as compared to an empty or a partially-filled section. Generally, torque during extrusion should in principle depend on discharge pressure, friction coefficient between material and barrel and the length of the compacted section. Obviously, friction coefficient of lubricated system is lower than that of

pure PP powder; however, due to the extended length of compaction, similar level of torque is maintained by the interplay of these two factors. Within this rationale, consistent torque is feasible in the system of PP/clay where shorter compaction range and higher friction coefficient are mutually compromised.

The torque for PP pellet/PE wax was measured to be 25% which is 6% lower than that of pure PP pellets. Again, the effect of lubricant on the overall torque can be consistently interpreted with the same notion above; the length of compaction here is about the same as that of pure PP pellets, while lubrication effect causes less friction.

The exit temperature of pure PP powder was about 10°C higher than that of pellets, which is due to the fact that small particles would cause higher friction and generate larger frictional heat dissipation energy, thus raising the temperature under the same operating conditions. The trend found in Fig. 6 and Fig. 7 reflects the fact that the exit temperature is closely related with the friction coefficient of the given system. Of course, the level of melt viscosity in the composition is, in part, pertinent here.

#### 4. Summary and Conclusions

Particle size has large effect on melting rates for pure PP, PP/PE wax, and PP/clay blends for both batch and continuous experiments. In twin screw extrusion, L/D required for melting is observed in shorter length when the particle size is smaller. Melting was delayed by the effect of lubrication in both blends with PP powder and pellet. Unlike batch mixing, where materials occupy and are melted in a fixed volume, melting in continuous process is governed by reduced interparticle friction and lower viscosity caused by the action of lubricant, which leads low frictional heat, less mechanical energy, and lower viscous energy dissipation, thus melting is delayed. Melting rates of PP pellet/clay

blends have been accelerated in both batch and continuous experiments compared to pure PP or PP/PE wax blend. Here melting occurs with large interparticle friction due to the fact that clay acts a abrasive additive which leads to high frictional heat, more mechanical energy and higher viscous energy dissipation, thus melting is expedited.

There was little variation in the torque of PP powder upon adding additives, while significant variation was observed in PP pellet based blends. The tendency found from the measurement of torque for various materials examined in this study is well understood by the interplay of two factors: friction coefficient between material and barrel and the length of the compacted section. In addition, the exit temperature appears to be affected by the particle size; since smaller size of PP powder has a high friction coefficient than large size of PP pellets, heat dissipation by powders is larger than that of powder, thus exit temperature rises.

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