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Environmental stress cracking of polymers: case studies from industry (ABS and LDPE)

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Abstract

Two industrial examples are described which demonstrate how environmental stress cracking (ESC) can give rise to unexplained, apparently random and catastrophic in-service part failures. In the two case studies, the companies could not identify the cause of failure through normal quality control procedures. Mild environmental stress cracking (ESC) was suspected and this project aimed to investigate and replicate the failures in a laboratory setting. The first case study involved ABS (acrylonitrile butadiene styrene) consumer parts which were exposed to an ester-based lubricant/glue during assembly. Samples were exposed to this product and aged at a range of temperatures (18-80°C and at elevated humidity) for 6 months. The second case study involved medical grade LDPE (Low-density polyethylene) tubing for use in medical ventilators which was exposed to isopropanol as an assembly aid. The aim was to investigate whether adding an elastomer poly(ethylene-vinyl acetate), or if using an alternative solvent (methyl ethyl ketone) would reduce the likelihood of failure. In both case studies it was found that the failures were due to mild ESC. In the ABS parts it was due to the combination of the polymer, lubricant and residual stress from injection moulding. In the medical tubing, the failures were also determined to be as a result of ESC. It was found that blending the LDPE with an elastomer and using an alternative solvent reduced the likelihood of failure.

Introduction

Environmental stress cracking (ESC) is a well-known phenomenon which is one of the leading causes for the premature in-field failure of plastics [1]. ESC is characterised as the brittle failure of a polymeric part at an unexpectantly low stress level because of exposure to a liquid such as a solvent. While there are standards which describe methods to test combinations of polymers and liquids to see whether they will fail due to ESC, this requires knowing whether ESC is likely to be an issue. It can also be difficult to predict what liquids a part may be exposed to after it leaves the factory. Examples of ESC from literature include the failure of automotive ABS/PC and ABS parts after exposure to PVC plasticisers or hydrocarbon oils containing an ester additive [2]. The consequences of ESC failures can be severe, such as in the case of the cracked PC tubing connectors used to feed premature babies. The widespread failure of the connectors was attributed to exposure to cleaning fluids and resulted in several cases of babies suffering serious inflections [3].

Analysis of parts which have been recovered after failing in service have found that ESC is responsible for an estimated 15 to 40% of all in service failures [4–6]. Often residual stresses from processes such as injection moulding are sufficient to cause failure after the parts are exposed to the fluid phase. The exact mechanism of ESC is not fully understood [6,7]. The most widely held explanation is that the stress creates nanometre scale voids (<30nm) in the polymer and the fluid phase penetrates these and acts as either a plasticiser [6] (giving the polymer chains more mobility and allowing the void to grow) or lowers the surface energy necessary for void formation [8]. The process is complicated, with many factors affecting both whether ESC occurs and how quickly. The crystallinity of the polymer plays a role, as does the molecular weight and slight changes in these within a sample can affect whether a polymer part undergoes ESC [5,9]. While ESC is more frequently associated with amorphous polymers, it has also been widely observed in semi-crystalline polymers such as HDPE [10]. In this paper we describe ESC failures in both an amorphous and a semi-crystalline polymer (ABS and LDPE). The combination of polymer and fluid is critical to whether ESC occurs, but given the myriad number of options this is often difficult to assess [5,11,12]. It been reported that the Hansen solubility parameter can be used to predict which liquids are likely to pose a risk of ESC and that liquids with a moderate level of hydrogen bounds are particularly aggressive ESC agents [12]. However, outliers do exist, and it is difficult to measure the various components that make up the solubility parameter of liquids [4]. As industrial polymers can be blends, contain recycled material and/or additives; making changes to the grade or supplier of a polymer can also result in ESC occurring in parts were previously there were no issues. The same is true with the fluid which comes into contact with the polymer, as it is likely to not be pure and will have contaminants and/or be a mixture of several different liquids such as is the case with cleaning solutions. This is especially true if the polymer is exposed to an unexpected fluid outside of a factory. One example of this was LDPE pipes which were only found to be susceptible to ESC when exposed to a soap solution after they had been installed [6]. The applied stress is also critical for ESC and this further complicates predicting the chances of ESC occurring. A part may perform as expected, but then fail due to ESC as a result of an unexpected loading, a liquid randomly coming into contact with an area under stress or due to slight changes in the design/manufacturing changing the amount of residual stress in the part [4]. Often ESC occurs as a result of factors which the companies are not aware of, such as the parts being exposed to unexpected liquids after they are sold [4,5,11,12]. In a typical example, a normally ductile polymer component will fail unexpectantly in a brittle manner at a low loading level after exposure to the liquid. Examples of known ESC agents include soap and solvents [4]. ESC has also been reported after exposure to gas, such as in the case of PVC pipes exposed to natural gas containing benzene [13].

ESC is widely known within the academic community, and there are standardised [4,5,11,12] tests which can be carried out to predict whether the combination of polymer and fluid is likely to lead to a risk of ESC failure. However, in the author's experience the awareness of ESC within industry varies considerably and there is a significant lack of understanding of the issue particularly among smaller producers. With the required knowledge companies can quickly and accurately investigate if ESC will be a potential issue. Counter intuitively, extreme ESC is often less of a problem than mild ESC as although it results in more parts failing sooner, it highlights the issue quickly. Mild ESC means that it may be months or even years before the company knows there is an issue with the parts and could lead to loss of reputation (with customers assuming the premature failure due to poor manufacturing practises or cheap material) [4]. It is a characteristic of mild ESC that there is a high degree of variability, with often only a small percentage of parts which have been exposed to the ESC agent failing. Not only would the parts which have failed need to be replaced, but depending upon the nature of the product a full recall may be required, such as in the case of safety critical products such as medical devices. Obtaining information on ESC from companies can be difficult as they may not want to publicise issues with their products.

