



COMPARATIVE STUDY ON THE IMPACT TRANSITION BEHAVIOUR OF PPS REINFORCED WITH 40% VF GLASS

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Abstract

Composite materials, in most cases polymers reinforced with fibers, are these days utilized in numerous applications such as aerospace applications in which lightweight, high strength, high specific modulus and low temperature resistance are critical issues. As these materials have possible applications in different designing areas, a lot of work has been put into enhancing their performance. This study's aim was to study the impact transition behavior of PPS and its composite under different ranges of temperatures by investigating their thermal, mechanical and structural characteristics. PPS and its composite reinforced with 40% vf (volume fraction) glass fibers are employed in this study. The impact transition behavior of PPS and 40% Vf glass fibers composite were investigated by analyzing the mechanical properties: impact, tensile, bending and, hardness at the following temperature ranges: 23°C, -26°C, and -78°C. A particular refrigerator and dry ice were used to achieve the extremely low temperatures (-26 C and -78 C, respectively). The results showed that the addition of 40% glass fibers improved the impact transition behavior of 40%GF PPS composite with temperature decreasing. Which with decreasing in temperature from 23°C to -78°C, the impact strength of PPS decreased by fifty five percent while it increased by twenty three percent for 40%GF PPS composite.

Keywords: PPS, glass fiber, mechanical properties, thermal properties

Nomenclature

ΔH° - the heat of fusion of fully (100%) crystalline PPS
 ΔH_f : - heat of fusion calculated from the DSC thermogram
 40% Vf GF - 40% volume fraction glass fibers
 DSC - Differential scanning calorimetry
 PPS - Polyphenylene Sulfide
 SEM - Scanning electron microscope
 W% - weight percentage of PPS in the composite

1. INTRODUCTION

Because of their superior strength-to-weight ratios and other financial advantages over aluminum or other metals, high-performance polymers are gradually displacing conventional materials. High-performance polymers such as polyphenylene Sulfide are commonly utilized in applications involving harsh environments in the automotive, aerospace, electric and electronic, industrial, and medical fields. They cost higher than engineering polymers, but they are preferred when their specific properties exceed their price. They are replacing conventional materials used in aerospace and automotive applications, such as ceramics and metals, due to their lightweight, high heat oxidative resistance, chemical inertness, high dimensional

stability, corrosion resistance, and capacity to maintain mechanical and physical properties over a wide temperature range. These plastics also provide flexibility in design to suit requirements for component downsizing, functional integration, safety measures, and aesthetic aspects, which led to their employment in automotive, electric, and electronic applications. Additionally, these plastics are simple to mold into thin-wall and intricate geometrical components. Due to their capacity to withstand a variety of sterilizing procedures, good mechanical and chemical characteristics, and biocompatibility, they are frequently employed in medical device applications [1][2][3][4]. Since the 1930s, glass fibers have been produced for commercial purposes and have found use as insulation, fire-resistant clothing, and reinforcement for fiberglass composites[5]. These polymers are undergoing continuous development with the goal of lowering manufacturing costs overall and expanding their range of uses [6]. The effects of temperature and strain rate on these polymers' mechanical characteristics are considerable. Impact at high speeds and low temperatures causes brittle fracture without any yielding for several routinely used structural materials (or plastic deformation). So, the structural component for aerospace applications

Received 2022-10-26; Accepted 2023-08-31; Available online 2023-09-21

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should present good energy absorption capability [7][8][9]. Aerospace, oil and gas, the chemical sector, nuclear and fossil-fuel power generation, and other industries do not frequently have brittle fractures. However, when they do, they could cause a sudden, unexpected, and catastrophic breakdown, which could be followed by the release of chemicals or other toxins or perhaps an explosion or fire. Therefore, anyone working in such businesses must be aware of cold temperature brittle fracture [10][11]. A brittle fracture is described as an abrupt, extremely quick breaking of machinery under stress where there is little to no sign of ductility or plastic deformation prior to the fracture. When a piece of equipment experiences a brittle fracture, there is no thinning or necking down, in contrast to the majority of other tensile failures, when the material plastically strains under overload conditions and thins out till the point of rupture. Instead, this damage mechanism frequently results in unanticipated cracking, occasionally shattering equipment into numerous pieces [12]. Brittle fracture takes place in two stages: (i) the beginning of the crack, and (ii) the fast spread of the crack, which results in total fracture. A brittle crack frequently begins at a pre-existing flaw, like a void or inclusion. In a place of high stress concentration, such as the edge of a drilled hole or notch, a fracture can also begin to form in a material that is free from defects. The stress required to cause a brittle fracture to form is greater than the stress required for the crack to widen [13][14][15][16]. The behaviour in which the stress to start a crack is smaller than the stress to enlarge a crack, separates brittle fracture from ductile fracture. Some methods used to avoid brittle fractures include [17][18][19][20]:

1. Selection of structural materials that show a ductile behaviour under all anticipated operating conditions, including some abnormal situations.
2. Avoidance of High stress (residual or applied)
3. Avoidance of impact loading or include a means to absorb the energy of the impact.

