Investigation on the influence of tungsten particulate in mechanical and thermal properties of HD50MA180 high density polyethylene composites

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Abstract
In this present investigation, the influence of reinforcing tungsten (W) particles in High-Density Polyethylene (HDPE) on mechanical and thermal properties, has been studied. W reinforced HDPE composites are processed by melt compounding method, with W varied in proportion of 1%, 3%, 5% and 7% by weight. The test specimens were prepared by injection molding as per ASTM standards and analyzed by X-Ray Diffraction (XRD), Scanning Electron Microscope (SEM), Mechanical and Thermal Characterization. XRD results show that, the intensity count at angle 40.3°, 58.7°, 73.6° and 87.1° increases with the increase in wt% of W particles. SEM analysis reveals that, composites containing 1wt% of W has uniform dispersion in the HDPE matrix. In mechanical characterization, tensile strength and flexural strength of the specimen reported a sharp increase with the addition of W at 1wt%, followed by a negative trend for the higher content of W particles. However, the impact strength result shows that specimen with 3wt% of W content has the highest toughness. Further from thermal characterization, Thermo Gravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) results show that degradation temperature and the melting point of composites improve with an increase in W content. Composite with 7wt% W content has the highest degradation temperature and melting point.

1. Introduction
Polymer matrix composite finds increased demand in industrial applications, owing to its improved strength and superior thermal properties. Typical applications involve sleeve bearings, pump impellers and agricultural equipment [1]. In all these applications, polymer composites are subjected to high mechanical and thermal stress. The thermal stability is as important as mechanical stability, for such polymers. Consequently, researchers are striving hard to improve the strength and thermal properties of polymers. To this end, research has been conducted with polymers reinforced with varieties of materials. The main parameters involved in developing such high strength polymers are processing methods and selection of matrix and reinforcements.

Polymer composites are prepared by the following methods, in situ preparation, hand lay-up method, compression molding method and melt compounding method. Saeed et al [2] developed the composites by the in situ method. This processing route is very complex, which involves a lot of chemical reactions, and thus the time taken for developing the composites was found to be very high. Ghosh et al [3] also developed the composites by chemical processing, the method gives uniform dispersion of fillers, yet the process is found to be very complex and time-consuming. Zhang et al [4] also used a chemical processing method, the filler coating was done by an electroless plating method and obtained uniform dispersion of fillers. This method involves complex chemical processing involving a lot of chemical reactions. Velmurugan et al [5] synthesized composites by hand lay-up method. Specifically, no measure was taken to prevent agglomeration of particles in this method which causes higher agglomeration in the case of metal particles. Neitzel et al [6] employed compression molding to
develop the composites. In this method, the materials are mixed manually which cannot ensure uniform mixing of polymer and reinforcements, also besides curing time was found to be very high. Tourneroche et al. [7] developed composites by melt compounding using twin-screw extrusion and obtained uniform dispersion of reinforcements in the matrix material. Also, melt compounding by twin-screw extrusion itself prevents agglomeration, and it is the most suitable method where the agglomeration of particles is a major setback [8]. Composites prepared by melt compounding has a uniform dispersion of reinforcements in the matrix material and reduced agglomeration rate [7, 9]. From the results it can be observed, that melt compounding by twin-screw extrusion is the most suitable method, to develop composites with uniform distribution of reinforcement, in the matrix material.

