ORIGINAL PAPER

Influence of heat treatment on the mechanical, thermal and thermophysical properties of low-density polyethylene

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ABSTRACT

This study demonstrates that quenching and annealing significantly influence the mechanical and thermophysical behavior of low density polyethylene (LDPE). Rapid quenching at temperature of –25 °C enhances ductility by increasing elongation at break, despite reducing thermophysical properties, likely due to microstructural refinement. In contrast, post-quenching annealing especially at 100 °C improves thermal conductivity and crystallinity but reduces ductility. The results underscore a tunable balance between thermal and mechanical performance, governed by the interplay of beta (β-) and alpha (α-) relaxation modes during heat treatment. Post-quenching annealing of low density polyethylene LDPE, particularly at 100 °C, significantly enhanced thermal conductivity, diffusivity, and crystallinity, albeit with a trade-off in ductility and increased brittleness. Quenching within the beta (β-) relaxation range promoted maximum ductility, while annealing in the alpha (α-) relaxation range improved thermophysical properties. These findings reveal that precise control of heat treatment conditions enables a tunable balance between mechanical flexibility and thermophysical performance in LDPE.

Keywords: heat treatment; low-density polyethylene; mechanical properties; thermal properties, thermophysical properties.

INTRODUCTION

The use of nanofillers, particularly montmorillonite (MMT), has become a widely adopted strategy for enhancing the mechanical and thermal properties of polymer matrices. Even at low loadings, MMT can significantly improve performance, as demonstrated in studies such as Al-Jumaili et al. [1], where 1–2 wt% MMT increased the tensile strength of LDPE. However, higher filler contents (>3 wt%) may reduce mechanical integrity due to increased brittleness. Despite ongoing advancements, many polymer systems still require further optimization to achieve balanced mechanical strength and thermal stability. Therefore, it is essential to rigorously optimize processing parameters and heat treatment conditions to fully exploit the intrinsic thermal and mechanical properties of the polymer.

A previous study [2, 3] examined the effects of free quenching on the mechanical properties of two amorphous polymers: ductile polycarbonate (PC) and brittle polystyrene (PS). Quenching PC near its secondary relaxation temperature (~40 °C) significantly enhanced its ductility. In contrast, PS showed a slight increase in impact strength under similar conditions, also linked to a relaxation mode around 40 °C. However, the thermophysical properties of both polymers remained unchanged.

Furthermore, it was discovered that in the instance of PC, quenching below Tg significantly altered the thermophysical properties in the temperature range that corresponded to the secondary relaxation mode of PC, whereas quenching above T_g had no effect [4].

The effects of heat treatment were examined on titanium dioxide-pigmented polystyrene and polycarbonate (PS/TiO_2, PC/TiO_2) at 3% TiO_2 and ABS. In a recent investigation carried out at the French laboratory CERTES. The obtained results show that the mechanical and thermophysical parameters and the quenching temperature have been found to be related. Through these efforts, it has been determined that the peculiar behavior of the analyzed data is caused by the existence of a secondary mode of relaxation of type β_1 [5–7].

Low-density polyethylene (LDPE) is a widely used thermoplastic polymer known for its flexibility, low density and good chemical resistance. The mechanical and thermophysical properties of LDPE such as tensile strength, hardness, crystallinity and thermal conductivity, can be significantly influenced by thermal processing methods like annealing and quenching. Annealing, which involves heating the polymer to a specific temperature below its melting point followed by slow cooling, promotes molecular rearrangement and increases crystallinity, resulting in improved dimensional stability and enhanced mechanical strength. In contrast, quenching rapid cooling from an elevated temperature tends to retain the polymer in a more amorphous state, preserving flexibility but often reducing mechanical strength and increasing thermal expansion. Understanding the impact of these heat treatments under different conditions is crucial for tailoring the performance of LDPE in various industrial applications ranging from packaging materials to components in automotive and electrical industries. High-density polyethylene (HDPE spherulitic structure and lamellae thickness have been the focus of numerous investigations, which have shown that changes in crystallization conditions have a substantial impact on the material's morphology and, in turn, its mechanical performance. Lamellar crystals, the building blocks of polyethylene, are semicrystalline and typically form spherulites after cooling from the melt, based to their research. Many descriptions of the spherulitic structure and polymer crystal formation in bulk polymers can be found in the literature. A lamellae structure represents the configuration of the macromolecular chains. The thickness of the lamellae in polyethylene is just a few hundred Angstroms, but the other dimensions are roughly several micrometers [8, 9]. The thickness of the lamellae is additionally affected by the heat treatment and the crystallization conditions.

The dynamic mechanical investigation of commercial low-density polyethylenes (LDPEs) has been studied by Leslie Poh et al. [10]. They revealed that each dispersion zone reflects a separate relaxation process and those damping peaks can be observed in both the G″ and tan d curves, indicating the existence of three dispersion regions. The inflection points of curves resulting from their peaks can be utilized to estimate the temperature range of each relaxation zone. From high to low temperature, the relaxation/dispersion areas are defined as follows: α-relaxation ($0 \leq T_\alpha$ [°C] ≈ 100), β-relaxation ($-92 \leq T_\beta$ [°C] ≈ 0), and γ-relaxation ($-150 \leq T_\gamma$ [°C] < -92).

Md. Tanbhir Hoq [11] has investigated the impact of heat treatment on the morphology and dielectric characteristics of polyethylene. A few tests were carried out with annealing times of 0, 1, 2, 4, 8, 16, 32, and 72 hours, and two annealing temperatures of 50 and 80 °C were agreed upon in her study. He observed that heat treatment have a major impact on the thickness and shape of polyethylene samples. César Leyva-Porras et al. [12] have examined the impact of molding parameters on the microstructure and crystallinity of LDPE. The response surface graphs (SRP) exhibited different behaviours: the size of the spherulite increased as the mold temperature rose, while the crystallinity showed higher values at low melt temperatures and intermediate mold temperatures.