In this work, two industrial case studies are presented. In both cases, the companies were having products returned or were receiving complaints from customers due to early failure. Despite an internal audit and investigation, both companies were not able to pinpoint the source of the premature failures, which appeared to be random in nature. In both cases, an extensive laboratory investigation determined that the parts were failing due to ESC. It is hoped that the information presented will not only be of use to companies working with the particular polymer/liquid combinations discussed, but will also be of value to a wider academic and industrial audience interested in ESC.

Case study 1 – ABS with Grip-It™ ™ (a water-based ester lubricant/glue)

The company involved in this work produce an injection moulded part using ABS, which is then assembled with an elastomeric component. Grip-It™ was used as a lubricant to help the two parts to slide together, but once it dries it acts as an adhesive to hold the components together. P80 Grip-It™ was purchased from International Products Corporation and was used as received. According to the manufacturer, Grip-It™ is used in a wide range of industries including automotive, aeronautical and consumer products. The components of the Grip-It™ were not revealed, but the company did state that it contained an ester. They also claimed that when the water evaporates and the Grip-It™ dries, the ester is absorbed into elastomers [14,15]. This research came about as the company were receiving complaints of the ABS parts breaking prematurely, in some cases failing even before they had been removed from the packaging. The company were not able to determine why the parts were failing as it appeared to be random with no correlation between batches, production date, or colour (which was an additive). However, there was some evidence to suggest that the failures were more likely to occur in hotter climates. This problem was only reported after the company modified the part geometry. The company carried out routine quality control on each batch of parts produced, but this did not highlight any potential issues.

They suspected that the combination of Grip-It™ and the ABS may be the reason for failure and asked the supplier of the ABS for technical assistance. International Products Corporation reported carrying out a study using a modified version of ASTM D543-95 (they immersed ABS parts for 10 days at room temperature). They did not find a significant change in the mass or swell of the parts (a 0.2% and 0.1% increase respectively), with a slight decrease in hardness (0.4%) compared to parts which were not submerged [14,15]. Here we describe a detailed study untaken to explore the root cause of the failures.

Materials and methods

Samples were obtained from the company's normal production. The parts were approximately 200mm long, 30mm wide and 20mm thick. Approximately two thirds of the length of the parts were hollow, with the remainder being solid. The parts which displayed premature failure did so where the hollow portion met the solid section, and it is thought that this was a site of residual stress due to the difference in cooling rates after injection moulding. Mould flow software analysis was carried out and it verified that there was a high likelihood that there would be residual mould stress in this region. The grade of ABS used was Polylac™ PA-727 (manufactured by Chi Mei) and was obtained from their normal commercial supplier. Prior to processing, the polymer was dried for 3 hours at 80°C in a Colourtronic CT342 hopper system.

To test whether the cause of the failure was due to ESC, two sets of samples were tested: one set with the parts as received and the other with Grip-It™ deposited at the interface between the hollow and solid sections. 10ml of Grip-It™ was swirled around to coat the internal surface and left overnight to dry. This was a somewhat greater amount of Grip-It™ than would normally be used during production as during production the Grip-It™ was normally applied using a sponge.

It was noted by the company that more failures were being observed in hotter climates and it was thought that prolonged exposure to elevated temperature may also play a role in the observed failures. In order to study the influence of both temperature and exposure to Grip-It™, samples were placed in ovens set at 18, 40, 50, 60 and 80°C and in a humidity chamber set at 60°C and 80% Relative Humidity for 6 months. 6 samples treated with Grip-It™ and 6 control samples were removed every month for 6 months for tensile testing at each temperature. The Arrhenius relationship states that the rate of a chemical reactions increases exponentially with temperature. This phenomenon is widely used in accelerated ageing studies, when storage at elevated temperature is used to mimic longer room temperature ageing [16]. It was thought that storage at elevated temperature may accelerate the processes that drive ESC. The tensile testing of samples stored at elevated temperature without prior exposure the Grip-It™ would also highlight the influence of other ageing mechanisms such as physical ageing or oxidative damage. Tensile testing was carried out using a Zwick Z005 Proline Universal testing machine. The grip distance was 150mm and the testing was conducted at a crosshead speed of 10mm/min.

Results and discussion

A photograph of parts after tensile testing is shown in Figure 1 and it is apparent that exposure to Grip-It™ can alter the failure behaviour. Normally breakage occurred at the thinnest portion of the part in a ductile manner with evidence of necking and an area of white grazing extending ~5mm at either side of the failure. However, in the parts which failed prematurely after exposure to Grip-It™, the breakage occurred at the interface between the solid and hollow section. After exposure to Grip-It™ the parts failed in a brittle manner which matches reports of ESC in literature[8].