HDPE finds vast industrial applications in the automotive industry and biomedical applications. In the biomedical field, HDPE composites were recently investigated for application in total hip artificial joints [10]. Previous researches focused on improving the strength of HDPE composites by reinforcing, varieties of non-metallic reinforcements [11–14]. Song et al. [11] reinforced HDPE with Nanodiamond to improve the fire retardability of such polymers. However, this process produced low strength polymer and in addition, the cost of such polymer was found to be high. Johnsen et al. [12] used Alumina as reinforcements in HDPE and observed a considerable increase in mechanical properties. However, the analysis of thermal properties does not show any significant change. Ou et al. [13] and Zhou et al. [14] reinforced HDPE with wood particles and Boron Nitrate respectively. From the results of the research, it can be observed that the mechanical properties of the composites increase, whereas the thermal properties decrease. Form these studies, it can be observed that non-metallic reinforcement in HDPE improves the mechanical properties of polymers, whereas thermal properties on such polymers do not show any significant change. Metallic particles can also be used as reinforcements. There exists a variety of metal particles that could be used as reinforcements. Chang et al. [15] developed tungsten reinforced epoxy composites, Alavian et al. [16] developed tungsten reinforced LDPE composites and they studied gamma-ray shielding characteristics of composites. Yet the mechanical and thermal properties of the developed composites have not been reported. From the literature, it was found that the volume of work done with tungsten metal particles as reinforcements, was found to be very less. Tungsten exhibits higher thermal stability, and thus in this study tungsten is used as reinforcement in the HDPE matrix. Further, its influence on the mechanical and thermal properties of such composites are studied.

In this work, an attempt has been made to develop tungsten reinforced HDPE composite specimens, containing varying tungsten content in the proportion of 1%, 3%, 5% and 7% by weight. The influence of varying tungsten content on morphological, mechanical and thermal properties of the composites was analyzed.

2. Materials and methods

2.1. Materials
HDPE used as the matrix material is supplied by Reliance Industries Ltd, with the grade name HD50MA180. It has a density of 0.950 gm cm\(^{-3}\) and a melt flow index of 20 gm / 10 min. Tungsten in powder form is selected as the reinforcement, which is supplied by Sigma Aldrich, Bangalore with purity 99.9%. Tungsten has a melting point of 3422\(^\circ\)C, a density of 11.5 gm cm\(^{-3}\), and an average particle size of 7 \(\mu\)m.

2.2. Preparation of HDPE/W composites
HDPE/W composites were prepared by melt compounding in a co-rotating twin-screw extruder. Spindle speed is fixed at 65 rpm and the temperature in the barrel is set, in a range from 125 \(^\circ\)C to 195 \(^\circ\)C. The outcoming strands were then cooled in water and air and it is palletized to small particles. The palletized particles are then fed into the injection molding machine in which the barrel temperature is maintained at 180 \(^\circ\)C to 200 \(^\circ\)C. Specimens were then prepared as per ASTM standards by injection molding machine where the injection time was set at 5 s and the specimens were water-cooled for 80 s. The specimen code used is described in table 1.

2.3. Testing and characterization
2.3.1. X-ray diffraction (XRD) analysis
In this study the XRD measurement of the prepared samples is recorded with Bruker AXS D8 Advance (Germany) diffractometer equipped with Cu as its source with a wavelength of 1.5405 A\(^\circ\) operated at 40KV and 35 mA. The diffractograms are recorded with a range of 2\(\theta\) from 10\(^\circ\) to 90\(^\circ\) at a speed of 2\(^\circ\) per minute.

2.3.2. Scanning electron microscopy analysis (SEM)
In this study, Field Emission Scanning Electron Microscope (FESEM) was used to investigate the dispersion of tungsten metal powder, into the matrix of HDPE and elemental mapping was done, to justify the presence of
tungsten particles in HDPE matrix. The cross-sections of the prepared samples were gold-sputtered and analyzed through Carl Zeiss Sigma FESEM operated at 20 kV.

2.3.3. Tensile, flexural and impact test
The tensile test of the prepared samples was conducted in Computerized Tensometer as per ASTM D638-14 standards. The crosshead speed was set at 5 mm min \(^{-1}\). The flexural test was conducted as per the three-point bending mode according to ASTM D790-17 standards. The crosshead speed was kept at 2 mm min \(^{-1}\) and a gauge length of 57 mm. The toughness of the specimens was tested by the Notched Impact test, using a computerized Izod impact testing machine as per ASTM D256-10 standards. Fives samples were tested in each category and their average values were noted.