Moyses et al. [13] showed that LDPE annealing leads to distinct melting behaviors, with crystallinity peaking due to recrystallized structures formed at higher annealing temperatures.

Previous studies by Merabet et al. [14] and Latreche et al. [15] have shown that controlled quenching can enhance the impact strength and toughness of polypropylene and polyethylene by influencing crystallinity and relaxation behaviors.

Dynamic spectrometry (DMA) corroborated this result [14, 16]. The primary morphology of iPP is dominated by the α structure based to the X-ray diffraction analysis.

For LDPE, alternative treatment methods such flame treatment have been investigated. The impact of flame treatment on the surface characteristics and heat sealability of low-density polyethylene coating has been investigated by Tuominen et al. [17]. The simultaneous reactions cross-linking and chain scission that take place on the LDPE surface were believed to be the cause of the heat sealing performance of the flame-treated LDPE coating. This ultimately influenced the LDPE-coated paper's heat-sealing ability by influencing the chain mobility and the amount of chain interdiffusion across the seal interface.

The occurrence of two phases in semi-crystalline polymers makes the process of residual stress formation extremely difficult; there are not many published studies on the topic, and even fewer for polyolefin and particularly low-density polyethylene. The objective of this work is therefore to study the effect of heat treatment (quenching and annealing) on the tensile, physical and thermophysical properties of compression-molded LDPE and to highlight the type of heat treatment that provides the best properties. Due to its high industrial demand, LDPE is being investigated utilizing a range of techniques, such as mechanical, thermal and thermophysical properties, to provide a comprehensive understanding of its internal consistency and behavior.

This paper describes the heat treatment in low-density polyethylene by optimizing the process of thermal quenching or annealing in the range of molecular relaxations α and β and the subsequent effects on mechanical, physical and thermophysical properties.

EXPERIMENTAL

Materials

Repsol Alcudia 2202f low-density polyethylene, which has a melting point of 111°C, a density of 0.92 g/cm3, and a melt flow index (MFI) of 0.25 g/10 min, constituted the polymer matrix used in this investigation.

Heat treatment

It should be mentioned that the annealing temperatures are only selected in the alpha molecular relaxation zone of polymer and practically can only be done in this temperature range, while the quenching temperature range is chosen to match to the two molecular relaxation zones, alpha and beta of LDPE.

Quench procedure

After inserting LDPE pellets into the mold and pressing them at 25 bars for 8 minutes at a molding temperature of 170°C, they were rapidly removed from their melt state in an antifreeze coolant bath at -25°C, a water bath at 15°C, and the air for 15 minutes. The thickness of each specimen is 3 mm. "Quenched samples" is the appellation assigned to these samples.

Annealed samples

Annealed specimens were prepared using samples quenched in bath water at 15°C. Then, these samples were heated in the oven at different temperatures (80, 90,100 and 110 °C) during a period of 3 hours, and then gradually cooled in the oven at a rate of about (10°C/30min) until it reached room temperature. "Annealed samples" is the name assigned to these samples

Characterization

Tensile test

Dumbbell specimens of 115 mm in length, 13 mm in width, and 20 mm in gauge length were used to evaluate their tensile characteristics. A universal testing equipment with a crosshead speed of 10 mm/min was used to conduct the test. ASTM D 638-72 was followed during the test process. Tensile characteristics (modulus of elasticity, stress at break, and elongation at break) of the quenched LDPE were estimated at room temperature based on the experimental stress-strain curves. After testing five specimens, the data plot was drawn using the average values.

Density Measurement

The Archimedes principle suggests that a specimen submerged in a liquid experiences pressure equal to the liquid's displacement. This approach was used to determine the density of the LDPE sample. Therefore, it is easy to determine the specimen's volume and specific mass by knowing the liquid's density. After knowing the specimen weight in air and its occupied volume in a liquid with a known density, the density which is the inverse of specific volume can be calculated. An HB Mettler analytical balance and distilled water at 25°C was the liquids we were using.

Differential scanning calorimetry

A Perkin Elmer Diamond calorimeter was used to measure the thermal properties. A nitrogen gas flow of (20 ml/min) was used to heat samples weighing roughly 10 mg in an aluminum pan between 50 and 200 °C at a cooling/heating rate of 10°C/min. The ratio of the crystalline portion of the semi-crystalline polymer can be defined with crystallinity (X_c), which can be calculated as follows:

$$X_c = \frac{\Delta H_m}{\Delta H_{100}} \times 100 \qquad (1)$$

Polyethylene's ΔH_{100} is 293 J/g, where ΔH_m is the enthalpy absorbed by the test sample during the heating process [18, 19].

The crystallinity of the samples of LDPE was calculated from the data of thermograms and the results are shown in Table 1.

Table 1. Values of density of LDPE quenched and annealed at different temperatures.