The breaking load of the parts without Grip-It™ can be seen in Figure 2. It would appear that the parts have a slight increase in the breaking load as a result of the exposure to elevated temperature. Thermal ageing has been reported to improve the tensile strength and modulus of polymers including ABS but with reductions in toughness as a result of embrittlement t[1]. In the case of ABS these changes during storage at elevated temperature have been attributed to a number of factors including cross linking at the part surface [17]. The relaxation of residual stress from the injection moulding process may also play a role. All of the as-received parts tested broke in the expected region of the part with none displaying premature brittle failure. The results for the parts which were exposed to Grip-It™ can be seen in Figure 3. A significant drop in the breaking load of the parts was noted compared to the parts which were not exposed to Grip-It™. The error bars in the graph are large because the parts either broke normally (at a similar load as the samples which were not exposed to Grip-It™) or at a much lower load (approximately 600-700N) due to premature failure. It was found that in addition to the samples breaking at a much lower load due to premature, the location of the break also changed and occurred in the hollow section. The average standard deviation in breaking load of the parts which were not exposed to Grip-It™ was approximately 60N; whereas for the parts exposed to Grip-It™ was approximately 660N. These results confirm the apparently random nature of ESC. There did appear to be some temperature dependence with parts aged at 18°C displaying the smallest reduction in breaking load, suggesting that elevated temperature accelerate ESC. The samples aged in the humidity chamber also showed a lower reduction in mechanical performance when exposed to Grip-It™ compared to the samples aged at the same temperature at ambient humidity. Other researchers have reported a reduction in the stiffness of ABS when aged in a humid environment [18,19]. It is likely that the moisture is absorbed into the acrylonitrile component of ABS [20–22] and acts as a plasticiser protecting against ESC to some extent.

A limited study was carried out with other grades of ABS, which were found to be more susceptible to ESC with some failing spontaneously in the ovens at 60 and 80°C after exposure to Grip-It™ prior to tensile testing. Further ISO 22088 testing with samples under continual flexural stress was conducted by the company to verify the findings of this study and it was found that painting on Grip-It™ caused surface crazing within 24 hours. This testing demonstrated an incompatibility between Grip-It™ and ABS and is consistent with reports in the literature that esters can cause ESC in ABS [23] as the SAN phase of ABS is soluble in esters [22].

Additional analysis was conducted using Thermogravimetric Analysis (TGA), Differential Scanning calorimetry (DSC) and Fourier Transform Infrared (FTIR) spectroscopy but these methods showed no significant differences after exposure to Grip-It™. As a result of this work, the company decided that the simplest and most cost-effective measure was to simply stop using the assembly agent (Grip-It™). Although this made assembly more difficult as they were reliant on mechanical interlocking to keep the parts together, it solved the issue.

Case study 2 - Environmental stress cracking (ESC) of LDPE medical tubes

The company involved in this case study produce respiratory tubing for anaesthesia machines and ventilators. These supply respiratory gases, including vaporous anaesthetic agents in addition to oxygen and medical air. These gases can be dry or humidified. The tubing assembly comprises a flexible tubing limb with an integrated connector which push-fits onto corresponding connectors on the equipment. During assembly, Isopropanol (IPA) was wiped over the ends of the connectors before fitting the connectors to the tubing to make it easier to fit the parts together. It was found that after assembly and on occasion in-service, that some of the connections between the tubes and/or the tubes and the respirator displayed visible cracking leading to potential failure of the joints. This can be seen in Figure 4. While the company was not aware that the issue may have been caused by ESC, they did suspect that using IPA was playing a role. Prior to this project, the company tried altering the composition of the tubing and the assembly solvent in an attempt to overcome the issue.

The LDPE formulation included pigment at 2 w.t. % and an antimicrobial additive at 0.5 w.t. % (BioCote). It was proposed that the addition of a thermoplastic elastomer into the LDPE would increase the ductility of the tubing and make it less susceptible to failure. LDPE samples with EVA content of up to 8% were investigated. The influence of adding BioCote and pigment to the blend were also studied.

Materials and Methods:

Samples were injection moulded using a Wittmann Battenfeld smart power 180 injection moulding machine. The process was carried out at a barrel temperature of 170°C at 1000 bar pressure. The mould temperature was 30°C with a cooling time of 20s. LDPE blends containing up to 8 w.t. % EVA we produced, together with samples containing 2 w.t % pigment and 0.5 w.t. % Biocote. This is summarised in Table 1.

The environmental stress crack susceptibility testing was carried out in accordance with two standards. For ASTM D1693[24] testing; rectangular samples with a length of 38mm, width 13mm and thickness 4mm were notched in the centre across their width to a depth of 0.5-0.6mm by a blade fitted into a notching device. The effects of both IPA and MEK were studied. Dip testing was carried out on half of the samples (with the samples being fully immersed in solvent) and paint testing was carried out on the other half. For the paint testing, the solvent was painted on the sample, after which they were bent into a U shape and placed in a rack to replicate the conditions experienced during assembly. Figure 5 a & b shows the ASTM test setup. For ISO 22088-3:2006 [25] testing, the moulded specimens were cut into ISO 527-2 type 5a specimens [26] and placed in a curved sample holder for 1000hrs/42days and held at 1% flexural strain before being subjected to tensile testing. As with the ASTM testing, the samples were subjected to either IPA and MEK by both immersion (Dip-In) or by having the solvent painted onto the surface.

FTIR was carried out on the samples immersed in IPA and MEK using a BIORAD FTS 3000MX FTIR machine in the single crystal ATR reflection mode. FTIR spectra of the samples were collected from 700 to 4000 cm^{-1} wavenumbers with 50 scans at a resolution of 8 cm^{-1}.

DSC was carried out using a TA Q100 from -80°C to 180 °C in a flowing nitrogen atmosphere at 10°C/min heating rate.

TGA was carried out to study the degradation behaviour using a TA instruments Q50 from 25 °C to 600 °C in a nitrogen atmosphere at 20°C/min heating rate.