2.3.4. Thermogravimetric analysis (TGA)
The thermal stability of the prepared samples was tested by Thermo Gravimetric Analysers NETZSCH model STA 449F3(Germany). The percentage reduction in the weight of the sample was found as a function of temperature as per the standard ASTM E1131. Samples of 10 mg were loaded in the aluminum crucible and heated at the rate of 10 °C/min from 0 °C to 600 °C under nitrogen atmosphere. The onset temperature, the temperature at 50% weight loss and char residue temperature were noted from the TGA curve.

2.3.5. Differential scanning calorimetry (DSC)
The melting behavior of the prepared HDPE/W composites was investigated with DSC Instrument NETZSCH model STA 449F3 (Germany). The HDPE/W samples of 10 mg were sealed in an aluminum pan and heated from 30 °C to 220 °C with a range of 10 °C/min as per ASTM D3418–15 standards. The melting temperature (\(T_m\)) was noted from DSC curves.

3. Results and discussions

3.1. X-ray diffraction (XRD) analysis
Figure 1 shows the typical XRD pattern of Pure HDPE, HDPE + 1 wt% W, HDPE + 3 wt% W, HDPE + 5 wt% W, HDPE + 7 wt% W composites and Pure W powder. XRD pattern of HDPE exhibits strong peaks at 2\(\theta\) = 21.6°, followed by a less intense peak at 24.0° which corresponds to the orthorhombic unit cell structure of (110) and (200) reflection planes. The obtained 2\(\theta\) value agrees well with the reported values of HDPE [17–19]. Further, there are two weak peaks at 2\(\theta\) values around 30.0° and 36.2° which corresponds to the reflection planes (210) and (020) respectively. The presence of strong peaks at 21.6° and 24.0° in pure HDPE indicates the presence of a crystalline phase in this polymer. The presence of planes (110), (200), (210) and (020) confirms the presence of orthorhombic unit cell structure in the HDPE. Patterns obtained are in line with the standard patterns for HDPE reported elsewhere [20, 21]. From the diffraction pattern of composites with 1wt% W, 3wt% W, 5wt% W and 7wt% W, it is observed that, the two characteristic crystalline peaks at 21.6° and 24.0° remain unaffected, even after the inclusion of tungsten into the HDPE matrix. This indicates that the addition of tungsten did not affect the original crystal structure of the HDPE matrix.

In figure 1, XRD for pure tungsten powder shows strong diffraction peak at 40.3° corresponding to the reflection plane (110) and tiny peaks at 58.7°, 73.6° and 87.1° corresponding to the planes (200), (211) and (220) for pure tungsten [22]. The presence of planes (110), (200), (211) and (220) confirms the presence of tungsten. The obtained diffraction patterns are in line with the patterns reported for tungsten particles coated with HDPE [8] and tungsten with carbon [22].

From figure 1, the XRD plot of composite with 1wt% of tungsten, primary peak at 40.3° is found to be very small, and with increasing addition of tungsten particles the peak height also increases. This fact indicates an increase in the intensity of X-ray scattering associated with an increase in the filler concentration in the specimens with 3wt%, 5wt% and 7wt% of tungsten. This indicates a change in the ratios of crystalline phases in

| Table 1. Code abbreviation of the specimen. |
|-------------------------------------------|
| Sample Code | Description                      |
| Pure HDPE   | Sample without reinforcement     |
| HDPE + 1 wt% W | HDPE containing 1 wt% tungsten particles |
| HDPE + 3 wt% W | HDPE containing 3 wt% tungsten particles |
| HDPE + 5 wt% W | HDPE containing 5 wt% tungsten particles |
| HDPE + 7 wt% W | HDPE containing 7 wt% tungsten particles |
| Pure W      | Pure tungsten particles          |
the structural organization of a filled system. Also, the secondary peaks at 58.7°, 73.6° and 87.1° take place only for the concentration of tungsten at 3wt% and above. The XRD plot of composites with 7wt% tungsten shows a primary peak at 40.3° and secondary peaks at 58.7°, 73.6° and 87.1° which confirms the existence of pure tungsten in composite with weight percentage varying by 1wt%, 3wt%, 5wt% and 7wt%. The crystalline peaks of pure HDPE and tungsten remain the same for composites with 1wt%, 3wt%, 5wt% and 7wt% of tungsten and there is no shift in the peak position in these composites which indicates the independence of the structural organizations of the polymer matrix and the filler.