One of the best solutions to increase the impact energy's absorption is the improvement of the fracture toughness of materials, which is one of the fundamental material requirements used to measure the performance of plastics products [21][22][23][24][25]. Blending and reinforcing methods are frequently used to enhance the toughness, wear and friction properties of polymers [26][27][28][29]. The study's aim was to study the impact transition behaviour of PPS and 40% Vf glass fibre composite under different ranges of temperatures by investigating their thermal, mechanical and structural characteristics.

2. EXPERIMENTAL WORK

Two types of polymeric materials sheets shown in figure 1 have been used in this work with dimensions of (4 ×300×300) mm supplied by

Guangzhou Engineering plastics industries Co. Ltd/china.

1. Pure polyphenylene sulfide (PPS).
2. PPS with 40% Glass fiber occupied shown in figure 1.

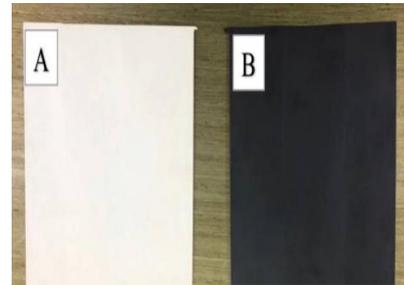


Fig. 1. Materials used in this study: (A) pure PPS and (B) PPS+40% glass fibers.

The mechanical properties of PPS and its composite have been investigated. The procedure to estimate the mechanical properties was done by evaluating the mechanical properties at three temperatures (23°C, -26°C and -78°C) [30][31]. Specifically designed refrigerator and dry ice shown in figure 2 were used to achieve the extremely low-temperature (-26°C and -78°C, shown in figure 2) [32][33]. At 23°C the specimens were tested at room temperature [34], while at -26°C the specimens were put in a specifically designed refrigerator for 7 hours and for -78°C the specimens were kept between two layers of dry ice for 24 hours.



Fig. 2. (A) A specific refrigerator. (B) A block of dry ice.

2.1. Tensile test

Due to the fiber's increased strength and stiffness, the fiber in polymer materials often improves the tensile characteristics of the composite [33]. An instrument (Bongshin model WDW-SE) shown in figure 3 was used to conduct this test. The tensile instrument applies loads up to (200 KN) at speeds between (0.001 to 500 mm/min). A characteristic of polymers in the tensile diagrams is based on the specimen's measurements and form. The following figures show the samples of tensile tests that can be used for the examination according to ASTM D-638 shown in figure 3.

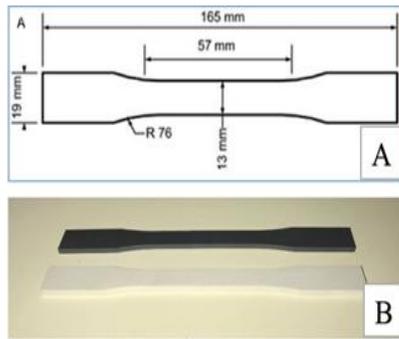


Fig. 3. (A) Schematic tensile specimen.
(B) Experimental tensile specimens

2.2. Bending test

Bending behaviour of samples are tested using a three-point bending, by a Universal Tensile Test machine (Bongshin model WDW-SE) in the laboratories of the Department of Polymer and Petrochemical Industries. Samples dimensions (160×13×4) mm are shown in figure (4); were cut according to ASTM D 7264.

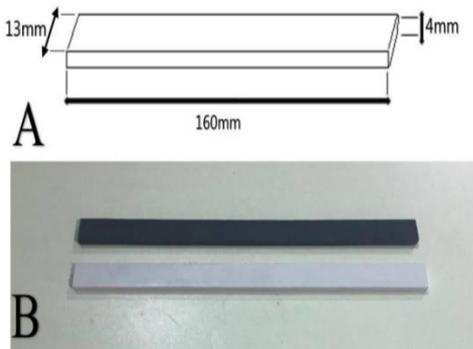


Fig. 4. (A) Schematic bending specimen.
(B) Experimental bending specimens

2.3. Hardness (Shore D) test

The Chinese Hardness Device, Model TH 200, is used in this test to measure the hardness of (PPS) and (PPS+40% GF) specimens that have been prepared in accordance with ASTM D 2240.

2.4. Impact test

It is one of the most common tests for determining the impact resistance of plastics. Specimens were machined according to ASTM D 256. The test was conducted at three impact temperatures (Room Temperature $\approx 23^\circ\text{C}$, -26°C and -78°C). Figure (5) shows standard and experimental un-notched samples.

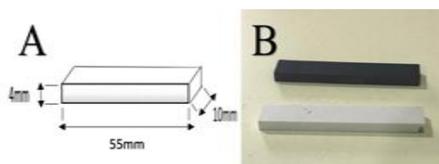


Fig. 5. (A) Schematic impact specimen.
(B) Experimental impact specimens

In this test, the specimen was fixed from both sides in a horizontal position. The specimen is struck by the pendulum's arm. The breaking energy is the energy absorbed by the specimen during the breaking process. The breaking energy is measured by joule unit. Pendulum impact tester made in Germany by gant (HAMBURG), Model WP 400 charpy type as shown in figure (6).



