Mechanical and Thermal Characterization of Melt-Filtered, Blended and Reprocessed Post-Consumer WEEE Thermoplastics

Erik Stenvall * and Antal Boldizar

Materials and Manufacturing Technology, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden;
antal.boldizar@chalmers.se
*   Correspondence: erik.stenvall@borealisgroup.com; Tel.: +46(0)73-062-83-68

Abstract: A melt-blended and melt-filtered real post-consumer and recyclable waste electrical and electronic equipment plastics blend (WEEEBR) was studied, where the WEEEBR contained mainly acrylonitrile-butadiene-styrene copolymer (~40 wt %), high impact polystyrene (~40 wt %) and polypropylene (~10 wt %). The main aim was to better understand the influence of different reprocessing conditions on the mechanical and thermal properties of WEEEBR and to compare these properties with the corresponding properties of model material blends of samples from single screw extrusion, twin screw extrusion and injection molding. For all the reprocessing alternatives studied, WEEEBR was found to be processable and an acceptable surface character could be obtained within narrow processing condition windows. It was found in particular that the reprocessing conditions influenced the elongation at break of WEEEBR, and to a lesser extent also the width of the polypropylene melting temperature region. The highest yield stress and elongation at break of WEEEBR was obtained after twin-screw extrusion at low barrel temperatures (180–200 °C) and a low screw rotation rate (60 rpm). Injection molding produced brittle materials with low impact strength, possibly due to molecular orientation effects.

Keywords: WEEE; blend; extrusion; reprocessing

1. Introduction

Legislation provides strong incentives for increasing the recycling of plastics from waste electrical and electronic equipment (WEEE) [1]. Previous studies have indicated that WEEE consists of about 20–33 weight % (wt %) plastics [2,3]. A higher plastics content has been found in small WEEE, around 35 wt % [4] and as much as 60 wt % in waste from cell phones [5]. The plastics are mainly re-meltable thermoplastics of many different types, but acrylonitrile-butadiene-styrene copolymer (ABS), high impact polystyrene (HIPS) and polypropylene (PP) have been found to constitute the main part of the WEEE plastics fraction [4,6–9].

Although there are many different waste management options for WEEE, landfilling is probably still the most frequently employed option globally [10]. In the European Union, the reuse and recycling rates are relatively high, the problem being that the collection rate in many countries is low and imposes significant uncertainties in the WEEE management [11]. The main alternatives for waste management of plastics, apart from landfilling, have been presented as energy recovery, feedstock recycling and mechanical recycling [12]. Feedstock recycling has not been commercialized to any significant extent, mainly due to the high costs of the processes and the low quality of the feedstock produced compared to that of normal grade commercial feedstock [13]. It has previously been shown from a life cycle assessment perspective that there are significant benefits in mechanical recycling of

waste plastics rather than using the waste for energy recovery, with regard to both resource utilization and greenhouse gas emissions [14]. Considerable efforts have been devoted to the mechanical recycling of plastics by separation of the different plastic types normally occurring in the mixed WEEE stream [15]. The separation of different plastic types has been associated with large investment costs, and many of the separation technologies used have a limited efficiency, often producing substantial residue fractions or partially contaminated materials. For example, density-based separation techniques have limited efficiency in separating plastics containing different amounts of additives, since the additives may have a large influence on the density of the plastic [16]. This means that it is also necessary to consider blending mixed WEEE plastics when performing mechanical recycling, especially when the waste volumes or investment possibilities are limited. One often mentioned drawback of blending mixed WEEE plastics is the variation in composition. To some extent, the variation in composition cannot be avoided, but on the other hand, waste management sampling studies have shown the main components in such a blend to roughly be found in similar amounts in several different studies [6,8,9]. Most likely, additives and compatibilisers are also necessary to enhance and even out the properties of mixed WEEE plastic blends. In particular, antioxidants should be important considering recycling of such blends, to avoid premature degradation of the plastics during the reprocessing and use-phase and to not exclude the possibility of repeated recycling.

It has however been found that a WEEE plastics stream that can be considered to be recyclable may also contain 1–2 wt % non-thermoplastic contamination that cannot be melted in a conventional plastics processing machine and thus significantly lowers the quality of the recycled material [9]. Different types of melt-filtration have previously been used to remove this non-thermoplastic contamination in a continuous recycling process [17].

The present study considers the possibility of recycling a WEEE plastics blend (free of brominated flame retardants) by continuous melt-filtration followed by various reprocessing alternatives. This approach builds on previous studies of the WEEE plastics composition [9] and on the mechanical and thermal properties of model material blends [18]. The two main aims of this work were to study the mechanical performance of a melt-filtered WEEE plastics blend and to compare it with model material blends of similar compositions and also to study the influence of the processing conditions during recycling on the mechanical and thermal properties of the product.