The characteristic diffraction peak of HDPE at 2θ = 21.6° and 24.0° did not change even after the addition of tungsten particles into the HDPE matrix. This indicates that the addition of tungsten particles did not affect the crystal form of HDPE and is always belonged to the orthorhombic lattice. In contrast, the intensity corresponding to each diffraction peak decreases with the addition of tungsten content into the HDPE matrix which might be due to the introduction of tungsten particles into the HDPE matrix which disrupts the ability of polymer strands to rearrange themselves in an orderly fashion thereby decreasing the crystallinity of the polymer. Crystallinity defines the weight percentage of the crystalline portion of polymers. The mechanical properties of polymers considerably depend on the crystallinity of polymers. XRD is frequently used to measure the crystallinity of polymers. To quantify the results, the crystallinity index of the composites is calculated form the XRD pattern using equation (1) [23].

\[ \text{CrI} = \frac{I_s - I_f}{I_f} \times 100 \]  

where \( I_f \) is the peak intensity of the fundamental band and \( I_s \) is the peak intensity of the secondary band. For the pure HDPE sample, the fundamental band is the strong peak at 21.6° and the secondary band is the less intense peak at 24.0°. The crystallinity index of the composites calculated is given in table 2.

From table 1, it is clear that the crystallinity index of the polymer decreases with an increase in addition of tungsten particles into the HDPE matrix. The decrease in the crystallinity index indicates that the amorphous part of the polymer increases. This shows changes in the structural regularity of the main chain of polymeric molecules. Thus, the inclusion of tungsten particles produces variations in the macromolecular and micromolecular structure of HDPE.

3.2. Field emission scanning electron microscopy analysis (FESEM)

FESEM micrographs of the specimen with 1wt%, 3wt% and 7wt% tungsten is shown in figure 2. Composite with 1wt% of tungsten reinforcement shows, uniform dispersion of tungsten particles in the HDPE matrix (figure 2(a)). The dispersion of tungsten particles in HDPE is uniform for the lower content of tungsten particles. However, with the increase in tungsten content, with the addition of 3wt% of tungsten particles, agglomeration
of tungsten particles are observed. The agglomerated tungsten particles are indicated in figure 2(b). Figure 2(c) shows the micrograph of the specimen containing 7wt% of tungsten. From figure 2(c), it can be observed that the size of agglomerates is bigger than that of the agglomerates observed in specimen containing 3 wt% of tungsten. This indicates that the agglomerate growth occurs with an increase in tungsten content. On close observation of agglomerated particles, a weak interface is observed between the agglomerated particles and matrix, which is indicated in the inset in figure 2(c). This weak bonding tends to debond reinforcement from matrix material easily, with the application of load, which in turn decreases the strength of the composites.

Figure 3 shows the FESEM elemental mapping of HDPE with 1wt% of tungsten particles. In the figure, the red colour indicates tungsten particles and green colour indicates carbon in HDPE. It is observed that red coloured tungsten particles are uniformly distributed in a green coloured HDPE matrix.

### 3.3. Tensile strength

Figure 4 shows the tensile strength of the manufactured composites as a function of tungsten content. The tensile strength is increased by 10%, with the addition of tungsten particles at 1wt%. This is due to the fact that at the lower content of tungsten particles, there is a uniform dispersion of tungsten particles in the HDPE matrix as shown in figure 2(a). As a result of uniform distribution, there is a good bonding between tungsten particles and the HDPE matrix. Also, if the bonding between tungsten particles and the HDPE matrix is good, then the tensile strength of manufactured composites will be higher than that of the matrix material. On further increase in tungsten content, the tensile strength of the manufactured composites decreases gradually. This deterioration is due to the uneven distribution of tungsten particles in the composites due to their aggregation. When the concentration of tungsten particles is increased, particles tend to attract each other due to their high surface