The SEM (Scanning Electron Microscopy) was conducted using a SEM Joel 6500 FEG. Samples were analysed at acceleration voltage of 10kV. The sample were splutter coated with gold prior to analysis.

Tensile testing of the samples was conducted in accordance with ISO 527-2 using an Instron 5500R Electro-Mechanical Universal Test Frame with a 5 kN load cell at a crosshead speed of 50mm/min.

Results and Discussion:

Figure 6 shows a SEM image of environmental stress cracking which occurred in the LDPE sample during ESC testing via ASTM D1693. It was observed that the crack grew perpendicular to the initial notch. The crack begins at the surface and propagates into the samples. Brittle fracture features were observed and no clear fibrillation or crack ridges to slow or stop the crack growth were apparent on the fracture surfaces. It has been reported that smooth crack surface is a typical characteristic of ESC [22]. These observations were supported by previous studies, where it was concluded that ESC is a brittle failure, starting from the surface due to the creation of micro-voids and cracks by the surface-active liquids or agents [6,11,27,28].

The time to failure of the ASTM D1693 aged samples can be seen in Table 2. The time to failure is defined as the time in days until the first test specimen of each type fails during the ESC test. Several trends can be observed. It can be seen that MEK exposure led to more rapid ESC failure than that seen with IPA. Interestingly though, when comparing the painted samples this appears to be reversed with the time to failure of the samples painted with IPA being significantly lower than the samples painted with MEK. The painting of the samples better reflects the industrial production process. The results also show that the presence of the BioCote and the pigment also seem to reduce the failure time of the samples illustrating that they increase susceptibility to ESC. It has been reported that the presence of pigments [29,30] and additives such as BioCote can change the degradation and cracking profiles and expedite the process of brittle crack formation initiated by surface active agents [27,29–31]. It has also been reported that the pigments can oxidise which in addition to deteriorating their colour properties can also create deleterious interactions with stabilisers in the polymers which can result in degradation of the main polymer chains [29]. EVA is an elastomeric material and when blended into LDPE improves the toughness, making the resulting blend less susceptible to brittle failure through ESC [27]. Increasing the percentage of EVA improves the ESC resistance and no failures were detected in the ASTM test in the LDPE samples containing 8% EVA. However, while this level of EVA loading does not fully protect the samples in ASTM tests when the pigment and BioCote are added to the blend.

FTIR was carried out for all the samples. No significance difference was found between the spectra of untreated samples and those exposed to MEK or IPA solution. An increase in peak height at 1600-1700 cm^{-1} was observed which may be attributed to formation of ketonic group by oxidation reactions[18,32]. This peak was also found to increase with the addition of EVA content in LDPE which may suggest that these samples are less protected to oxidation. This may explain the observed failure of high EVA content used in pigmented and bio-coated LDPE samples.

TGA showed no significant difference in the degradation behaviour of the blends. This indicates that if either MEK or IPA was not absorbed into the polymers or else the amount absorbed was below the detection limits of the equipment.

DSC showed no significant changes in the melting behaviour or of the blends, but did show a change in the crystallinity with increasing EVA content leading to a reduction in crystallinity at higher EVA addition rates [31]. This is summarised in Table 3. It has been reported in literature that changes to the crystallinity can affect the ESC behaviour of a polymer[4] and this could explain the difference in performance of the blends.

ISO bent strip testing was conducted in accordance with ISO 22088-3 to assess the effect of ESC on the mechanical properties of the blends with the unaged LDPE blends as a control. It was found that no cracks or failures were observed in any of the samples after 1000hrs/42 days. This is in contrast with the samples aged used in the ASTM standard and is attributed to lower strain which was applied to the samples during the ISO ageing process. It was also found that there were no significant changes in the strength of the samples (for each polymer blend) when exposed to either liquid (regardless of whether it was applied by dipping them in the liquids or painting it on). However, the stiffness of the samples was found to change when they were exposed to the two solvents. The Young's modulus of the samples which were dipped in the liquids can be seen in Figure 7.A and the Young's modulus of the samples which had the liquids painted on can be seen in Figure 7.B. Interestingly, the data suggests that the additional of the Biocote and pigment increased the stiffness of the samples potentially rendering the material more suspectable to ESC failure. It is clear from both sets of data from Figure 7 that the presence of the two solvents lead to a signifiacnt drop in the Young's modulus, with IPA having the largest impact. The addition of increasing percentages of EVA reduced the Young's modulus of the blend which was expected as it is an elastomer and this reduction in stiffness could help protect against ESC. In agreement with the data from the ASTM tests it can be seen that the presence of the pigment and Bio-cote appear to have a determinantal effect on the ESC resistance. The effect of the MEK and IPA on Young's modulus are similar with some of the samples displaying a smaller drop in stiffness with MEK compared to that seen with IPA.

Conclusion

In the two industrial case studies presented, a high number of premature failures were experienced and the root cause could not be determined by the companies using their standard quality control testing.

In the first case study, parts were made from ABS and a water-based lubricant/glue called Grip-It™ was used during assembly. The parts had two sections (a hollow one and a solid section) and it was at this interface that the customers were reporting that failure had occurred. The company conducted testing which involved immersing flexural samples in Grip-It™ and then comparing the results with the unexposed samples but found no measurable change.

This study was conducted on the actual parts to replicate the failure in a controlled setting. In half the samples, the parts were aged without exposure to Grip-It™, while the other half had Grip-It™ inserted at the failure site. These were then aged at 18, 40, 50, 60 and 80°C and in a humidity chamber at 60°C and 80% relative humidity.