Previous studies have indicated that ABS and HIPS are miscible at least in some proportions, since the mechanical properties followed the rule of mixtures and the blend had a common glass transition (T_g) well predicted by the Fox equation [19–21]. Although most mechanical properties of a HIPS/ABS blend seem to follow the rule of mixtures, blending the two plastics may have a detrimental effect on the impact strength [22]. It has also been reported that some reprocessing procedures may result in a partial separation of the ABS from the HIPS component. In particular, ABS has been seen to form a skin around a more HIPS rich core in injection molding [23]. Although HIPS and ABS have been found to be compatible under some conditions, blends of polyolefins and polystyrenes are normally considered immiscible with a low interfacial adhesion [24,25]. The incompatibility of these blends is also reflected in the mechanical properties, such as impact, tensile and flexural strength. Lower mechanical properties than would be expected from the rule of mixtures have, for instance, been reported for blends of ABS and PP [22]. A contamination content of 6 wt % PP in recycled ABS has been reported to lead to a significantly lower impact strength and yield stress, and the elongation at break was reduced to almost one fourth of that of the uncontaminated recycled ABS [16]. Poor injection molding processability was also reported for ABS blends contaminated with PP [22]. In general, the commonly used mechanical characterization methods for blends with different combinations of HIPS, ABS and PP are tensile testing and impact testing [19,22]. Differential scanning calorimetry (DSC) and dynamic mechanical thermal analysis (DMTA) have also been used to study the miscibility of polystyrene and polyolefin blends [19,20,22].

2. Experimental Section

2.1. Materials

The material used was a melt-blended and melt-filtered WEEE plastics blend of recycled material (WEEEBR) from post-consumer waste. This material should be compliant with the European directive on the "Restriction of the use of certain Hazardous Substances in electrical and electronic equipment" (RoHS) [26]. This collected post-consumer waste plastics blend was obtained from Stena Technoworld in Halmstad (5 July 2011), and it has previously been analyzed with respect to its composition [9]. Prior to being reprocessed in our laboratory, the material had undergone a dust- and surface-cleaning, melt-blending, melt-filtration and hot die granulation at Next Generation Recycling Machinen in Feldkirchen, Austria. The recycling equipment used was an S:GRAN 85 in conjunction with an Ettlinger rotating drum melt-filter and hot die granulator. The extruder was run at a screw rotation rate of 145 rpm, a throughput of 280 kg/h and a temperature profile of 210-230-190-190-210-230 °C. It was found that the continuous Ettlinger melt-filter filtered out about 1 wt % of mainly non-thermoplastic contamination in order to form the WEEEBR material. WEEEBR was compared to two model material blends; one ternary blend of virgin ABS, HIPS and PP (TBV, Ternary Blend of Virgin plastics) and one ternary blend of collected and separated fractions of ABS, HIPS and PP (TBR, Ternary Blend of Recycled plastics). A more detailed description of the compositions of the TBV and TBR can be found in a previous work [18].

2.2. Processing Equipment

WEEEBR was melt processed by single screw extrusion (SSE), twin-screw extrusion (TSE) or injection molding (IM). The SSE used was a Collin type 132 single screw extruder with a 50 × 1.5 mm slit die. It had a conventional polyolefin processing screw with a diameter (*D*) of 25 mm, a length of 25*D* and compression ratio of 1.93. The screw rotation rate was kept at 60 rpm and the cylinder temperature profile was straight at 180, 200 or 220 °C. The extrudate was oriented and flattened by a 3 + 2 roll puller, type Brabender 843316003.

The TSE was a co-rotating Werner & Pfleiderer ZSK 30 M9/2 (1984) with five heating zones along the barrel and one heating zone for the die. The length of the screws was 966 mm and the barrel bore diameter 31 mm. The configuration of the screws had been optimized for mixing and compounding, as shown schematically in Figure 1. In this case, screw rotation rates of 60, 90 and 120 rpm were used and the temperature profiles are shown in Table 1. A humped barrel temperature profile was applied for all twin-screw extrusion runs to avoid over-heating and resin degradation [27]. The roll puller used for SSE was also used for TSE. In both cases, the roll puller was set to achieve a draw down ratio of approximately four, which had previously been found to yield the highest ductility of TBV [18].
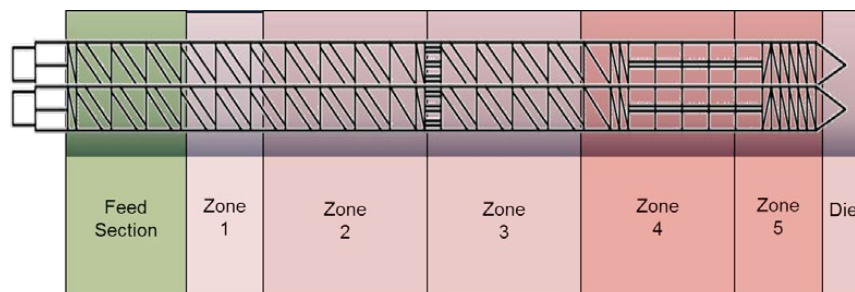