Thermal history of LDPE	Density
PEBD quenched at -25°C	0.918 ±0.00125
PEBD quenched in air	0.924 ±0.0023
PEBD quenched at 15°C	0.923 ±0.0045
PEBD annealed at 80°C	0.924 ±0.0052
PEBD annealed at 90°C	0.925 ±0.0056
PEBD annealed at 100°C	0.926 ±0.0023
PEBD annealed at 110°C	0.929 ±0.0075

Thermophysical measurements

A thermophysical analysis was conducted following ISO 22007-2:2008 guidelines [19] using a transient plane source (TPS 2500S) hot disk from Sweden, under standard atmospheric conditions at room temperature. This technique involves applying a slight temperature variation to a sample shaped like a rectangular prism (44 × 44 × 3 mm^3). The heating power utilized for the measurements was set to 20 mW for a duration of 10 seconds. For every measurement, two identical samples were employed; one positioned above the sensor and the other located below it. The heat source served to warm the specimen, and data was collected from both samples concurrently. The software then calculated the average thermal properties of the two samples. Thermal conductivity and thermal diffusivity were assessed at the same time, from which the specific heat (Cp) can be inferred. A minimum of three measurements was taken for each sample, and the average values are presented.

Vicat softening temperature

Vicat softening temperature evaluations were conducted to assess the softening point of the substance. A Zwick Vicat softening temperature testing device, applying 50 N of force and a heating pace of 5 °C/min, was used to identify the temperature at which the probe goes 1 mm into the material.

RESULTS AND DISCUSION

The process of cooling of LDPE

During the cooling of LDPE from the melt state to temperatures between -25°C, 15°C and in the air, cooling stresses form due to uneven temperature distribution. The surface of the material cools and solidifies first, while the inner layers remain hot and shrink more slowly. This creates a temperature gradient that leads to differential contraction. As the core cools and solidifies, the already rigid outer layer, causing internal stresses to build up, restricts it. These residual stresses caused by temperature gradients and non-uniform solidification can affect the material's mechanical performance, thermal and thermophysical properties.

Effect of quenching and annealing temperature on mechanical properties and density

The stress at break, elongation at break, Young modulus and density as a function of quenching and annealing temperature for LDPE samples are depicted in Figures 1, 2, 3 and

Table 1 respectively. From figure 1, the stress at break remains relatively constant for samples subjected to quenching at –25 °C, in air and in water at 15 °C (Figure 1). This indicates that the different quenching conditions do not significantly affect the initial mechanical strength of the material. However, when the samples are subsequently annealed at increasing temperatures of 80 °C, 90 °C, 100 °C, and 110 °C, a noticeable increase in breaking stress is observed compared to the sample quenched in water at 15 °C. This increase suggests that annealing at these temperatures promotes microstructural evolution such as the reduction of internal stresses or partial recovery processes that enhances the material's mechanical resistance. Indeed, the stress at break increases as crystallization increases, due to the compact structure of the crystal matrix.

The increase in stress at break with annealing temperature is directly linked to the increase in crystallinity. A more compact crystal matrix formed during annealing strengthens the LDPE by restricting molecular mobility and enhancing load-bearing capacity, requiring more stress to break the material.

The highest values of elongation at break and Young's modulus (Figure 2 and 3) are observed for the sample quenched at –25 °C, compared to those quenched in air or in water at 15 °C. This can be attributed to the rapid cooling rate at the lower quenching temperature, which leads to a finer and more homogeneous microstructure. Quenching at – 25 °C suppresses the mobility of polymer chains (or atomic diffusion in metals), reducing the formation of large crystalline regions or internal stresses that could act as weak points. As a result, the material retains higher internal energy and structural uniformity, which contributes both to greater ductility (higher elongation at break) and increased stiffness (higher Young's modulus). In contrast, slower cooling in air or at higher quenching temperatures may allow partial relaxation or phase segregation leading to a less favorable combination of mechanical properties.

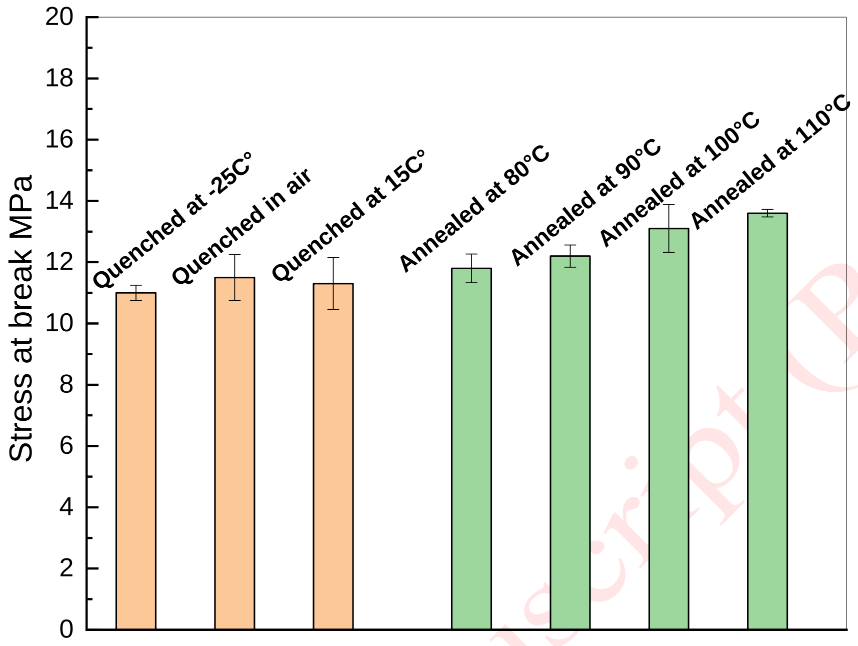

Figure 1. Stress at break of LDPE quenched and annealed at different temperatures.