Fig. 6. (A) The impact machine (B)
Fixation of the specimen

2.5. DSC test

This test was used to study the effect of the addition of 40 wt% GF on the crystallinity of pure PPS at temperature range (-80 – 300°C). The samples of (PPS) and (PPS+40% GF) were prepared according to ASTM D3418-03 and tested by using instrument (NETZSCH –model DSC F3Maia, pan Aluminum) as shown in figure (3.14). The heating rate is $10^\circ\text{C}/\text{min}$ and the gas specification is N_2 (50 ml/min).

2.6. Scanning electron microscope

SEM and element analysis with Oxford Inca Energy 250X EDS system were used to provide microscopes with first class detectors and used to show the initial crack on the sample's surface, based on the technology of synthetic crystals. The shattered sample was first chopped into a rectangular block (4X10X25 mm), and then the specimens were coated with a thin layer of gold using sputter-coating equipment. (EM Technologies L.T.D Company, UK).

3. RESULTS AND DISCUSSION

3.1. Tensile test

The results of tensile test for Pure PPS and its composite at exposure temperature varying between (-78°C to 23°C) are shown in figure (7). The tensile strengths are calculated from the load-deformation curves shown in figure (8). It is noted from the results that there is an increase in tensile strength of PPS as temperature decreases this is because with temperature decrease there is a marked decrease in elongation and a corresponding decrease in toughness due to the increase in stiffness and intermolecular bonding that occur with temperature decrease. Therefore, the polymer deformation results in the higher strength causing oriented chains that will lead to increase the chain's arrangement that cause the improvement in hardness and reduce the

toughness. While from the tensile test results of (PPS+40%GF) shown in figure (7) it is very clear that tensile strength tends to decrease as temperature reduces from 23°C to -78°C. Due to the difference in shrinkage between the matrix and the fibers, glass fibers got not affected by temperature decrease that is why it will slid and obstruct matrix shrinkage and chains arrangement that occur with temperature decrease.

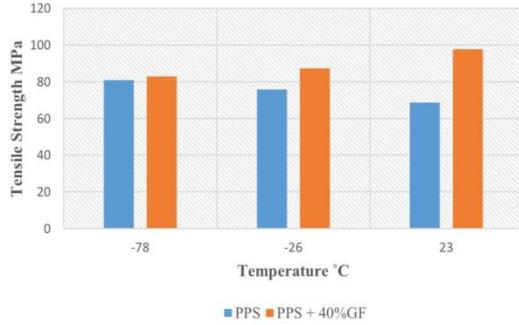


Fig. 7. The variation of tensile strength with temperature for PPS and PPS+40%GF

By comparing the area beneath the load-deformation curves for pure PPS demonstrated in figure (8), it is clear that the area under the curve at 23°C is higher than the areas at -26°C and -78°C. In

addition, the curved line became slightly straight with temperature decrease. Those signs are an evidence on the decrease of toughness and the transition in material's behavior from ductile to stiff not brittle.

Moreover, by comparing the area under the load-deformation curves for PPS+40%GF shown in figure (8), it is clear that the area at 23°C is lower than the area at -26°C and -78°C. In addition, the straight line became more curved with temperature decrease. Those signs are an evidence on the increase of toughness and the transition in material's behavior and became more ductile.

3.2. Bending test

The bending test results of (Pure PPS) at exposure Temperature varying between (-78°C to 23°C) are shown in figure (9). The bending strengths are calculated from the load-deformation curves shown in figure (10). It is noted from the results that there is an increase in the bending strength as the temperature decreases from 23°C to -78°C, a change in the material behavior is observed. PPS becomes less ductile due to the decrease in toughness and the increase in stiffness and intermolecular bonding that occur with temperature decrease, but no significant ultimate flexural strength change is reported. Nevertheless, the bending strength of GF/PPS