Figure 1. The twin-screw extruder (TSE) screw configuration and zone distribution along the screw. The feed section and Zones 1–2 consist mainly of fast transportation elements and end with one pressure element, then one mixing and four fast transportation elements follow in Zone 3. Zones 4–5 consists of two pressure elements, five mixing elements (kneading blocks), one reversed flow pressure element, and five pressure elements.

Table 1. Twin-screw extrusion (TSE) temperature profiles used.

Twin Screw Extrusion	Temperature Profile ("Hopper to Die")
T1	140-170-170-180-180-170 °C
T1.5	150-180-180-190-190-180 °C
T2	160-190-190-200-200-190 °C
T2.5	170-200-200-210-210-200 °C
T3	180-210-210-220-220-210 °C

The IM was performed with an Arburg Allrounder 221M 250-55 (1996) with a maximum clamping force of 250 kN. The dimensions of the screw were 25 mm in diameter (*D*) and 20 *L/D* (length/*D*). From hopper to nozzle, the temperature profile used was 140-180-180-190-180 °C (LT, Low Temperature) or 160-220-220-230-220 °C (HT, High Temperature). The mold was oil-tempered to 60 °C. The sample shapes produced were according to ISO (International Organization for Standardization) 3167-B (single cavity) for impact testing and ISO 527-2-5B (twin cavity) for tensile testing. The processing conditions used to produce the samples are listed in Table 2.

Table 2. Injection Molding (IM) setup, ISO 3167-B for impact testing and ISO 527-2-5B for tensile testing.

Cavity Standard: Parameter/Dimensions	ISO 3167-B	ISO 527-2-5B
Thickness	4 mm	1 mm
Mass (including sample, runners, sprue)	14 g	3.9 g
Total Cycle Time	**30 s**	**11 s**
Injection Time	0.7 s	0.2 s
Holding Pressure Time	8 s	2 s
Total Cooling Time	24 s	5 s
Holding Pressure	700 bar	800 bar

2.3. Material Characterization

The modulus of elasticity, yield strength and elongation at yield and break were determined. For some brittle materials, the yield strength was not obtainable and the stress at break was instead measured. The tensile properties were measured with a Zwick/Z 2.5 tensile tester equipped with pneumatic grips and a 500 N load cell. The test bars were produced from extruded strips by die punching and had a thickness of 0.5–0.8 mm. Tensile tests were performed at 22 ± 2 °C and $40\% \pm 10\%$ relative humidity (RH). The cross-head speed during tension was set to obtain a strain rate of 10% elongation per min and a pre-load of 1 N was used. Seven tensile test specimens were evaluated for each type of sample, and samples failing within the clamped region of the test bars were discarded from the evaluation. Average values for seven samples were calculated and the standard deviation was taken as a measure of statistical uncertainty unless otherwise stated.

The impact properties were evaluated by a Charpy Edgewise single notch test according to ISO 179/1eA. The impact tester was a CEAST 9850 with impact energy of 0.5 J. The samples were notched with a CEAST AN50 to a final notch depth of 2 mm by repeated cutting of 0.1 mm 20 times at a cutting speed of 16 m/min. The impact specimens were cut, notched and evaluated at Swerea IVF (in Mölndal, Sweden). Nine impact specimens were evaluated for each material and average values and standard deviation were calculated.

Thermal properties were studied by differential scanning calorimetry (DSC), with a Perkin Elmer DSC7, equipped with an intracooler. Samples approximately 10 mg in weight were punched out from thin extruded strips or from injection molded test bars and placed in aluminum crucibles. The transitions were studied by heating from 50 to 200 °C at a rate of 10 °C/min in a nitrogen environment. Two measurements per material type were used and the results were averaged.