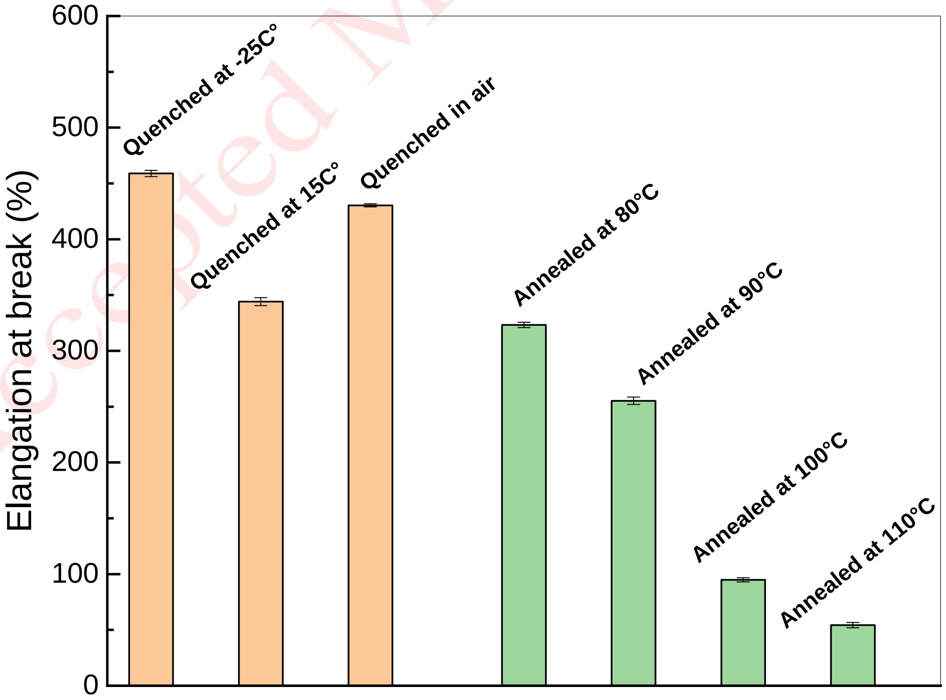

Figure 2. Elongation at break of LDPE quenched and annealed at different temperatures.

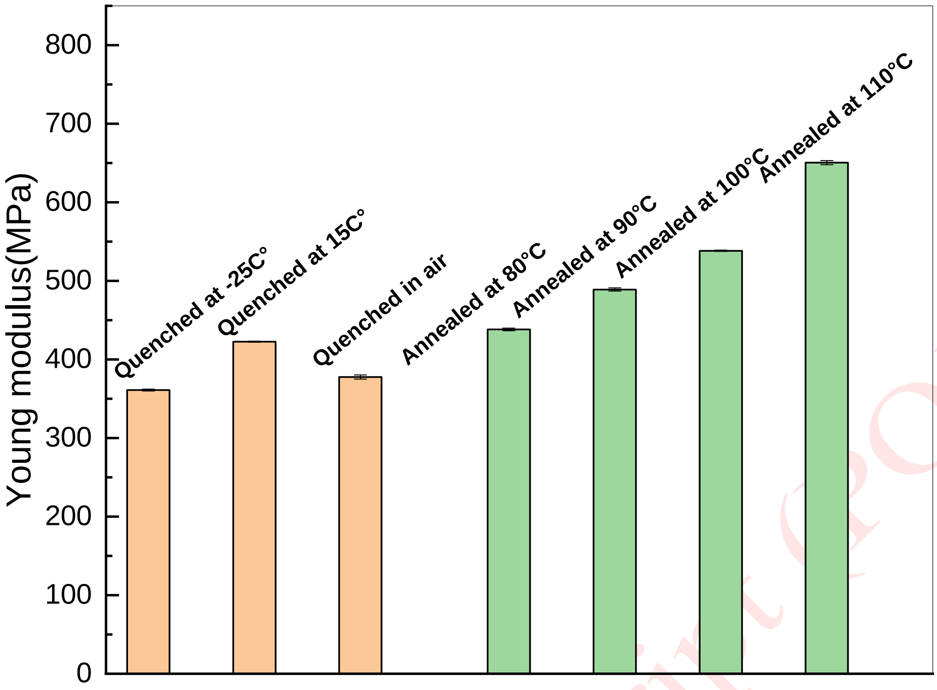

Figure 3. Modulus of elasticity of LDPE quenched and annealed at different temperatures.

With increasing annealing temperatures (80, 90, 100, and 110 °C), the elongation at break decreases while the Young's modulus increases compared to the sample quenched in water at 15 °C. This behavior is primarily due to thermally induced structural rearrangements in the material during annealing. As the temperature rises, the material undergoes partial relaxation of internal stresses and an increase in molecular or atomic ordering. These changes reduce the mobility of the polymer chains (in polymers), making the material more rigid and less able to deform plastically. Consequently, the stiffness of the material increases, reflected in a higher Young's modulus. At the same time, the reduced molecular mobility and increased structural order limit the material's ability to elongate before breaking leading to a decrease in elongation at break. In essence, annealing improves stiffness at the expense of ductility due to enhanced structural stability and reduced freedom of movement within the material's microstructure.

The reduction in elongation at break with higher annealing temperatures is linked to increased crystallinity and molecular ordering that limit chain mobility. This agrees with Md. Tanbhir Hoq [11], who showed that prolonged heat treatment promotes structural thickening and smoother surfaces via polymer chain relaxation and rearrangement.

Merabet et al. [14] showed that quenching iPP near its α-relaxation region reduces crystallinity and enhances impact strength. Latreche et al. [16] observed increased ductility but decreased thermal resistance in HDPE under similar conditions. In contrast, our study demonstrates that deep quenching LDPE at –25 °C below its α-relaxation range produces a mostly amorphous structure with improved elongation at break while preserving stiffness. These results underscore the key role of polymer type and quenching temperature relative to relaxation behavior in tuning mechanical properties.

