ISSN: 2096-3246
Volume 58, Issue 02, 2026

ANALYSIS OF THERMAL AND MECHANICAL PROPERTIES OF BIAXIALLY ORIENTED POLYPROPYLENE (BOPP) FILMS USED AS LABELS

Pradumna Kumar, Dr. Mohit
Scholar, M. Tech, Printing technology, GJUS&T, Hisar
Assistant Professor, Dept. Of Printing Technology, GJUS&T, Hisar

Abstract

This study conducts multi-dimensional thermal and mechanical property tests on commercial BOPP label films used for wrap-around labels and pressure-sensitive labels. It sequentially completed thickness and density measurement, DMA analysis, and heat shrinkage testing. The experiments cover a temperature range from -20°C to 120°C, while distinguishing performance differences between the material's MD (longitudinal direction) and TD (transverse direction). Test results confirm that the film exhibits excellent production reproducibility and wide-temperature-range stability, and can meet the core application requirements of commercial labels including high-speed labeling and thermal-sensitive label applications. This study uses DMA to characterize the relevant properties of BOPP label films.

Key words: BOPP, Lbels film, DMA, thermal shrinkage, tensile properties, viscoelasticity.

1. Introduction

In early industrial contexts, most labels were manufactured using raw materials such as coated paper, wax paper, and GSM paper of varying grammages. The reliability flaws of these paper-based labels have been confirmed by existing studies [1][2]; they are prone to tearing, cannot resist water or moisture, and deteriorate rapidly under environmental impacts. Biaxially oriented polypropylene (Biaxially Oriented Polypropylene, BOPP) is a mainstream material in the flexible packaging and label market [3], and labels made from polypropylene, polyethylene, and vinyl materials achieved rapid popularization starting in the 1960s [4][5].

This study sorts out the development context of the polymer label field: In 1833, chemist Berzelius first proposed the term "polymer"[6]. In 1933, Fawcett and Gibson discovered low-density polyethylene, which achieved commercialization in the mid-20th century; before synthetic polymers became widespread, labels mostly used natural base materials [7][8]. After synthetic polymers were popularized, they provided label materials with better performance for packaging, product identification, and industrial applications. All core nodes are marked with their corresponding academic literature [9][10].

The stereoregular catalyst system proposed by Ziegler and Natta overcame the prior technical bottleneck that only weak, amorphous atactic polypropylene could be synthesized. This system enabled the production of crystalline polypropylene, and later isotactic polypropylene, which features superior strength, stiffness, and melting point, was rapidly commercialized in multiple countries [11][12][13].

Today's general-purpose industry labels have long outgrown their basic role of product identification. They can support a wide range of diverse functions including brand building, compliance labeling, product traceability, and consumer interaction, and are widely adopted across sectors such as food and beverage, pharmaceuticals, and logistics. The associated value of these labels is supported by existing literature [14][15].

Polypropylene currently holds an extremely large share of the global components market. Backed by its excellent fundamental physical and chemical properties, processing compatibility, and multiple practical additional advantages, it has been widely applied in four core scenarios: food packaging, textiles, automotive parts, and consumer goods. According to references [16] and [17], its comprehensive performance, versatility, and cost-effectiveness have made it one of the most widely used polymers worldwide.

Thermally induced dimensional instability is the core failure mode of labels. While the hot filling process offers advantages, when filling juice and sauce products at temperatures of 85–95°C, excessive thermal shrinkage of labels can lead to curling, wrinkling, and delamination, a conclusion cited from reference [18].

The authors of this paper propose that material mismatches between packaging labels and their containers reduce sorting efficiency and contaminate recycling streams. Reference [19] notes that closed-loop recycling requires material compatibility; for example, polypropylene containers should be paired with labels made of the same material.

This study selects standard commercial BOPP label films as test subjects and conducts four core tests to assess their performance uniformity, strength anisotropy, dimensional stability, and viscoelasticity. The findings obtained can establish a performance baseline to support quality control and predictive modeling throughout label processing and application.

2. Materials and Methods

2.1 Materials

The commercial biaxially oriented polypropylene (BOPP) film used in this study was produced by Polyplex Corporation Limited via the blown film extrusion process and is widely applied in the label and packaging fields. The film has undergone biaxial stretching in the machine direction (MD) and transverse direction (TD), a treatment that boosts its tensile strength, dimensional stability, and optical transparency. All parameters of the film used, including its thickness, grammage, as well as the tensile strength, stretch rate, and shrinkage rate in both directions, are fully documented.