3. Results and Discussion

3.1. Mechanical Properties

To better understand the relationship between material quality and reprocessing, WEEEBR has been reprocessed by SSE, TSE and IM, and for each melt-blending technique, different processing conditions have been used. A small part of the study concerned the influence of moisture on the properties of the WEEEBR. Although most thermoplastics found in WEEE are non-hygroscopic, ABS normally requires drying prior to processing due to the acrylonitrile content, for example, four hours at around 90 °C [27]. It has also been reported that talc-filled PP and plastics containing carbon black absorb moisture and require drying [28]. Since all these plastics have previously been found in the studied WEEE stream [29], it was important to study the moisture-sensitivity of WEEEBR. It was found that WEEEBR absorbed less than 0.2 wt % of water, after saturation by immersion in water. A comparison study of seven samples dried according to the recommendations for ABS and seven samples stored at 40% $\pm$ 10% RH, all processed in the same way by TSE, showed no significant differences in stiffness (E), elongation at break (ε_b) or yield stress (σ_y). This applies to the short-term properties, and it is not clear whether the long-term properties might be affected by drying.

In Figure 2, stress at break (σ_b) is shown instead of σ_y, since WEEEBR did not yield before breaking when SSE was used, except for one sample processed at 180 °C. As can be seen in Figure 2, processing at 200 °C or higher resulted in very low ε_b and σ_b, probably due to excessive degradation of WEEEBR already around 200 °C, as was previously reported for TBV [18].
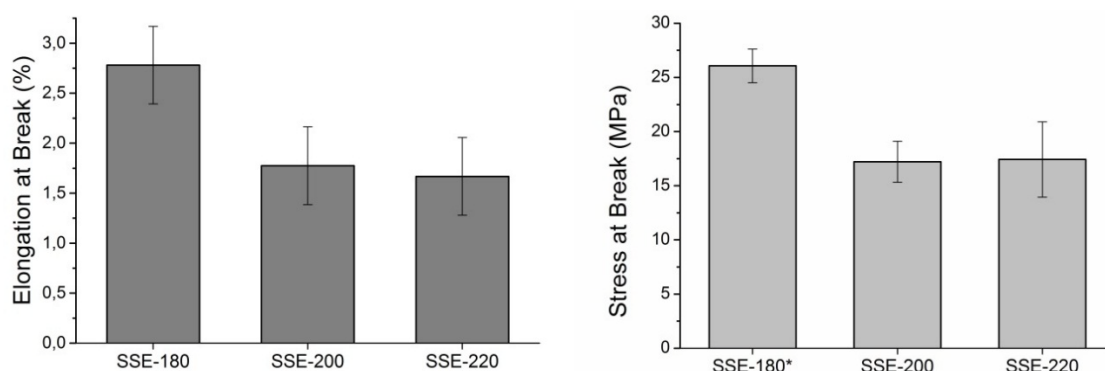

Figure 2. The influence of SSE barrel temperature (straight profile) on ε_b and σ_b for WEEEBR processed at 60 rpm. * Only samples breaking before yield have been included. Error bars show $\pm$ one standard deviation.

In the TSE reprocessing of WEEEBR, the screw rotation rate and barrel temperature were varied independently in order to study their influence on the mechanical properties of the collected and reprocessed blend. It is, however, well known that these parameters are not independent, as the melt-blending of WEEEBR is considered to be a complex interplay between screw design, feed rate, barrel temperature and shear rate. Figure 3 shows that processing at 60 rpm and avoiding the highest used temperature profile T3 were beneficial in increasing the ductility. A low screw rotation rate was previously found to result in a higher strength and ε_b of both TBV and TBR [18]. Processing at 60 rpm and T2 may be considered to be a favorable processing condition with TSE for WEEEBR, since it yielded the highest values of both ε_b and σ_y. Higher screw rotation rates are expected to result in considerable degradation due to the high shear rates which might, at least locally, increase the temperature load on the material.

Table 3 summarizes the main results from the TSE runs of WEEEBR, TBV and TBR under different processing conditions. Both E and σ_y tend to be slightly higher in the recycled materials than in the virgin materials, as has also been observed previously for HIPS, PP and compatibilised blends of these