Density

The variations of the value of density as a function of quenched and annealed LDPE are shown in Table 1. It can be seen that the minimum values of density was observed when the sample was quenched from the melt state to –25 °C compared to quenching to air or 15 °C. This reduction in density at –25 °C can be attributed to an increase in free volume, as rapid cooling to lower temperatures tends to trap polymer chains in a less densely packed, non-equilibrium state leading to higher free volume and thus lower overall density. In the process of rapid cooling, where the quenching temperature is -25°C, the long molecular chains have a shorter duration to rearrange themselves. This leads to a rise in the free volume and consequently results in a decreased density. However, the density increased progressively with increasing annealing temperature from 80 °C to 110 °C. This behavior is associated with a reduction in free volume, as higher annealing temperatures allow polymer chains to rearrange into a more thermodynamically stable and closely packed structure, thereby decreasing the amount of trapped free volume and increasing overall density.

Effect of quenching and annealing temperature on thermal properties

Figure 4 and 5 shows the melting characteristics of LDPE. It can be seen from Figure 4 that the highest melting temperature (113.76 °C) was observed for the sample quenched from the melt state to –25 °C, compared to quenching to air or 15 °C. This may be due to the formation of more perfect or larger crystalline regions during rapid cooling to –25 °C, which can increase thermal stability and result in a higher melting point. The highest melting temperature (114.09 °C) and enthalpy of fusion (135.08 J/g) of LDPE were obtained after annealing at 100 °C (Figure 5), compared to samples annealed at 80, 90, and 110 °C. This indicates that 100 °C is the optimal annealing temperature for enhancing crystalline structure, allowing sufficient molecular mobility for crystal growth and perfection without inducing thermal degradation or excessive chain relaxation that may occur at higher temperatures. As a result, more stable and well-ordered crystalline regions are formed leading to increased thermal properties. Some studies have suggested that heating to a temperature just above the crystallization temperature [21] and increases as the annealing temperature rises within the 25–136˚C range [22]. Since thicker lamellae have higher thermal stability, the observed rise in lamellae thickness can be attributed to the higher melting temperature. While DSC results (Table 2) show minimal changes in overall crystallinity among the quenched LDPE samples, the marked reductions in thermal conductivity and diffusivity for the –25 °C quenched sample indicate that microstructural features such as crystal size, disorder, and phase continuity play a more critical role in thermal transport. These findings suggest that thermal behavior in LDPE is influenced not only by crystallinity content but also by morphological characteristics not fully captured by DSC.

Consistent with Moyses et al. [13], our results highlight the key role of annealing temperature in optimizing LDPE crystallinity. While Moyses et al. linked increased crystallinity to partial melting and recrystallization (endotherm II), our data show that annealing at 100 °C yields the highest melting point (114.09 °C) and enthalpy of fusion (135.08 J/g), reflecting improved lamellar structure without thermal degradation. These findings reinforce the importance of precise thermal control in tuning LDPE's structural and thermal performance.

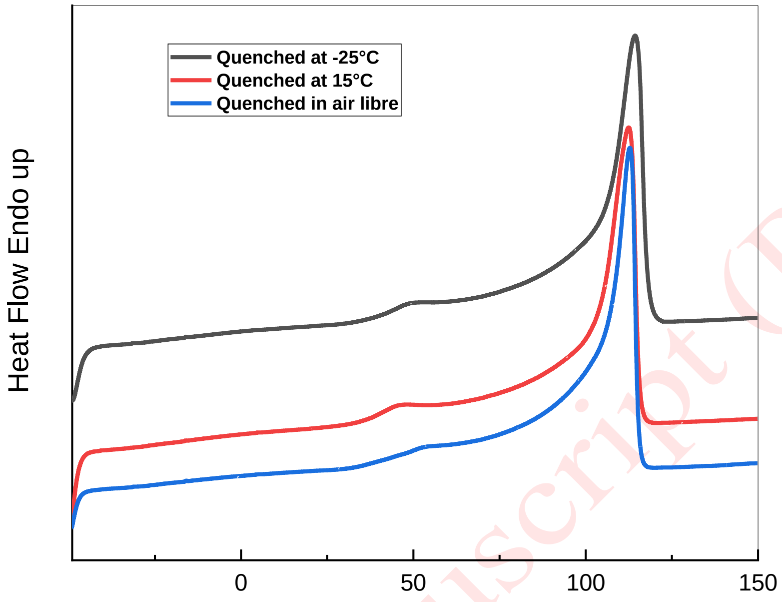

Figure 4. Thermograms of LDPE quenched at different temperatures**.**

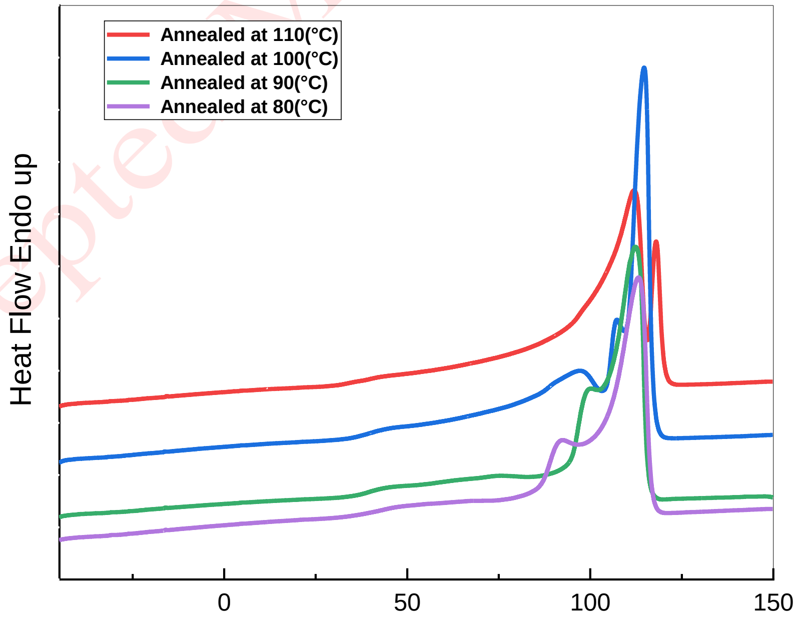

Figure 5. Thermograms of LDPE annealed at differents temperatures.