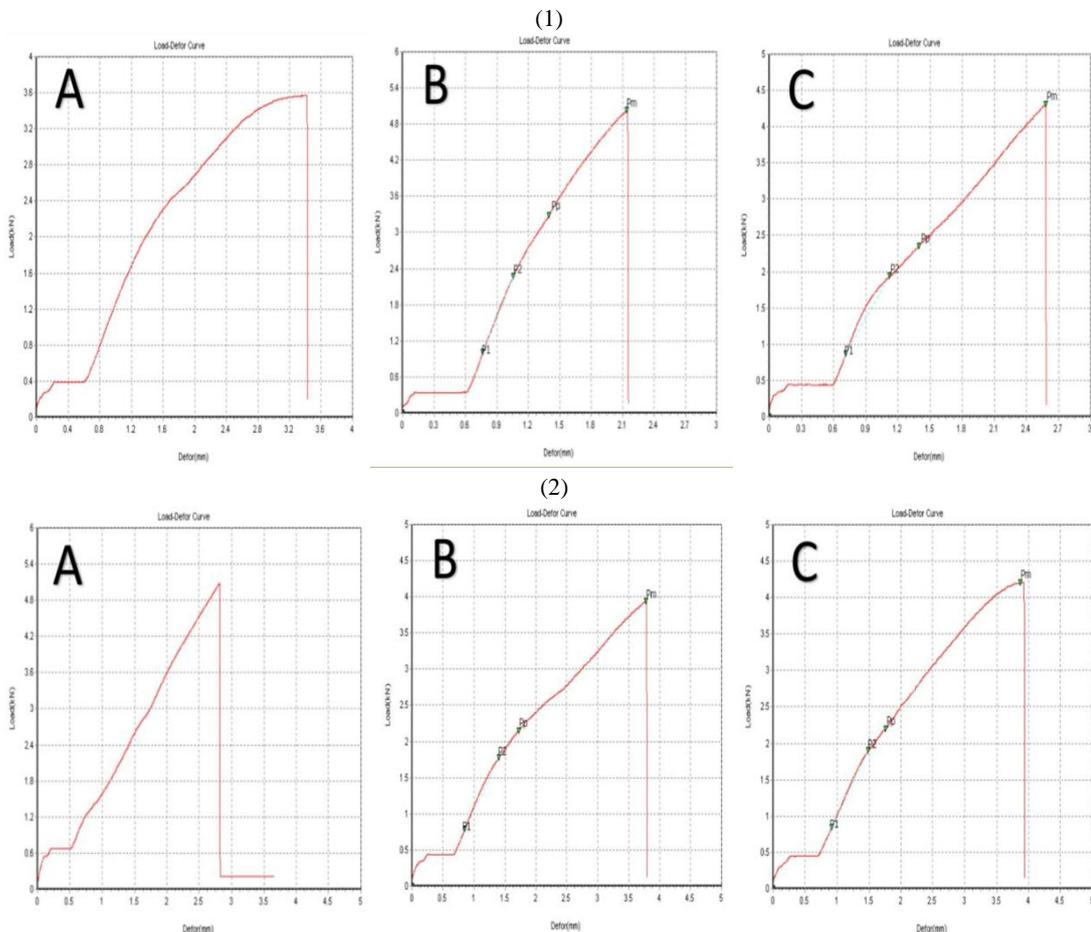


Fig. 8. Load-deformation curves from tensile test for (1): PPS and (1):PPS+40% GF at (A) 23°C, (B) -26°C and (C) -78°C

composite has a slight decline as it gets cooler as shown in figure (9). This is because of the decrease in intermolecular bonding that led to the wrapping of glass fibers with matrix molecules, which led to decrease in chains arrangement that occur with a reduction in temperature, and this agree with Wang [35].

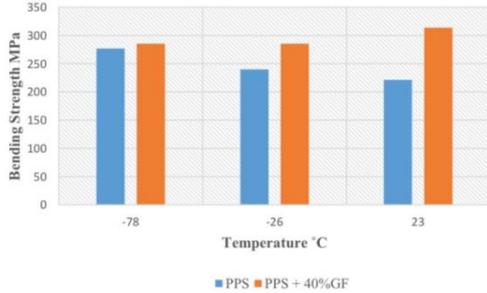


Fig. 9. The variation of bending strength with temperature for pure PPS and PPS + 40%GF

3.3. Hardness (Shore D) test

As demonstrated in figure (11), the hardness of pure PPS has increased as the temperature decreased, due to the decrease in the free volume and that cause a decrease in flexibility of the material, and increased its brittleness.

While the hardness of PPS+40%GF as shown in figure (11) has decreased with the decrease of

temperature. This is because of the exist of the glass fibers that led to increase the free volume between the fiber and the matrix molecules which gives more flexibility to the composite as the temperature decreased to reach -78°C.

3.4. Impact test

The impact test results of PPS at exposure Temperature varying between (- 78°C to 23°C) are shown in figure (12). It is noted from the results that there is a significant reliance of the PPS impact behavior on the decrease of temperature. While at ambient temperature conditions, it was discovered a clearly ductile behavior of PPS material according to an experimental impact test and that is agree with prior experiments[36]. When a temperature of -26 C is achieved, it has been observed that the failure mode changes, changing how the polymer behaves. The change in behavior from ductile to stiff not brittle starts to be significant if the temperature is decreased until - 26°C and -78°C. In addition, that belongs to the change in the microstructure morphology that happened due to temperature decreasing, which leads to a shrinkage in the material, decreasing the free volume which led to decrease in the chains' capacity to absorb impact energy.