two [30]. No significant differences were found in the elongation at yield (ε_y), except perhaps for TBV processed at 60 rpm and T1 that was the most ductile material, and exhibited a slightly higher ε_y than the other materials. An important characteristic of the materials was whether they exhibited a yield point. All TBV and TBR materials showed a yielding behavior, but for WEEEBR, it was mainly the materials processed at low screw rotation rates (60 rpm) or low barrel temperatures (T1 or T2) that showed a consistent yielding.
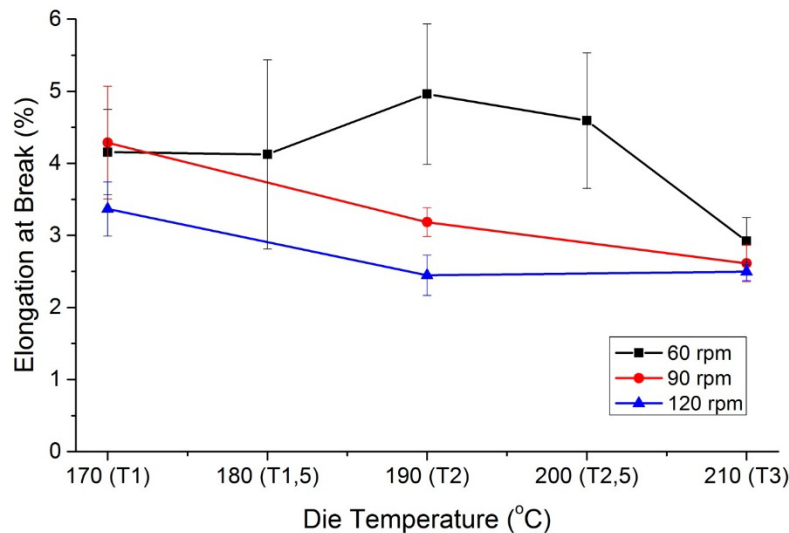

Figure 3. Elongation at break (ε_b) with respect to TSE temperature of WEEEBR at 60, 90 and 120 rpm screw rotation rate. The temperatures are referring to the die zone temperature. The complete temperature profiles are given in parenthesis and are explained in Table 1. The error bars show $\pm$ one standard deviation.

Table 3. Tensile properties for twin-screw extrusion (TSE) samples of waste electrical and electronic equipment plastics blend (WEEEBR), a ternary blend of virgin plastics (TBV) and a ternary blend of recycled plastics (TBR). The standard deviation were based on 7 samples except for; * average and standard deviation based on 6 samples; ** too few samples to calculate standard deviation, average based on remaining samples.

Samples	Tensile Modulus (GPa)	Yield Stress (MPa)	Stress at Break (MPa)	Elongation at Break (%)	Elongation at Yield (%)	Number of Samples Yielding
WEEEBR TSE 60-T1	1.20 ± 0.02	30.1 ± 0.4	-	4.2 ± 0.6	3.1 ± 0.2	7/7
WEEEBR TSE 60-T2	1.24 ± 0.01	31.6 ± 0.7	-	5.0 ± 1	3.2 ± 0.1	7/7
WEEEBR TSE 60-T3	1.23 ± 0.01	30.5 **	28.8 ± 0.5 *	2.9 ± 0.3	3.1 **	1/7
WEEEBR TSE 90-T1	1.24 ± 0.02	31.5 ± 0.5 *	31.4 **	4.3 ± 0.8	3.2 ± 0.1 *	6/7
WEEEBR TSE 120-T1	1.25 ± 0.01	30.4 **	29.9 **	3.4 ± 0.4	3.0 **	4/7
WEEEBR TSE 120-T3	1.29 ± 0.02	-	28.1 ± 1.1	2.5 ± 0.1	-	0/7
TBV TSE 60-T1	1.05 ± 0.03	28.6 ± 1.2	-	22 ± 9	3.4 ± 0.2	7/7
TBV TSE 60-T3	1.16 ± 0.01	30.7 ± 0.5	-	5.4 ± 0.6	3.2 ± 0.1	7/7
TBV TSE 120-T3	1.19 ± 0.03	30.3 ± 0.4	-	5.4 ± 0.9	3.0 ± 0.0	7/7
TBR TSE 60-T1	1.24 ± 0.04	33.1 ± 1.1	-	13 ± 6	3.2 ± 0.1	7/7
TBR TSE 60-T3	1.32 ± 0.06	34.7 ± 0.4	-	8.7 ± 5	3.1 ± 0.1	7/7

The IM of WEEEBR was very sensitive to the processing conditions, the level of holding pressure and the injection speed for instance, had an essential influence on the material quality. Only within a narrow processing conditions window could the material be injection molded. The first impression of some industrial partners was that the surface appearance could be considered acceptable for many applications.