Table 2. Melting process parameters and crystallinity of LDPE quenched and annealed at different temperatures.

Sample	T_m (°C)	H_m (J/g)	X_c (%)	T_{onest} (°C)
LDPE quenched at -25°C	113.76	129.05	44	102.85
LDPE quenched in air °C	112.24	130.96	44.69	103.83
LDPE quenched at 15°C	111.92	128.7	44	100.68
LDPE annealed at 80°C	113.76	129.05	44.6	102.85
LDPE annealed at 90°C	111.74	130.95	44.6	101.11
LDPE annealed at 100°C	114.09	135.08	46.1	100.66
LDPE annealed at 110°C	111.39	133.5	45.5	97.68

Vicat softening temperature

The Vicat softening point lowers as crystallinity rises. Moreover, it is affected by the amount of free volume, which allows for the movement of segmented molecules. Figure 6 illustrates the changes in VST as a function of quenched and annealed sample. A cooler second cooling temperature is noted to decrease the VST. This occurs because this lower cooling temperature results in increased compressive stresses and more free volume. The maximum values of vicat softening point, measured as 48.1°C was obtained for the LDPE sample quenched at 15 °C.

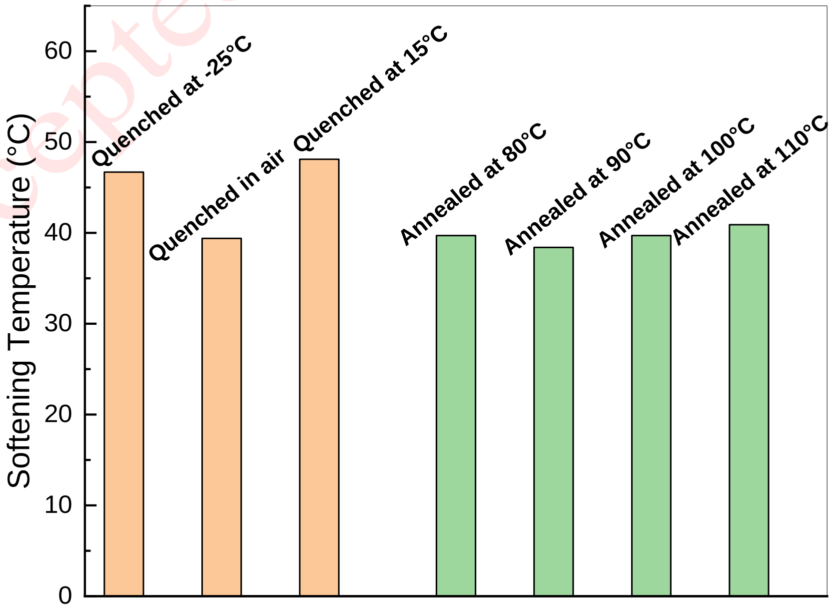

Figure 6. Vicat softening temperature of LDPE quenched and annealed at different temperatures.

LDPE with higher crystallinity has a higher Vicat Softening Temperature (VST) due to its tightly packed, ordered crystalline regions. These regions have stronger intermolecular forces that restrict polymer chain movement, making the material more heat-resistant. In contrast, LDPE with lower crystallinity has more amorphous regions with weaker forces, allowing it to soften more easily under heat, resulting in a lower VST (39.4°C) which correspond to the sample quenched in air. However, the VST are almost constant and are in the order of 40°C with the increasing of annealing temperature.

Although VST is typically linked to crystallinity, the DSC results (Table 2) show minimal variation among samples, suggesting that structural factors like lamellar thickness and crystal perfection play a more significant role. Annealing enhances these features without substantially altering total crystallinity, leading to improved thermal stability and increased VST despite similar crystallinity levels. Latreche et al. [16] reported that quenching HDPE improves ductility but reduces thermal stability, highlighting a trade-off in performance. In contrast, our results show that deep quenching of LDPE at –25 °C enhances flexibility without compromising VST. Despite little change in overall crystallinity, the VST increase suggests improved crystalline organization, indicating that LDPE can achieve better ductility and thermal resistance concurrently.

Effect of quenching and annealing temperature on thermophysical properties of LDPE Thermal conductivity and the thermal diffusivity.

The measured thermal conductivity and thermal diffusivity values, along with their corresponding standarddeviations for theannealed LDPE and the second quenched samples, can be found in Table 3. It is noted that the standard deviations for the thermal conductivity of LDPE remain stable, around 0. 01 (W/m.K). On the other hand, the standard deviations for thermal diffusivity fluctuate between 0.425×10^{-7} and 2.2933×10^{-7} (m^2/s). These values are acceptable and show minimal variation.

Table 3. The values of the thermal conductivity, the thermal diffusivity and specific heat capacity of LDPE quenched and annealed at different temperatures and their standard deviations.