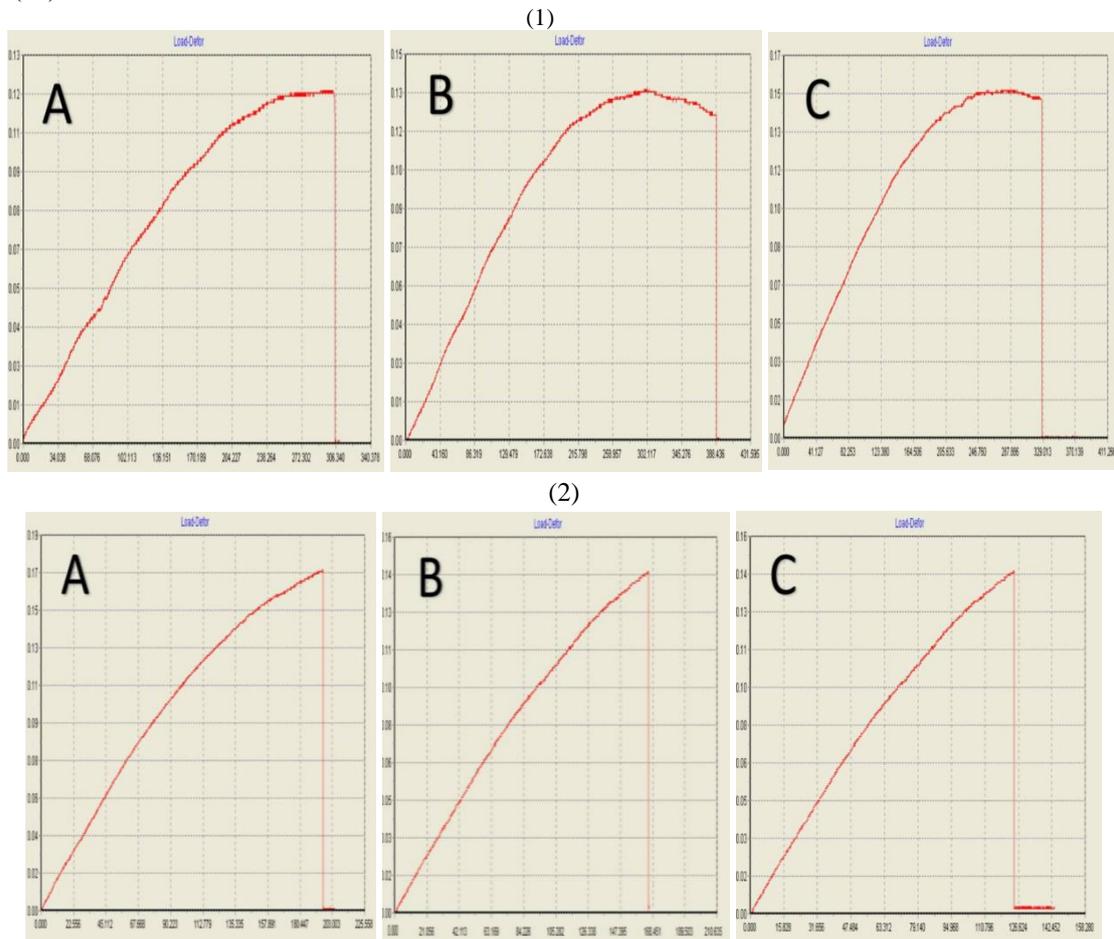


Fig. 10. Load-deformation curves from bending test for (1): PPS and (2): PPS+40% GF at (A) 23°C, (B) -26°C and (C) -78°C

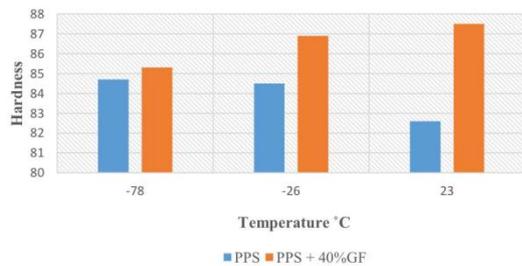


Fig. 11. The variation of hardness with temperature for pure PPS and PPS + 40% GF

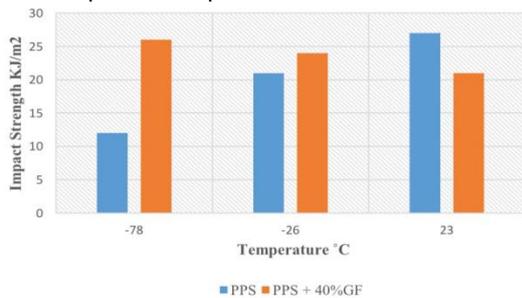


Fig. 12. The variation of impact strength with temperature for pure PPS and PPS + 40% GF

While the impact test results of (PPS+40% GF) at exposure Temperature (-78°C to 23°C) has shown in figure (12), showed that at room temperature, the addition of 40% GF causes a decrease in the impact strength of PPS due to a decrease in flexibility and the material became stiffer and less able to absorb the impact energy. While at -26 and -78°C, it is noted that the addition of 40% GF can lead to simultaneous improvements in impact strength. The maximum impact strength is obtained at -78°C for the reinforced PPS with 40%GF. This because of the difference in thermal shrinkage between the fiber and the matrix that led to the wrapping of glass fibers with matrix molecules which led to decrease in chains arrangement and increase the free volume between the fiber and the matrix and subsequently increase the capacity of the material to absorb the impact energy and improve its impact strength.

3.4.1 Fracture toughness

The figure (13) shows the difference in the fracture toughness with temperature for pure PPS and its composite. It can be seen that the fracture toughness of pure PPS decreases with temperature decreasing and this is because of the increase in stiffness at low temperature and the material became less able to absorb the energy of the impact due to the reduction in free volume. The fracture toughness of PPS+40%GF increases with temperature decrease to reach -26°C as shown in figure (13) and this is because of the presence of the glass fibers that obstruct the matrix shrinkage and led to increase the free volume and subsequently increase the ability of material to absorb the impact energy and improve its fracture toughness.