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**Table 2. Crystallinity index of the composites.**

| Sample          | Fundamental Band $I_f (AU)$ | Secondary Band $I_s (AU)$ | $CRI$  |
|-----------------|-----------------------------|---------------------------|--------|
| HDPE + 0 wt% W  | 45229                       | 10880                     | 75.94  |
| HDPE + 1 wt% W  | 38348                       | 9726                      | 74.63  |
| HDPE + 3 wt% W  | 24454                       | 6787                      | 72.24  |
| HDPE + 5 wt% W  | 12484                       | 3728                      | 70.13  |
| HDPE + 7 wt% W  | 11434                       | 3534                      | 69.09  |
energy and thereby forming agglomerates which make uniform dispersion of tungsten particles in the HDPE matrix difficult, as shown in figure 2(b). For agglomerates, the interfacial layer increases, which according to all data consists of the amorphous phase of HDPE. It can be seen from the XRD data shown in figure 1, the crystalline phase of HDPE decreases with increasing filler, therefore the amorphous phase increases and is displaced into the boundary layer between the matrix and filler. These agglomerates can be easily debonded from the matrix, and the debonded material will not bear any fraction of the external load, and hence the tensile strength decreases. Also, agglomerates are surrounded by HDPE matrix material and these agglomerates act as voids in the HDPE matrix. The presence of voids in the polymer matrix decreases the strength of the polymer. The obtained results are compared with the tensile strength predicted by Nicolais- Narkis equation [24].

\[ \varphi_c = \varphi_m (1 - 1.21 \varphi_f^{2/3}) \]  

(2)

where \( \varphi_c \), \( \varphi_m \) are tensile strength of composite (subscript c) and matrix material (subscript m) respectively and \( \varphi_f \) is the volume fraction of the filler. From figure 4, it is quite clear that the experimental results are higher than the predicted values, indicating that there is a strong interaction between tungsten particles and the HDPE matrix [25].
Figure 5 shows that the elongation at break for composite increases with the addition of 1 wt% of tungsten particles. Elongation at break increased by 79% than that of pure HDPE. The improvement in elongation at break for the addition of 1 wt% of tungsten is due to enhanced adhesion of tungsten particles with the HDPE matrix. On further addition of tungsten particles, it was observed that the percentage elongation at break decreased, which is due to the decrease in ductility of the composite. Also, at higher concentration of tungsten, particles tend to agglomerate due to high surface energy between them and these agglomerates acts as the stress concentrators prevent further extension.

The interfacial adhesion between the filler and polymer can be quantified by yield stress. The expression for yield stress is given by equation (3) [26]

$$
\sigma_y = \sigma_{ym} \left(\frac{\varphi_f}{1 + 2.5\varphi_f}\right) \exp(B\sigma_f\varphi_f)
$$

(3)

where $\sigma_y$ and $\sigma_{ym}$ are the yield stress of the composites and the matrix respectively, $\varphi_f$ is the volume fraction of the filler in the composite and B $\sigma_f$ is the parameter characterizing interfacial interaction.

To evaluate the interfacial interaction the equation (3) could be rearranged as follows

$$
\ln \left[ \frac{\sigma_y}{\sigma_{ym}(1 - \varphi_f)} \right] = B\sigma_f\varphi_f
$$

(4)

B $\sigma_f$ calculated is displayed in Table 3. From table 3, it is clear that the sample containing 1 wt% of tungsten has the highest B $\sigma_f$ value indicating the highest interaction between the polymer and filler materials which is the main cause for the increase in the tensile strength of the sample.

### 3.4. Flexural strength

The flexural strength of composites is found to increase with the addition of tungsten at 1 wt% and beyond increasing the tungsten content, the flexural strength is found to decrease as shown in figure 6. A similar trend was observed for alumina/epoxy composites [27]. Flexural strength increases by 15% for the addition of 1 wt% of tungsten particles to the HDPE matrix. This increase in strength is due to strong interfacial adhesion between the HDPE matrix and tungsten particles, which enables the effective stress transfer between HDPE and tungsten.
reinforcements. Also, the tungsten reinforcements obstruct crack growth and propagation during bending, which ultimately improves the flexural strength of the composites.