It was found that only the samples exposed to Grip-It™ failed prematurely and that the temperature played a role in premature failure. Testing such as DSC, TGA and FTIR failed to find any significant changes between the parts at failure and the pristine ABS. It was concluded that the failure was due to ESC and the combination of the polymer, residual stress (from the different cooling rates between the hollow and solid sections) and the Grip-It™.

The second case study involved a company supplying tubing for anaesthesia machine and ventilators which were found to be cracking. The tubing is connected to this equipment by inserting connectors inside the tubing using a solvent to assist in assembly. The tubes were made of LDPE with an anti-microbial additive and pigment and IPA was used to aid assembly. The aim of this work was to investigate whether the failures were due to ESC and if so, whether changing the solvent or adding an elastomer would minimise the failure. MEK (methyl ethyl ketone) was tested as an alternative solvent and EVA poly(ethylene vinyl acetate) was blended with the LDPE in varying quantities. Samples were aged in accordance with ASTM D1693 and ISO 22088-3:2006.

It was found that of the two test standards, the samples tested using ASTM D1693 displayed visible cracking after exposure to the solvents. FTIR showed a small change which was attributed to ketonic groups being formed through oxidative reactions. TGA showed no measurable changes in the degradation of the samples. DSC showed no change in the melting characteristics of the samples but it was found that adding EVA reduced the crystallinity of the material. It has been reported that changes of crystallinity can affect the ageing behaviour of a polymer. Whether this is the reason for the changes in the ageing behaviour is not clear. The samples aged using ISO 22088-3:2006 did not display any visible cracking or failure which was attributed to the lower stress the samples were aged at. Mechanical testing showed that the strength of the samples was unaffected, but there were variations in the stiffness of the samples. It was found that in all cases, the exposure to IPA and MEK reduced the stiffness of the samples. Both the results from the ASTM D1693 and ISO 22088 testing revealed that the EVA addition offered some protection against ESC.

This work was driven by industry and it shows that despite ESC being a well-documented phenomenon, it still has the potential to be a significant problem for companies producing polymer parts. In these examples the ESC was mild which meant that the companies would receive sporadic complaints from customers about the parts prematurely failing, but struggled to identify the issue as it could not be tied to a particular batch, tool, storage conditions, etc. It is hoped that this work will be of use to companies working the materials studied and to a wider audience concerned with ESC induced failures.

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Sample name	Composition
LDPE	LDPE
LDPE. 0.5Bio	LDPE+ 0.5% Bio-cote
LDPE. 2Pig	LDPE+ 2% Pigment
LDPE. 0.5Bio+2Pig	LDPE+ 0.5% Bio-cote+ 2% Pigment
LDPE. 2EVA	LDPE+ 2% EVA
LDPE. 4EVA	LDPE+ 4% EVA
LDPE. 6EVA	LDPE+ 6% EVA
LDPE. 7EVA	LDPE+ 7% EVA
LDPE. 8EVA	LDPE+ 8% EVA
LDPE. 7EVA+0.5Bio+2Pig	LDPE+ 7% EVA + 0.5% Bio-cote + 2% Pigment

Table 1. Details of the LDPE polymer blends

Sample	t_f (days)			
	Dip-in test		Painted test	
	MEK	IPA	MEK	IPA
LDPE	5	1	--	28
LDPE 0.5 Bio	16	--	--	--
LDPE 2Pig	--	10	--	7
LDPE 0.5Bio+2Pig	7	10	5	5
LDPE 2EVA	21	--	25	--
LDPE 4EVA	21	--	35	7
LDPE 6EVA	--	--	35	8
LDPE 7EVA	--	--	40	12
LDPE 8EVA	--	--	--	--
LDPE 7EVA+0.5Bio+2Pig	10	--	33	10

Table 2. Failure time (t_f) in days of the samples

Blend	Crystallinity (%)
LDPE	35.27
LDPE. 0.5Bio	36.00
LDPE. 2Pig	33.84
LDPE. 0.5Bio+2Pig	34.25
LDPE. 2EVA	35.06
LDPE. 4EVA	32.46
LDPE. 6EVA	33.76
LDPE. 7EVA	31.76
LDPE. 8EVA	31.10
LDPE. 7EVA+0.5Bio+2Pig	31.71