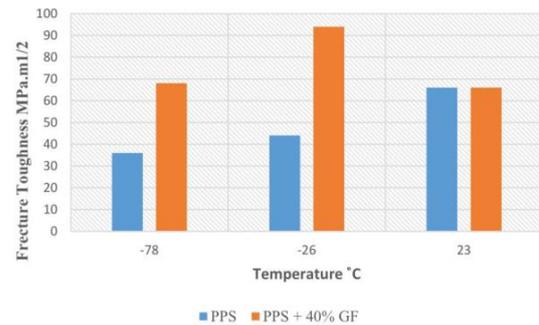


Fig. 13. The variation of fracture toughness with temperature for pure PPS and PPS + 40% GF

3.5. DSC test

At temperature range (0 _ 400°C), Pure PPS from the company has a melting temperature (T_m) 277.94°C as shown in Figure (14, A). While, when tested the PPS+40% GF, the melting temperature (T_m) increased by about 3°C to reach 280.02°C and the (T_g) appears at 75.84°C as shown in figure (14, B).

At temperature range (-80 _ 300°C), DSC is used to show the effect of 40% of glass fibers on the crystallinity of pure polyphenylene sulfide. DSC curves for low temperature range for PPS and 40%GF PPS composite are shown in figures (15) and (16).

The following formula is used to determine a sample's crystallinity percentage ($X_c\%$):

$$X_c\% = \frac{\Delta H_f / W\%}{\Delta H^*} \times 100$$

Where:

ΔH_f : the heat of fusion of PPS in a composite calculated from the DSC thermogram,, ΔH^* : is the heat of fusion of fully (100%) crystalline PPS, $W\%$: is the weight percentage of PPS in the composite.

Figure (17) shows that the PPS has a higher degree of crystallinity than the PPS+40% GF composite, due to the presence of the glass fibers and its brittle nature and that prove that the fracture toughness for PPS is higher than that for PPS+40%GF.

3.6. Scanning electron microscope

Scanning electron microscopy allows high magnification than optical microscopy, which enables observing the surface, and fracture region of polyphenylene sulfide and its' composite. The fractured surfaces of pure polyphenylene sulfide tested by SEM are demonstrated in figure 18. As shown in figure 18-A, that the behavior of pure PPS is ductile at room temperature. It was observed a difference in the failure mode when a -26°C and -78°C temperatures are reached (18-B,C), this causing to a change in the polymer's behavior. The change in behavior from ductile to stiff not brittle starts to be significant if the temperature is lowered until -26°C. The chains became more compacted and regularly arranged as the temperature decreased due to the shrinkage of PPS with cooling, and this agree with the results of the mechanical tests.