2.2 Methods

2.2.1 DMA Measurement

This study carried out testing using dynamic mechanical analysis (DMA). The instrument used is the Q800 dynamic mechanical analyzer from TA Instruments of Newcastle, the United States. The test specimens are rectangular samples measuring 20 mm × 5 mm with a thickness of 40 µm. Tests are performed in tensile mode at a frequency of 1 Hz, over a temperature range of -20°C to 120°C, with a heating rate of 3°C/min. The quantities to be measured include storage modulus E′, loss modulus E″, and loss factor Tanδ.

$$\tan\delta = E'/E''$$

2.2.2 Thermal Shrinkage

In this heat shrinkage test, a 10 mm × 10 mm sample was first prepared, then placed in a 120°C hot-air oven for 5 minutes of treatment. Subsequently, the dimensions of the sample along the MD and TD directions were measured sequentially, and the shrinkage rate was calculated.

$$\text{Thermal Shrinkage (\%)}=[(L_0-L_f) / L_0] \times 100$$

L_0 is the initial length, and L_f is the final length.

2.2.3 Tensile strength test

This study used rectangular specimens with dimensions of 250×15 mm. All tests were conducted at a normal room temperature of 23°C, using an Instron 68TM-10 universal material testing machine manufactured in Boston, Massachusetts, USA. In compliance with the ASTM D882 standard, tests were run with a crosshead speed of 80 mm/min and a 1 kN load cell, to measure the Young's modulus, elongation at break, and tensile strength in the MD and TD directions.

2.2.4 Thickness and Density measurement

The micrometer used for thickness measurement in this experiment is a Mitutoyo model ID C112X, which features a flat anvil with a 10 mm diameter and applies a constant pressure of 0.5 N/cm². Fifty sets of random thickness readings were collected along each of the two orientations of the BOPP film: the machine direction (MD) and the transverse direction (TD).

This study adopts the buoyancy method based on Archimedes' principle to measure density. The immersion liquid used, isopropyl alcohol, has a density of 0.785 g/cm³. First, the weight of the calibration block in air is measured; the block is then suspended in isopropyl alcohol to obtain its in-liquid weight, after which all measured values are substituted into the density formula for calculation.

$$\rho_{film} = \frac{W_{air}}{W_{ai} \ - W_{liquid}} \times \rho_{liquid}$$

where W_{air} and W_{liquid} are weights in air and liquid, respectively [20].

3. Results and Discussion

3.1 Dynamic Mechanical Analysis

3.1.1 Storage Modulus (E′)

This study observes that in fig. 1. the storage modulus E′ of BOPP films exhibits a significant temperature dependence. Between -40°C and -20°C, the modulus in the machine direction (MD) is 1500–1800 MPa, while that in the transverse direction (TD) is 1400–1500 MPa. Within this temperature range, crystalline regions dominate to form a rigid structure.