The tensile properties of WEEEBR, TBR and TBV processed by SSE, TSE and IM under similar processing conditions are shown in Figure 4 and 5. The same screw rotation rate and draw down ratio was used in both SSE and TSE. Figure 4 indicates that E and σ_y for the recycled materials TBR and WEEEBR were higher than those of TBV for all processing methods, as is also shown for TSE in Table 3. Recycled plastics are often found to exhibit poorer mechanical properties than virgin ones, but the change in properties is not unidirectional [31], while TBR and WEEEBR were found to exhibit poorer ductility (Figure 5), they also exhibited higher E and σ_y than TBV (Figure 4). Figure 5 shows that IM at LT resulted in very brittle materials that did not yield and had very low ε_b-values. This was possibly due to the relatively fast mold cooling, producing a layered structure and different molecular orientations in the layers, as described by Pisciotti [32]. A comparison of the blends in Figure 5 shows that TBV had the highest ε_b-values and that WEEEBR had significantly lower ε_b than both model material blends. The higher ε_b-values of the blends produced by TSE than by SSE were probably due to better mixing in TSE, as the kneading blocks in the TSE can be expected to lead to a more efficient distributive mixing [33].
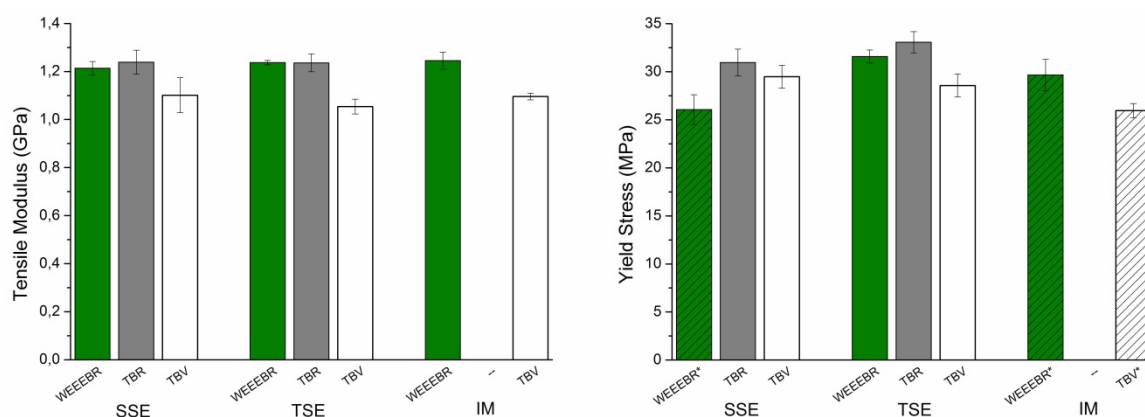

Figure 4. Comparison of E and σ_y when reprocessing WEEEBR, TBR and TBV by SSE, TSE and IM. The processing conditions were similar, about 180 °C barrel temperature and 60 rpm. * σ_b is used instead of σ_y for samples not yielding. Error bars show $\pm$ one standard deviation.
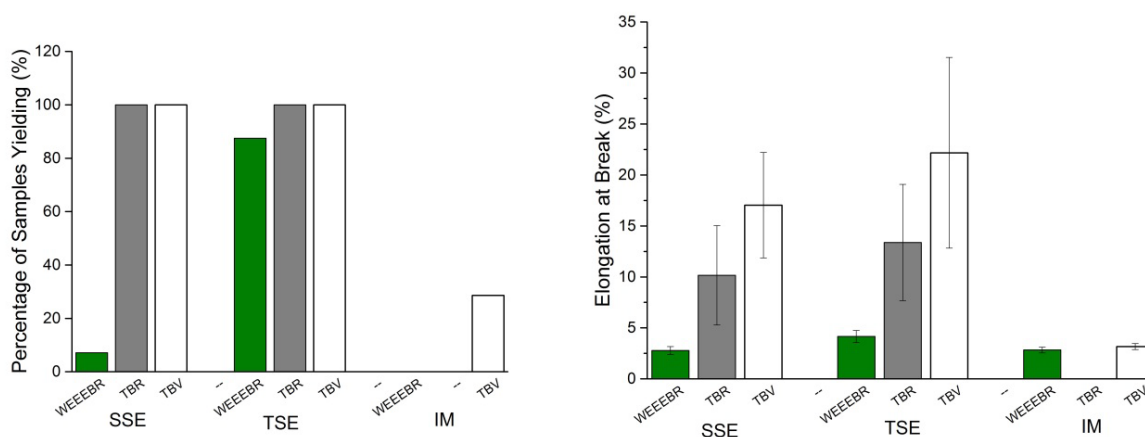

Figure 5. Percentage of samples yielding and ε_b when reprocessing WEEEBR, TBR and TBV by SSE, TSE and IM. The processing conditions were similar, about 180 °C barrel temperature and 60 rpm. Error bars show $\pm$ one standard deviation.