Table 3. Crystallinity of the blends

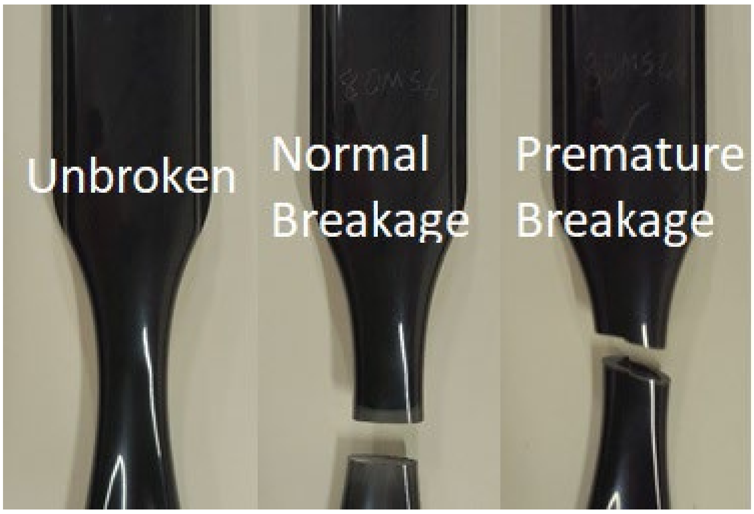

Figure 1. Breakage of the samples

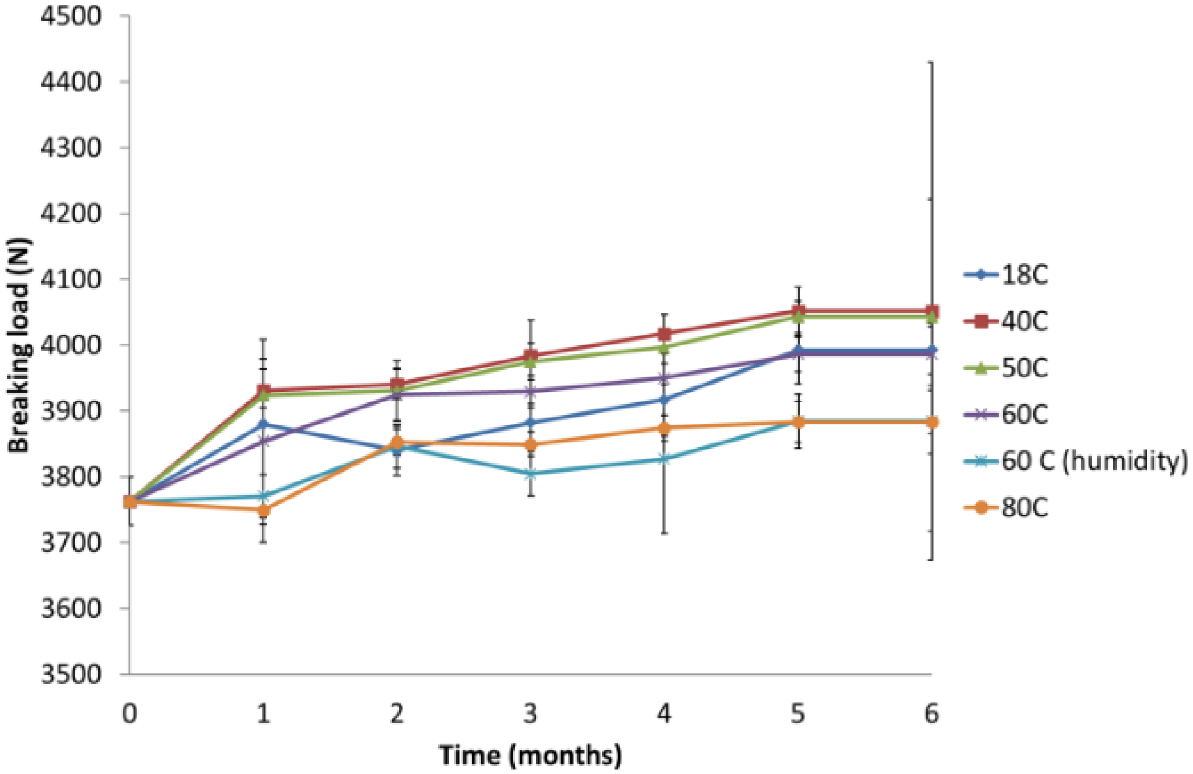

Figure 2. Breaking load of the parts (not exposed to Grip

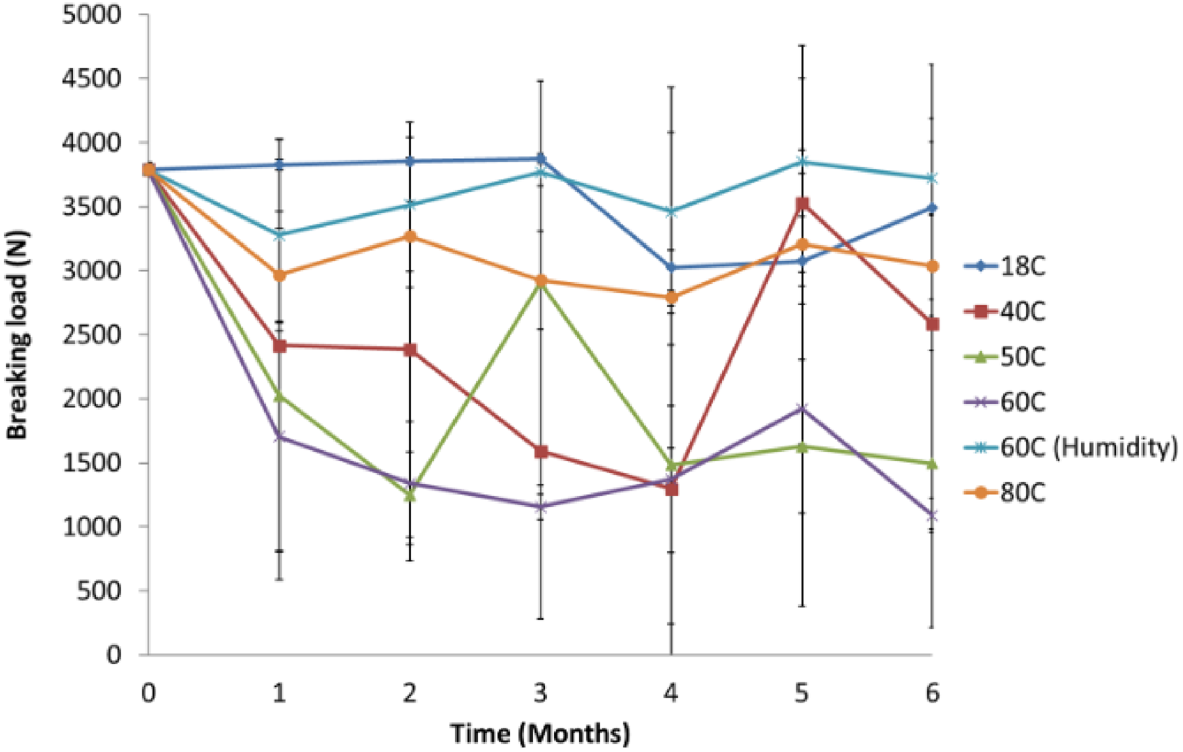

Figure 3. Breaking load of the parts (exposed to Grip-It)