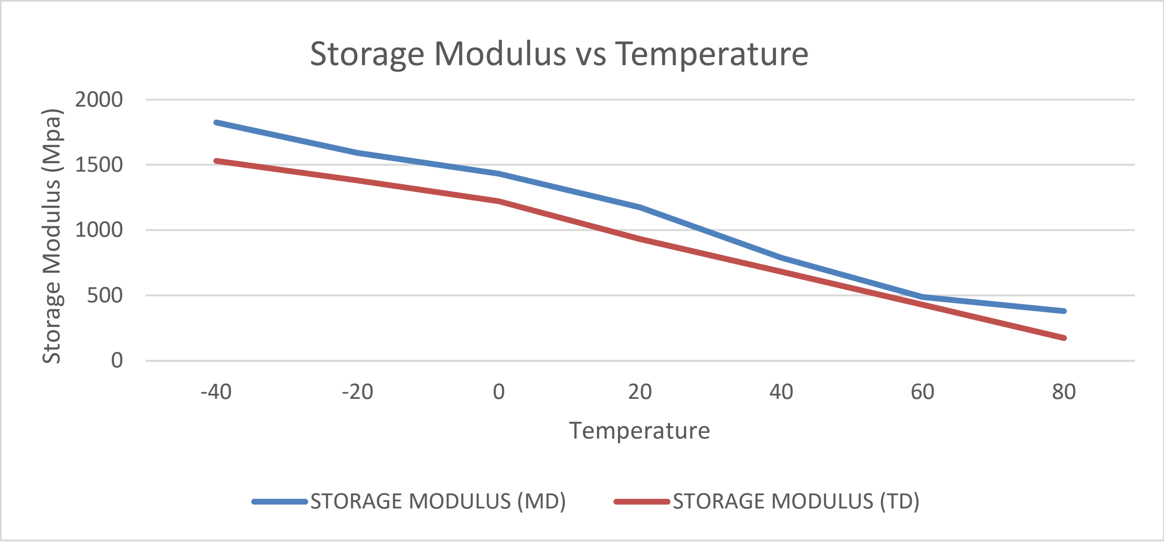


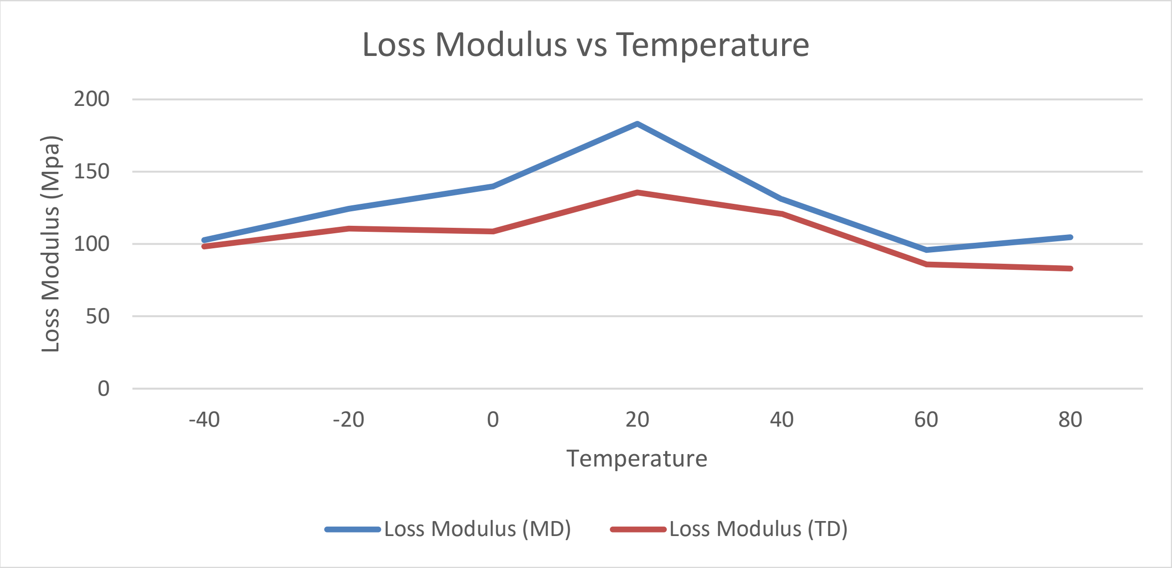
Fig. 1.

Storage Modulus vs Temperature

This experiment measured that the storage modulus E′ of the biaxially stretched polymer material varies across three temperature intervals: As the temperature rises above -20°C, the modulus of the longitudinal direction (MD, 1100–1400 MPa) and transverse direction (TD, 950–1200 MPa) declines slowly, which corresponds to the initiation of molecular migration in the glass transition region. Between 20°C and 60°C, the modulus sees the largest drop; softening of the amorphous phase reduces the MD modulus to 500–800 MPa and the TD modulus to 420–700 MPa. Between 60°C and 80°C, the moduli converge to 250–300 MPa, accompanied by reduced stiffness and emerging chain flexibility. The high orientation-induced modulus of MD matches the prediction put forward in reference [21].

3.1.2 Loss Modulus (E″)

Fig. 2. Loss Modulus vs Temperature



In fig. 2 the loss modulus E" of the BOPP films tested in this experiment is used to characterize the material's viscous energy dissipation. Observations show that across all tested temperature points of -40°C, -20°C, 20°C, 60°C, and 80°C, all E" values fall within the predetermined ranges for their respective intervals. The variations in E" match the following polymer states in sequence: chain segment freezing, activation of local molecular motion, glass transition, and flow in the high-elastic state. The E" values differ significantly between the machine direction (MD) and transverse direction (TD). It is deduced that molecular orientation significantly affects viscoelastic energy dissipation, and this core conclusion is supported by existing research [21].