The impact strength shown in Figure 6 could indicate that injection molded WEEEBR and TBV had a limited compatibility between the different polymeric phases. Drying seems to have no significant influence on the impact strength, as was also concluded earlier when drying prior to tensile testing.

A slight increase in impact strength was however seen for WEEEBR injection molded at a temperature about 40 °C higher (HT) than LT.
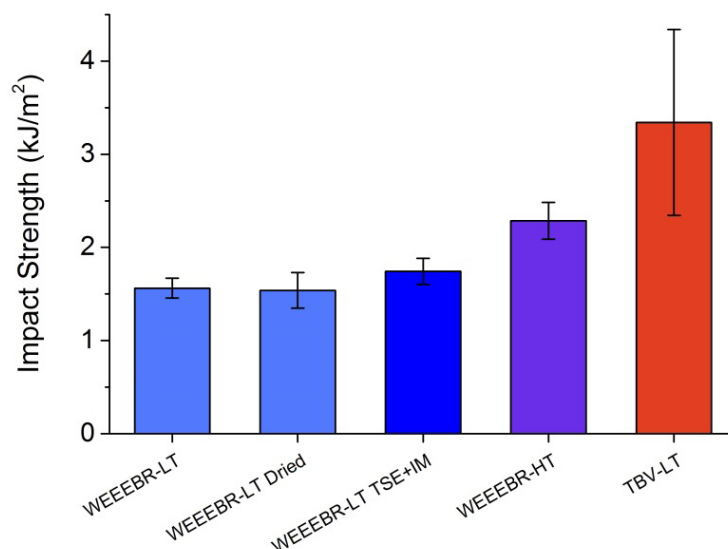

Figure 6. Charpy single notch impact strength of injection molded WEEEBR and TBV. Error bars show ± one standard deviation based on nine samples.

3.2. Thermal Properties

The influence of processing conditions on the thermal properties was more subtle than on the mechanical properties. Representative DSC curves for different ways of reprocessing WEEEBR are shown in Figure 7. An indication of a glass transition can be seen within the temperature range 100–115 °C. The individual glass transitions of the main components HIPS and ABS were, however, not distinguishable. The thermal analysis was focused on the melting of polyethylene (PE) and PP shown in Table 4. It has previously been reported that WEEEBR contains 1–2 wt % PE and around 10 wt % PP [9]. Since TBV is a ternary virgin blend, the PP fraction was free of any PE contamination, but both TBR and WEEEBR had PE in the blends. Both PP and PE are semi-crystalline thermoplastics and the amount of crystallinity can be expected to be of importance for WEEEBR because of the reinforcing effect of the crystals. Table 4 indicates that the onset temperature of the PP melting differs slightly depending on the reprocessing conditions of the WEEEBR. It was seen that WEEEBR processed by TSE and IM at HT exhibited the higher onset temperatures of the PP melting and a narrower peak distribution than, for instance, WEEEBR granules (before being reprocessed) and WEEEBR processed by IM at LT. The approximately 5 °C higher onset temperature of PP in WEEEBR processed by TSE and IM at HT indicated thicker crystals and a narrower crystal lamellar thickness distribution [34,35]. This may be related to a slower cooling rate at the crystallization temperature [36], which corresponds well with previous studies of a thin oriented skin region formed with IM at high processing temperatures [37]. The enthalpy of fusion of the PP fraction is indicated in Table 4 to be approximately 10 J/g for all the materials except TBR. Although this does not fully explain the lower enthalpy of fusion of TBR, a contributing factor may be the PE contamination of the separated PP fraction, resulting in a slightly smaller mass fraction PP than expected in TBR. From the enthalpy of fusion, a rough estimate of the degree of crystallinity of PP can be calculated according to Equation (1) [38,39]

$$X_c = \frac{\Delta H_{PP}(T_m)}{\Delta H_{PP}^0(T_m)(1 - m_a)} \tag{1}$$

where X_c is the weight fraction crystallinity, $\Delta H_{PP}(T_m)$ is the measured enthalpy of fusion for the PP melting in Table 4, $\Delta H_{PP}^0(T_m)$ is the theoretical enthalpy of fusion for the PP melting of a 100%