Flexural strength of composites decreases, by increasing the tungsten content beyond 1 wt% and it is due to agglomeration of tungsten particles as shown in figure 2(b). With the increase in the concentration of tungsten particles, the particles tend to attract each other and form large size agglomerates. These agglomerates act as a void in the matrix material which will deteriorate the flexural properties.

3.5. Impact strength
It was found that the impact strength of the prepared samples is found to increase, with the addition of tungsten particles at 3wt%. For further increase, the impact strength is found to decrease as shown in figure 7. A similar trend was observed in previous studies [28]. Impact strength of composite with 3wt% of tungsten particles show a 92% increase in impact strength than that of pure HDPE. Generally, in a polymer matrix composite, there exists a difference in elastic properties of reinforcements and matrix. In composites with metal reinforcements, there is a significant difference in elastic properties, between inorganic tungsten metal reinforcements and organic HDPE polymer matrix. As a result, tungsten particles act as the point of stress concentration leading to triaxial stress at the particle-matrix interface. This triaxial stress leads to debonding, creating voids, resulting in shear yielding of HDPE matrix material. Owing to shear yielding, composites absorb more energy upon fracture, and thereby increase the toughening effect of tungsten particles on the HDPE matrix.

Figure 6. Flexural properties versus tungsten particle content.

Figure 7. Effect of tungsten particle content on the impact strength of HDPE/W composites.
The decrease in impact strength with the addition of tungsten particles beyond 3wt% is due to the poor dispersion of tungsten particles in the HDPE matrix. At a higher particle content, metal particles stick together due to inherent high surface energy and thereby forming bigger agglomerates as shown in figure 2(C). These agglomerates reduce the toughening effect of the composites, as it introduces a defect inside the composites. The size of the agglomerates decides the toughening effect. If the agglomerate size is small, then it will be effective in preventing the propagation of the crack. Hence, the specimen with 3wt% of tungsten with smaller agglomerates are effective in preventing the propagation of the crack. But when the agglomerate grows, it acts as a void which deprives the strength. Thus, the strength of composites with higher particle content decreases.

3.6. Thermo-gravimetric analysis (TGA)

The thermal stability of pure HDPE and HDPE/W composites was analyzed from TGA thermograms. These plots are shown in figure 8. In addition, the numerical values of these plots are shown in table 4. In this table, onset temperature corresponding to 10% and 50% mass loss is represented as $T_{10}^\circ C$ and $T_{50}^\circ C$. In addition, char residue of composites at 550 $^\circ C$ is also presented in the table. $T_{10}^\circ C$ increases from 427.00 $^\circ C$ for pure HDPE to 447.00 $^\circ C$ for HDPE/7wt% W composites. Further, $T_{50}^\circ C$ increases to 475.70 $^\circ C$ for HDPE/7wt% W composites as compared to 469.69 $^\circ C$ for pure HDPE.

It can also be observed that char residue increases from 0% to 3.9% with an increase in tungsten content from 0 wt% to 7 wt%. This increase in $T_{10}^\circ C$, $T_{50}^\circ C$ and char residue indicates an increase in thermal stability of composites, with the increase in addition of tungsten particles in the HDPE matrix. The increase in decomposition temperature is due to incorporated inorganic particles, tungsten. These particles have higher thermal stability. Due to the adsorption of HDPE on the surface of tungsten particles, the latter particles act as a mass transport barrier to volatile products, generated during decomposition. As a result, polymer chain mobility will be reduced and the chain reaction will be suppressed, consequently delaying the degradation process. This
improves the thermal stability of composites. Thus, the inclusion of tungsten into the HDPE matrix inhibits the thermal destruction of HDPE by chain mechanism. It also influences the structural features of the filled polymer. These results are in line with the findings from the literature [29–31].