Thermal history of LDPE	Conductivity K (W/m.k)	Diffusivity α (m^2/s) $\times10^{-7}$	C_p (J/kg.K)
LDPE quenched at -25°C	0.16865 ± 0.00591	1.54 ± 0.425	1260
LDPE quenched in air °C	0.28246 ±0.0095052	2.3451 ± 0.8074	1330
LDPE quenched at 15°C	0.18762 ±0.0175	1.7523 ± 0.536	1280
LDPE annealed at 80°C	0.2072 ± 0.00532	1.83 ± 0.4098	1380
LDPE annealed at 90°C	0.2799 ± 0.0134	2.080 ± 0.904	1560
LDPE annealed at 100°C	0.3055 ± 0.0108	2. 546 ± 0.9125	1470
LDPE annealed at 110°C	0.32011 ± 0.018756	3.4667± 2.2933	1100

The lowest recorded thermal conductivity and thermal diffusivity were found to be 0. 16865 (W/m. K) and 1. 54×10-7 (m^2/s), respectively, for the LDPE sample that was quenched at -25 °C compared to the samples quenched at 15 °C and in air.The minimum values of thermal conductivity and thermal diffusivity for LDPE sample quenched at -25 °C can be explained by changes in the material's microstructure and degree of crystallinity caused by the quenching process.

The LDPE sample quenched at -25 °C showed the lowest thermal conductivity and diffusivity due to reduced crystallinity caused by rapid cooling. This fast quenching limited the alignment of polymer chains, resulting in a more amorphous structure with greater molecular disorder. The increased disorder and presence of voids hindered phonon transport, thereby reducing heat transfer efficiency. On the other hand, more crystalline areas were able to develop with slower cooling at 15°C or in air, which raised thermal conductivity and diffusivity.

Specific heat capacity

The specific heat depends on the bond strength as well as the morphology. Table 2 depicts the changes in the specific heat capacity of LDPE regarding quenching and annealing temperature. The values published in the literature for a Polyethylene with a density of 961 kg.m^{-3} is between 1331 and 2400 J/kg. K. In the case of quenching, it is observed that this follows the same trend as that of the thermal conductivity and diffusivity. The highest heat capacity was observed in the samples quenched in air (1330 J/kg. K) and the maximum heat capacity was obtained for the samples annealed at 90°C (1560 J/kg. K)." This can be explained as follows:

When LDPE is quenched in air, the cooling rate is relatively slower because air has a lower heat transfer coefficient compared to liquids like water at 15°C or antifreeze coolant at -25°C. This slower cooling can result in the material reaching a more stable thermal state and therefore having a higher heat capacity.

Quenching at -25°C and 15°C: Quenching in cold baths (like at -25°C or 15°C) causes the material to cool much more quickly. Rapid cooling can lead to structure that is more amorphous. In many cases, faster quenching leads to a reduction in the material's heat capacity, especially if it causes structural changes that reduce the ability of the material to store thermal energy.

The maximum heat capacity at an annealed temperature of 90°C occurs because this temperature allows the material to reach an optimal balance between recrystallization and residual stress. This results in a microstructure that is well suited to store thermal energy.

At 80°C, the material may not fully develop the desired structure, and at 100°C or 110°C, excessive grain growth, which lead to the increase in crystallinity or phase transformations, may reduce the material’s ability to store heat, leading to lower heat capacity.

Thus, the key is that the annealing temperature of 90°C represents the optimal temperature for achieving the ideal microstructure that maximizes heat capacity, while temperatures below or above this result in less favourable material properties.

CONCLUSION

The quenching process of low-density polyethylene (LDPE) at -25°C significantly affects its mechanical and thermophysical properties. When LDPE is rapidly cooled from its molten state to subzero temperatures, particularly around -25°C, it undergoes a transition that affects its crystalline structure and molecular orientation. This process enhances the material's elongation at break, a key indicator of its ductility and toughness.

At this low temperature, the rapid cooling prevents the formation of large crystalline regions, resulting in a more amorphous structure. This reduces the thermal conductivity and diffusivity of the material while increasing its flexibility. The improved elongation at break means that the polymer can stretch further before breaking, making it more resilient to mechanical stress. In addition to its enhanced mechanical properties, the thermophysical characteristics of LDPE are also affected by quenching at -25°C. The polymer exhibits a reduction in its thermal conductivity and heat capacity due to the reduced crystallinity. This makes the material more insulating and less responsive to temperature fluctuations.

Overall, quenching LDPE at -25°C offers a balanced approach to improving elongation at break while optimizing its thermophysical behavior for a variety of applications that require enhanced flexibility, low-temperature performance, and resilience under mechanical stress.

Annealing low-density polyethylene (LDPE) at elevated temperatures such as 80°C, 90°C, 100°C, and 110°C induces significant changes in the material's mechanical and thermophysical properties. During this process, LDPE is heated to a specific temperature and held for a period, allowing the polymer chains to relax and crystallize further, resulting in a more ordered molecular structure.

Elongation at break: One of the most notable effects of annealing LDPE at higher temperatures is a decrease in elongation at break. As the material undergoes annealing, the crystallinity of the polymer increases, which leads to greater stiffness and a reduction in its ability to stretch before breaking. This decrease in elongation at break is particularly pronounced at higher annealing temperatures, as the polymer chains align more rigidly in response to the thermal treatment. At 80°C, the decrease may be modest, but as the temperature rises to 90°C, 100°C, and 110°C, the elongation at break continues to diminish due to further crystallization and molecular orientation.

Improvements in molecular organization and crystal structure, rather than just crystallinity, are what cause thermally treated LDPE's VST to rise. This highlights that while improving thermal performance in semi-crystalline polymers, microstructural refinement must be taken into consideration in addition to crystallinity.