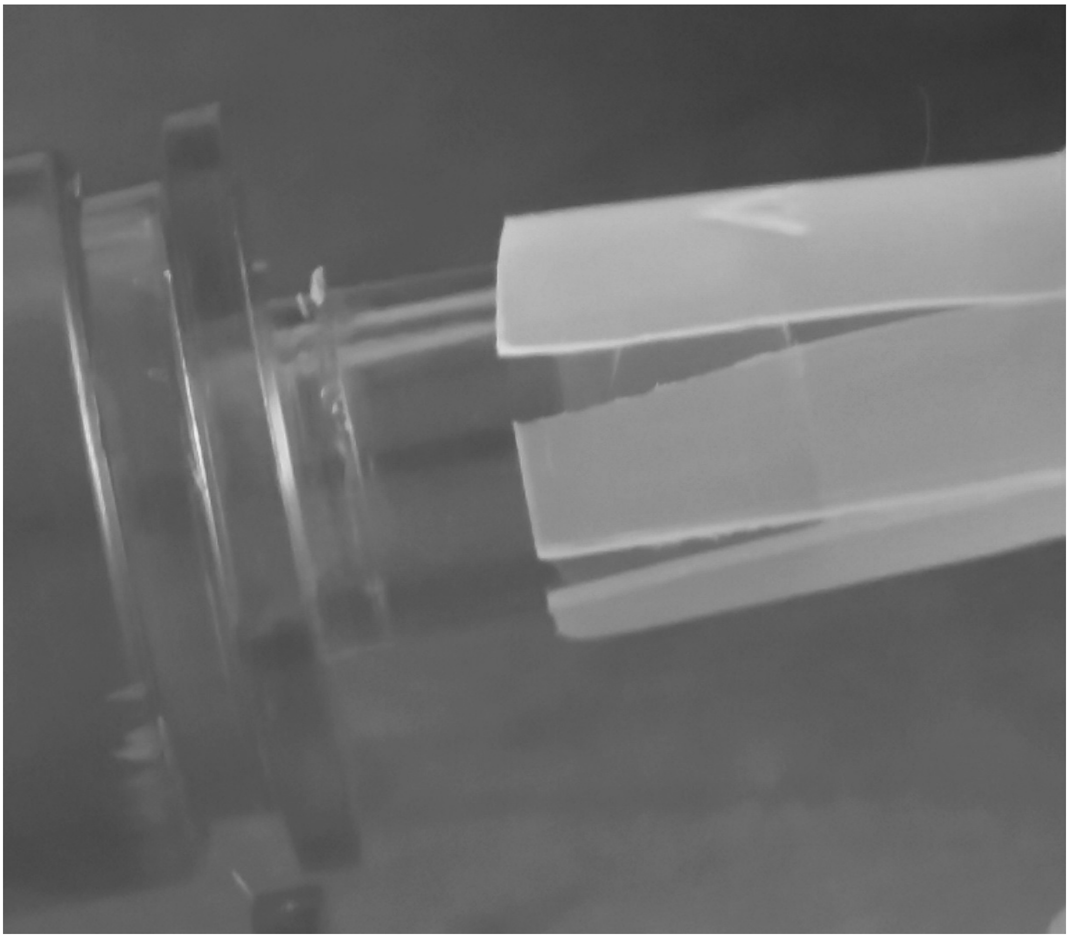

Figure 4. Failure of the LDPE tubing

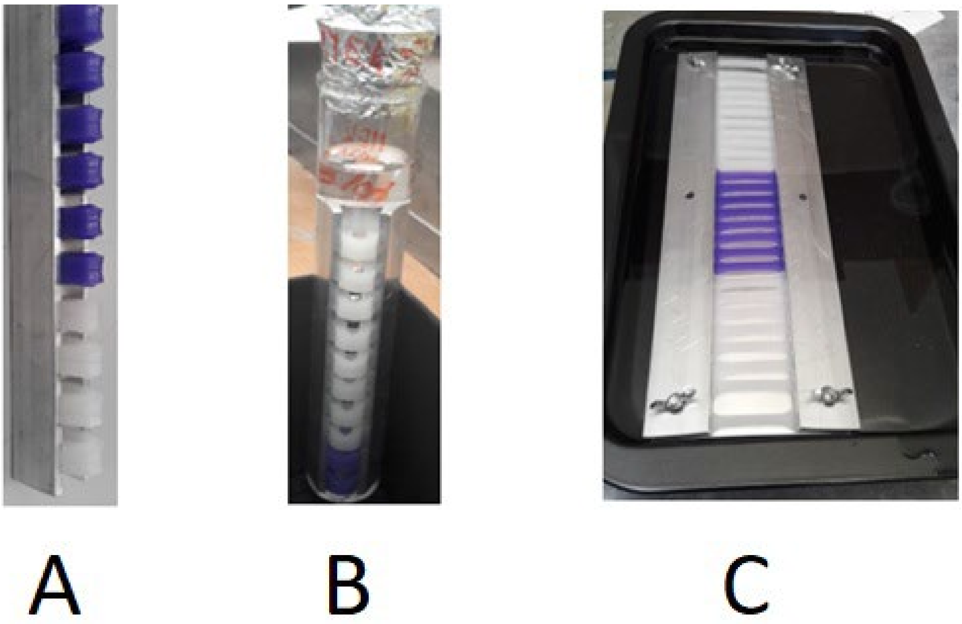

Figure 5. Samples inserted into holders: ASTM standard (A) painted and (B) dip-in test and ISO bent strip standard (C) dip-in test