3.7. Differential Scanning calorimetry (DSC) analysis
Figure 9 depicts the DSC heating thermograms for pure HDPE and HDPE/W composites. Melting point ($T_m$ °C), specific melting enthalpy ($\Delta H$) and degree of crystallinity ($X_c$) for the manufactured HDPE/W composites obtained from the graph is shown in table 4. It can be observed that the melting point of the manufactured composites increases from 131.88 °C for samples containing 1wt% tungsten to 146.12 °C for HDPE with 7wt% tungsten composites. It is evident that, with the increase in the weight percentage of tungsten particles, the melting point increases. This increase in the melting point of the manufactured composites is due to the presence of thermally stable tungsten particles which prevents the mobility of polymer chain, at higher temperatures and improves the overall thermal stability, of the manufactured composites.

Degree of crystallinity of the manufactured composites is obtained by the equation (5) [32]

$$Degree \ of \ crystallinity (X_c) = \frac{\Delta H}{\Delta H_0}$$

where, $\Delta H$ is the heat of fusion of composites calculated from peak of DSC thermograms and $\Delta H_0$ is the heat of fusion of 100% crystalline HDPE which is taken to be 293 J g$^{-1}$ [33]. Table 5 shows that the heat of fusion and degree of crystallinity of the manufactured composites decreases with the addition of tungsten particles into the matrix of HDPE. This is due to the fact that with the addition of tungsten particles the molecular polymer segments were rearranged during the crystallization process. The viscosity of the polymer chain increased with
the increase in the content of tungsten particles in the HDPE matrix, therefore the motions of the HDPE matrix are restricted which results in the reduction of the heat of fusion and degree of crystallinity. This result confirms the results obtained with X-Ray Diffraction analysis.

4. Conclusion

1. X-ray diffraction analysis shows that the studied samples contain crystal structures that are characteristic of HDPE and tungsten because composites exhibit peaks at $2\theta = 40.3^\circ$ and other tiny peaks at $58.7^\circ$, $73.6^\circ$ and $87.1^\circ$ for tungsten and $21.6^\circ$ and $24.0^\circ$ for HDPE. The crystallinity index calculated for the specimen decreases with the addition of tungsten particles indicating a decrease in the crystalline region of HDPE. It is evident that the concentration of tungsten plays a significant role in the morphological and microstructural changes in the HDPE matrix.

2. FESEM analysis shows uniform dispersion of tungsten particles in the HDPE matrix for composite with 1wt% tungsten. Agglomeration of tungsten particles in the HDPE matrix is observed, for composites containing 3wt% of tungsten. The size of agglomerates increases with the further addition of tungsten particles which is evident from the FESEM image of samples with 7wt% of tungsten. Elemental mapping of composites with 1wt% of tungsten shows, the presence of tungsten and its uniform distribution in the HDPE matrix.

3. Maximum tensile and flexural strength values were obtained for composites with 1wt% of tungsten content and it is due to the uniform dispersion of tungsten particles in the HDPE matrix. Addition of tungsten beyond 1 wt% decreases the strength of the composites, which is mainly due to the agglomeration of tungsten particles.

4. Impact strength is found to increase with the addition of tungsten particles at 3wt%. Addition of tungsten particles beyond 3wt% resulted in a decreasing trend. The increase in impact strength is due to the fact that tungsten particles act as stress concentrators and thereby absorb more energy during a fracture and hence create a toughening effect in the manufactured composites.

5. TGA results of HDPE/W composites show an increase in thermal stability, with an increase in the addition of tungsten content in the HDPE matrix. The presence of thermally stable tungsten prevents the destruction of macromolecules in the HDPE matrix at high temperatures, making composites thermally stable.

6. DSC curves show that the melting point of composite increases with the increase in addition of tungsten. Melting point increases by 15% with increasing the tungsten content from 1 wt% to 7 wt% in the HDPE matrix. The presence of tungsten particles restricted the movement and rearrangement of the HDPE matrix to an extent, which affected the crystal growth and lowered the degree of crystallinity of HDPE.

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