Thermophysical Properties: Annealing also significantly enhances the thermophysical properties of LDPE. As the material crystallizes, it exhibits an increase in thermal stability, as evidenced by an elevated melting temperature (Tm). The polymer's thermal conductivity and heat capacity are also improved as the increased crystallinity allows for more efficient thermal transfer. Overall, annealing LDPE at temperatures between 80°C and 110°C leads to a trade- off: while the material's elongation at break is reduced, its thermophysical properties such as thermal stability, crystallinity, are significantly improved. This makes annealed LDPE a better choice for applications requiring greater dimensional stability and performance at higher temperatures.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

FUNDING

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ABBREVIATIONS

LDPE: Low-Density Polyethylene

DSC: Differential scanning calorimetric

T_m: Melting temperature.
K: Thermal conductivity
α: Thermal diffusivity

REFERENCES

1. Al-Jumaili SK, Alkaron WA, Atshan MY (2023) Mechanical, thermal, and morphological properties of low-density polyethylene nanocomposites reinforced with montmorillonite: Fabrication and characterizations. Cogent Eng 10: 2204550 [CrossRef]
2. Rouabah F, Fois M, Ibos L, Boudenne A, Picard C, Dadache D, Haddaoui N (2008) Mechanical and thermal properties of polycarbonate, part 1: Influence of free quenching. J Appl Polym Sci 109: 1505-1514 [CrossRef]
3. Rouabah F, Dadache D, Haddaoui N (2012) Thermophysical and mechanical properties of polystyrene: Influence of free quenching. ISRN Polym Sci 2012: 1-8 [CrossRef]
4. Barka B, Rouabah F, Zouaoui F, Fois M, Nouar Y, Bencid A (2022) Thermophysical behavior of polycarbonate: Effect of free quenching above and below the glass transition temperature. Advanced Materials Research 1174: 123-136 [CrossRef]

5. Dadache D, Rouabah F, Fois M, Guellal M (2018) Effects of free quenching on mechanical, thermomechanical and thermophysical properties of titanium dioxide-pigmented polystyrene. Russ J Appl Chem 91: 1974-1983 [CrossRef]
6. Rouabah F, Dadache D, Fois M, Haddaoui N (2014) Effect of the quenching temperature on the mechanical and thermophysical properties of polycarbonate pigmented with titanium dioxide. J Polym Eng 34: 657-663 [CrossRef]
7. Bencid A, Rouabah F, Fois M, Djidjelli H (2017) Effect of the free quenching on mechanical and thermomechanical properties of ABS. Russ J Appl Chem 90: 2009-2015 [CrossRef]
8. Zhou H, Wilkes G (1997) Comparison of lamellar thickness and its distribution determined from d.s.c., SAXS, TEM and AFM for high-density polyethylene films having a stacked lamellar morphology. Polymer 38: 5735-5747 [CrossRef]
9. Alberola N, Cavaille JY, Perez J (1990) Mechanical spectrometry of alpha relaxations of high-density polyethylene. J Polym Sci Pol Phys 28: 569-586 [CrossRef]
10. Poh L, Wu Q, Chen Y, Narimissa E (2022) Characterization of industrial low-density polyethylene: a thermal, dynamic mechanical, and rheological investigation. Rheol Acta 61: 701-720 [CrossRef]
11. Hoq T (2014), Effect of heat treatment on morphology and dielectric properties of polyethylene, Phd Thesis Stockholm, Sweden
12. Leyva-Porras C, Balderrama-Aguilar A, Estrada-Ávila Y, Espelosín-Gómez I, Mendoza-Duarte M, Piñón-Balderrama C, Saavedra-Leos MZ, Estrada-Moreno I (2021) Injection molding of low-density polyethylene (LDPE) as a model polymer: Effect of molding parameters on the microstructure and crystallinity. Polymers 13: 3597 [CrossRef]
13. Moyses SC, Zukermann-Schpector J (2004) Annealing in low density polyethylene at several temperatures. Polym J 36: 679-683 [CrossRef]
14. Merabet S, Rouabah F, Fois M (2019) Heat treatment of isotactic polypropylene: the effect of free quenching from the melt state. Int J Polym Anal Charact 24: 313-325 [CrossRef]
15. Merabet S, (2019), Amélioration des performances du polypropylène isotactique : rôle de la trempe libre, PhD Thesis. Ferhat Abbas Setif University 1, Algeria
16. Latreche L, Rouabah F, Haddaoui N (2019) Influence of free quenching on mechanical physical and thermal properties of high density polyethylene. Chem Process Eng Res 59, 1–7 [CrossRef]
17. Tuominen M, Ek M, Saloranta P, Toivakka M, Kuusipalo J (2013) The effect of flame treatment on surface properties and heat sealability of low-density polyethylene coating. Packag Technol Sci 26: 201-214 [CrossRef]
18. Ahmed T, Mamat O (2011) The development and characterization of HDPE-silica sand nanoparticles composites. In: Proceedings of the IEEE Colloquium on Humanities, Science and Engineering, Penang, Malaysia, pp.: 6–11
19. Alapati S, Meledath JT, Karmarkar A (2014) Effect of morphology on electrical treeing in low density polyethylene nanocomposites. IET Sci Meas Technol 8: 60-68 [CrossRef]
20. ISO. 22007-2 (2008) Plastics – Determination of thermal conductivity and thermal diffusivity – Part 2: transient plane heat source (hot disc) method, 1st ed.; ISO: Geneva, Switzerland
21. Loos J, Tian M, Rastogi S, Lemstra PJ (2000) An investigation on chain mobility in solid state polymer systems. J Mater Sci 35: 5147-5156 [CrossRef]
22. Meinel G, Peterlin A (1967) Changes in noncrystalline regions of polyethylene during annealing. J Polym Sci B Polym Lett 5: 613-618 [CrossRef]

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