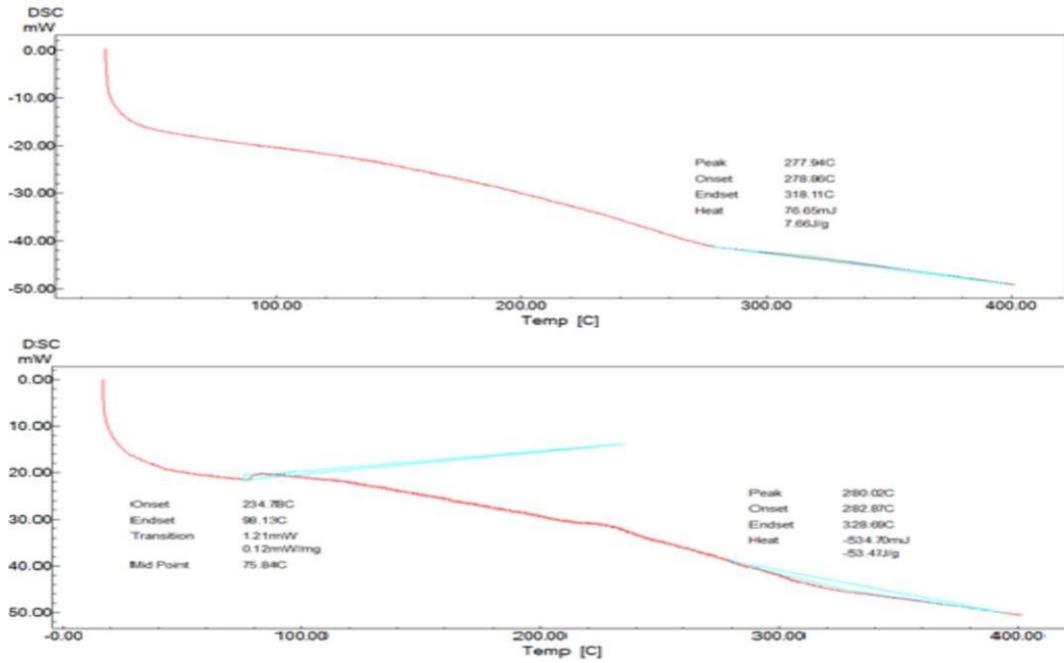


Fig. 14. DSC diagram for (A): PPS and (B): PPS+40%GF

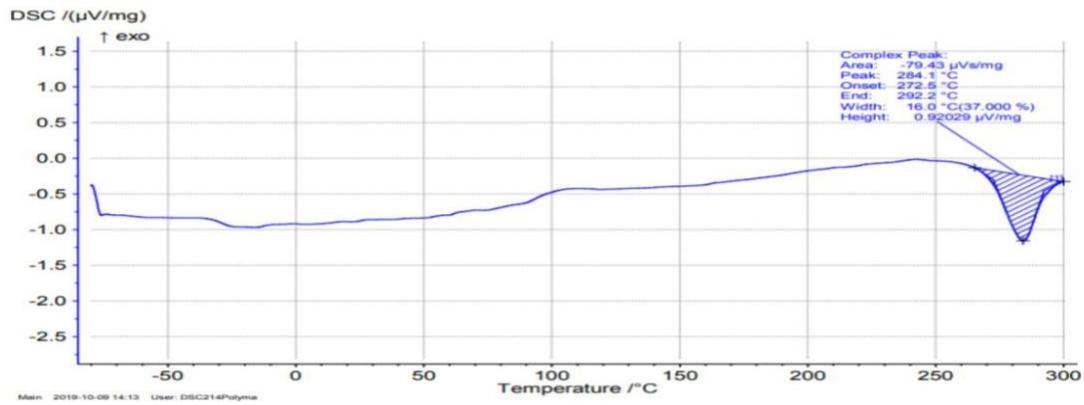


Fig. 15. DSC for PPS

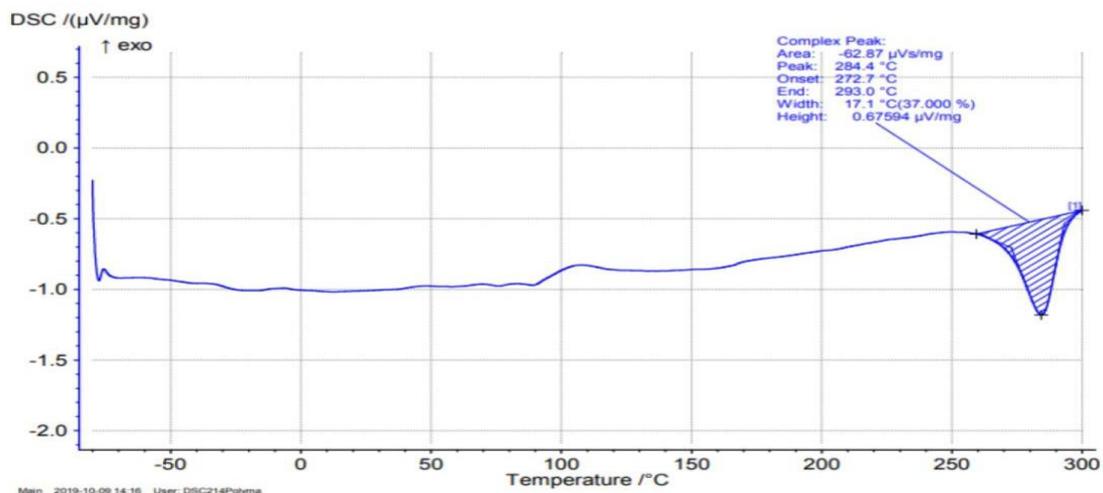


Fig. 16. DSC for PPS+40%GF

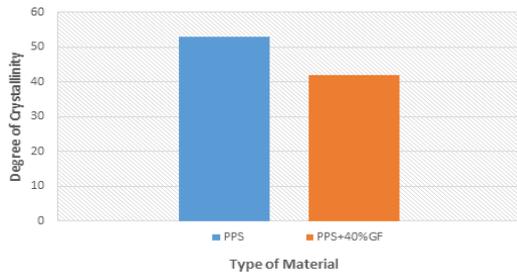


Fig. 17: Degree of crystallinity for PPS and PPS+40%GF

While the fractured surfaces of polyphenylene sulfide with the addition of 40% glass fibers tested by SEM are demonstrated in Figure 19. As seen in all photographs, Glass fibers were evenly distributed throughout the matrix. The fibers' short pull-out lengths served as proof of the interfacial bond between them and the matrix. Images (a)–(c) were the fractured surfaces after impact tests at RT, -26°C , -78°C . These three pictures demonstrate how impact tests pulled out glass fibers. Low temperature specimen fractures, such as those in (b) and (c), showed the effect of pulling more naturally. It was because of the shrinkage of the PPS matrix with the temperature decreased. From the photograph, we can

see that 40% reinforced glass fibers shows a stiff not brittle behavior at ambient temperature and going towards the ductile behavior as the temperature dropped to reach -78°C . In addition, the material showed more free volumes which means it is more able to absorb the impact energy.