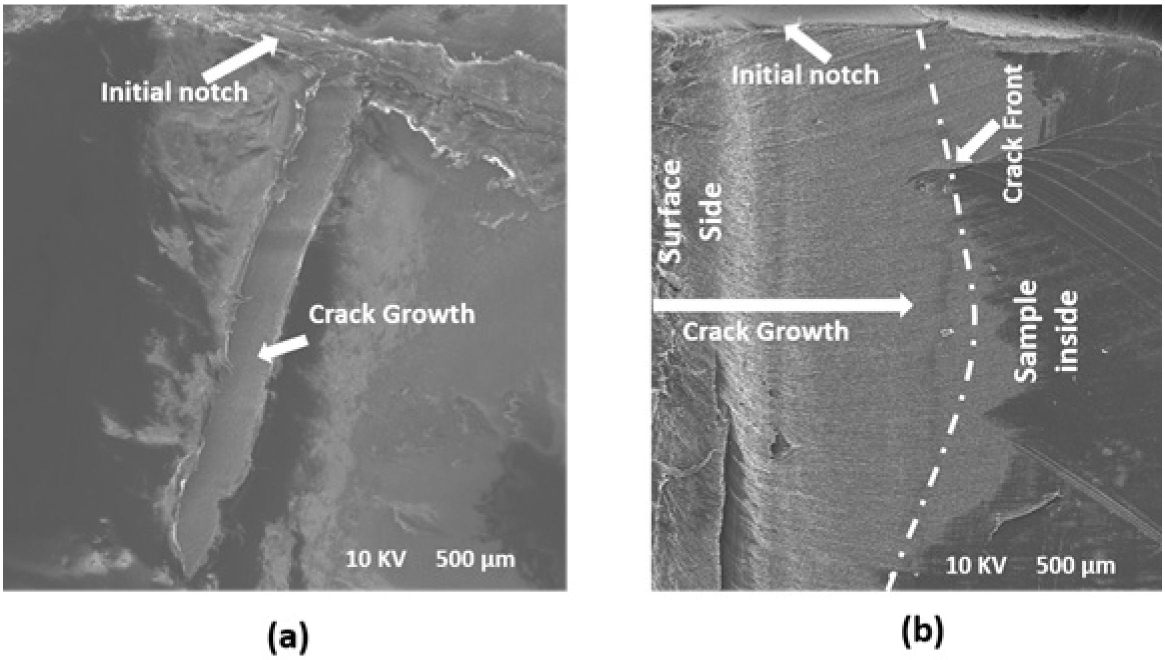

Figure 6. SEM of the LDPE samples exposed to MEK

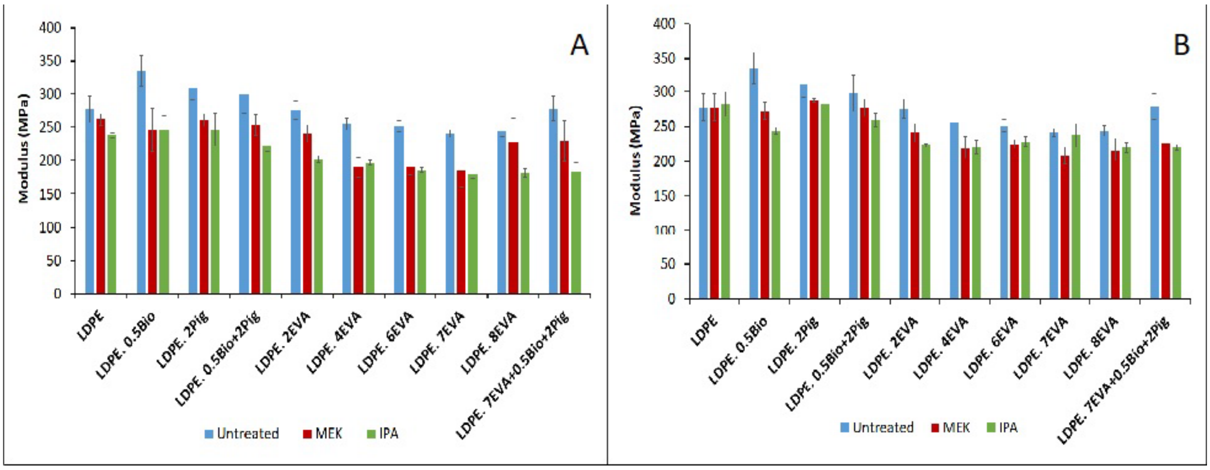

Figure 7. Tensile modulus of the polymer blends (A painted on, B dip in)