crystalline polymer and m_a is the mass fraction of non-polypropylene material. The value of $\Delta H^0_{PP}(T_m)$ has previously been reported to be 207 J/g for PP [40]. From Table 4, the weight fraction crystallinity was calculated to approximately 40 wt % for WEEEBR and TBV, while it was slightly lower for TBR. The calculated degree of crystallinity may be considered reasonable for PP, although the results calculated from Table 4 must be considered to be merely indicative due to the approximated figures for both the measured enthalpy of fusion and the weight fraction of PP in the blends.
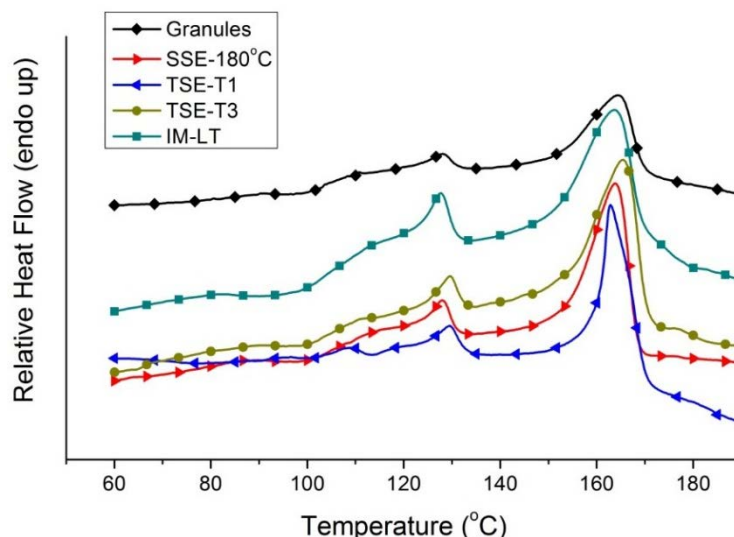

Figure 7. Some DSC curves of WEEEBR reprocessed in different ways.

Table 4. Thermal characterization of the melting of polyethylene (PE) and polypropylene (PP) by differential scanning calorimetry (DSC).

Samples	PE Melting Peak (°C)	PP Melting Onset (°C)	PP Melting Peak (°C)	PP Melting Point (°C)	PP Enthalpy of Fusion (J/g)
WEEEBR Granules	128	153	164	169	8
WEEEBR SSE-180	128	155	164	168	10
WEEEBR SSE-220	129	155	165	169	9
WEEEBR TSE-T1	129	158	163	170	9
WEEEBR TSE-T3	130	156	166	170	9
WEEEBR TSE + IM-LT	128	154	164	169	10
WEEEBR IM-LT	128	153	164	170	8
WEEEBR IM-HT	130	158	165	171	9
TBR TSE-T1	129	152	163	169	4
TBV TSE-T1	-	151	161	168	7
TBV TSE-T3	-	152	162	167	7

4. Conclusions

WEEEBR was found to have a potential to be processed by SSE, TSE or IM. Under favorable processing conditions, the surface character of WEEEBR was considered acceptable for many applications. It was also seen that the processing parameters used in SSE, TSE and IM had a significant influence on the mechanical properties, especially the properties related to ductility. The ε_b-value of WEEEBR was observed to be particularly sensitive to high processing temperatures or high screw rotation rates.

A comparison of SSE, TSE and IM showed that there were relatively different characteristics of the reprocessed materials. The reprocessing of WEEEBR by TSE was favorable for both σ_y and ε_b. Both TBV and TBR had higher ε_b values when processed by TSE, but σ_y was not significantly different

from that of SSE. Almost all the materials produced by TSE at low temperatures exhibited a yield point, which is an important material character for many applications. Materials produced by IM were more brittle than those produced by extrusion, probably because of their different states of molecular orientation. The brittleness was also seen in the impact strength, which indicated limited compatibility in the blends. Interestingly, higher impact strength was obtained for WEEEBR injection molded at a high temperature (HT), probably because it had a thinner skin region and more uniform orientation distribution in the cross-section.

WEEEBR was found to exhibit a low degree of water absorption. Drying the material prior to processing did not influence the properties significantly, as was seen for TSE and IM and has also been shown previously for TBV produced by SSE [18].

It can be concluded from the DSC studies that PE was present in all the real post-consumer recycled materials. The enthalpy of fusion of WEEEBR indicated that the degree of crystallinity of the PP (approximately 40 wt %) was independent of the reprocessing conditions. Although the degree of the crystallinity was similar, reprocessing by TSE or IM at HT seemed to narrow the PP crystal melting temperature region.

Author Contributions: Erik Stenvall; main author, has taken part in planning the experiments, experimental work, evaluating the results and main part of writing the manuscript. Antal Boldizar; supervisor, has taken part in planning the experiments and evaluating the results.

Conflicts of Interest: The authors declare no conflict of interest.

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