4. CONCLUSIONS

In this work when decreasing in temperature from 23°C to -78°C , the tensile strength of PPS increased by seventeen percent while it decreased by fifteen percent for 40%GF PPS composite and decreasing in temperature from 23°C to -78°C , the bending strength of PPS increased by twenty five percent while it decreased by nine percent for 40%GF PPS composite. However decreasing in temperature from 23°C to -78°C , the hardness of PPS increased by two percent while it decreased by two percent for 40%GF PPS composite. While in temperature from 23°C to -78°C , the impact strength of PPS decreased by fifty five percent while it increased by twenty three percent for 40%GF PPS composite. The rate of crystallinity for PPS is higher than that for 40GF PPS composite, according to DSC curves for PPS and 40GF PPS composite. SEM

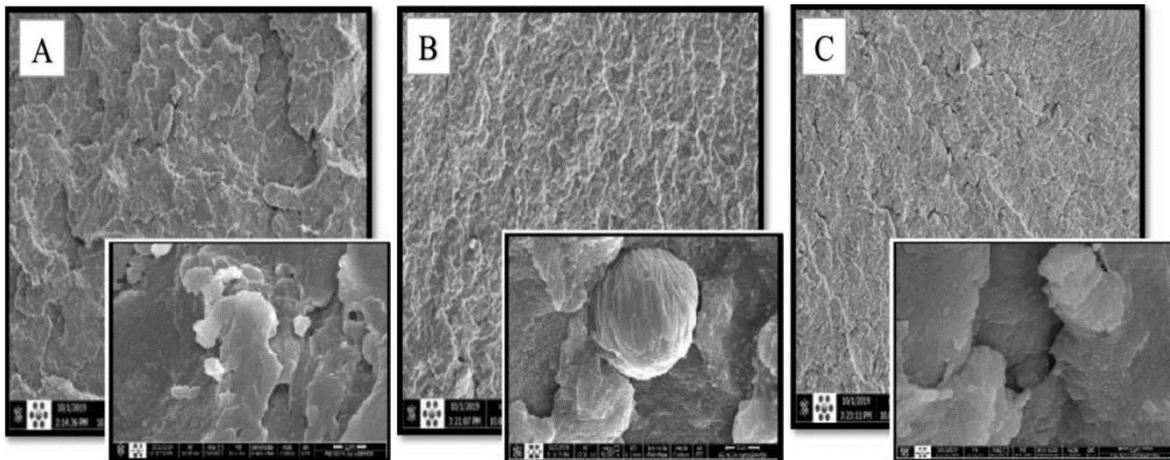


Fig. 18. SEM micrographs taken from the impact fracture morphology of Pure PPS: (A) at RT, (B) at -26°C , (C) at -78°C

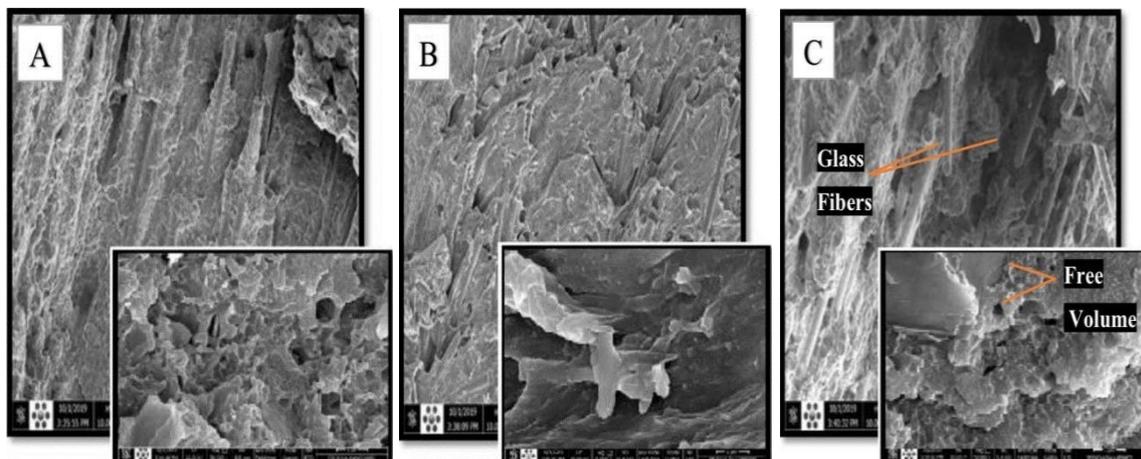


Fig. 19. SEM taken from the impact fracture surfaces of 40% glass fibers reinforced PPS: (A) at RT, (B) at -26°C , (C) at -78°C

results show a transition in pure PPS and 40%GF PPS composite behavior, Whereas PPS exhibits ductile behavior at ambient temperature, it becomes stiff rather than brittle as the temperature drops to -78 °C. At room temperature, 40%GF PPS composite exhibits a stiff, non-brittle behavior, but when the temperature drops to -78 C, it becomes more ductile.

ACKNOWLEDGEMENTS

This study was supported by Al-Mustaqbal University College (grant number MUC-E-0122).

Author contributions: *research concept and design, R.F.K.; Collection and/or assembly of data, R.F.K., N.A.S.J.; Data analysis and interpretation, R.F.K., N.A.S.J., M.J.A.; Writing the article, R.F.K.; Critical revision of the article, R.F.K., M.J.A.; Final approval of the article, R.F.K., M.J.A..*

Declaration of competing interest: *The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.*

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