3.1.3 Damping Factor

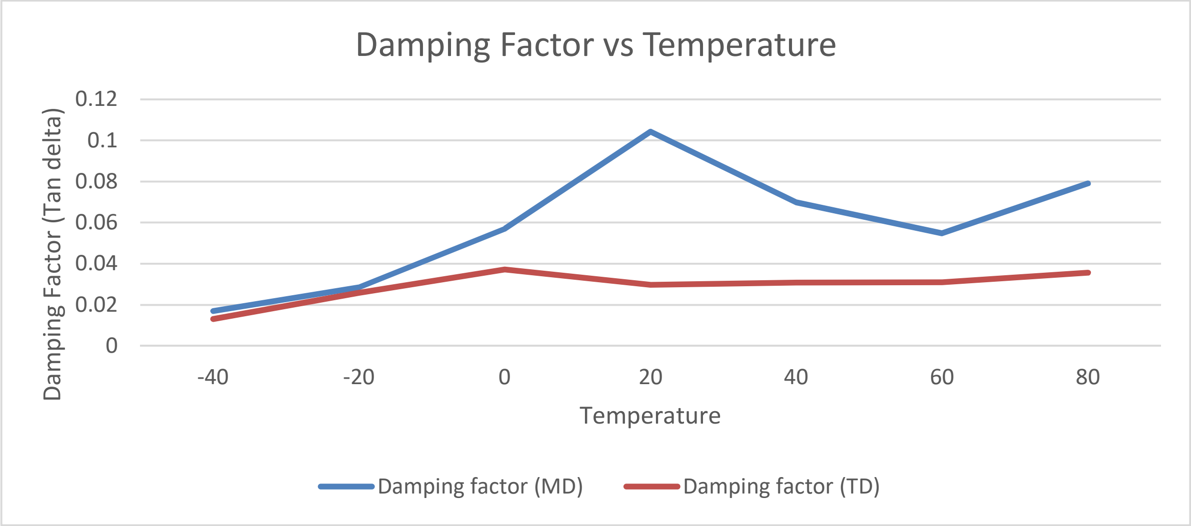


Fig. 3. Damping Factor vs Temperature

In fig. 3. this study carried out experimental performance observations on BOPP films. First, we defined the core test parameter, the loss factor tanδ, as the ratio of the loss modulus to the storage modulus. We then split the full temperature range into four intervals ordered from low to high to sort out the variation rules of tanδ, and derived the molecular motion states corresponding to each temperature, including the molecular relaxation characteristics in the glass transition region and the corresponding dominant type of viscoelasticity. Finally, based on the tanδ peak difference between samples with longitudinal (MD) and transverse (TD) orientation, we verified that the molecular arrangement induced by biaxial orientation leads to anisotropic damping behavior. This conclusion is supported by reference [21], and the temperature intervals, value ranges, and error margins of all experimental data are clearly marked.

3.2 Tensile Strength Test

3.2.1 Tensile Strength

This study measured that in fig. 4. the tensile strength of 40 μm-thick biaxially oriented polypropylene (BOPP) films exhibits orientation dependence: the tensile strength along the machine direction (MD) is 130–150 MPa, while that along the transverse direction (TD) is 240–260 MPa.

The improvement in transverse direction (TD) tensile strength of the films prepared in this study stems from a dual-orientation mechanism, which enhances molecular order and strengthens radial stress transfer; multiple groups of samples have a tensile strength of 8–14 MPa (error ±2 MPa), uniform quality, are compatible with label products, and can avoid tearing damage during label application.

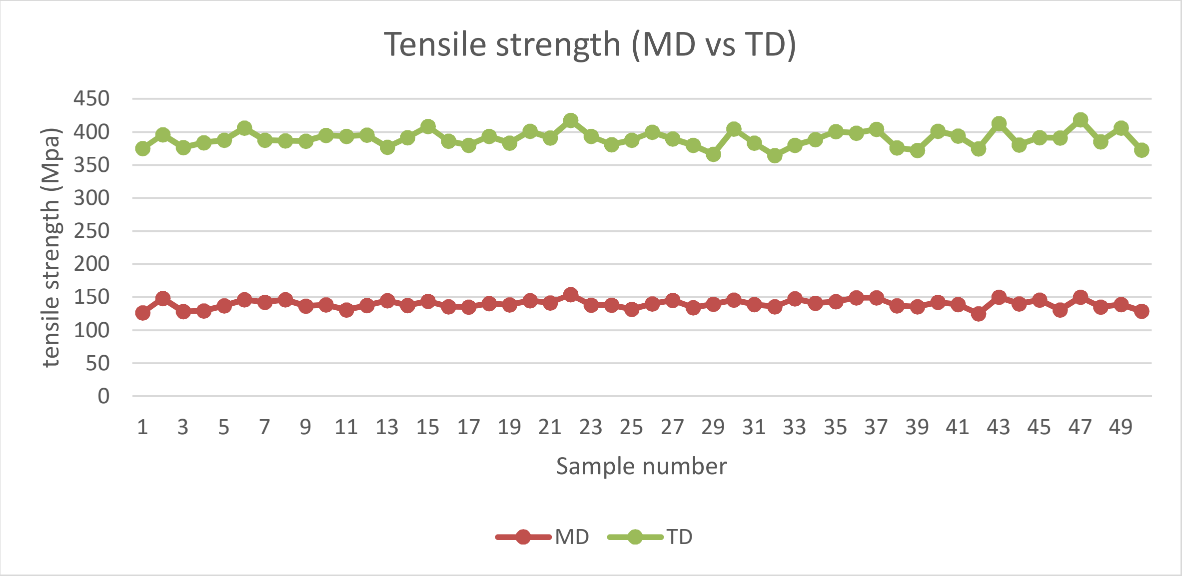
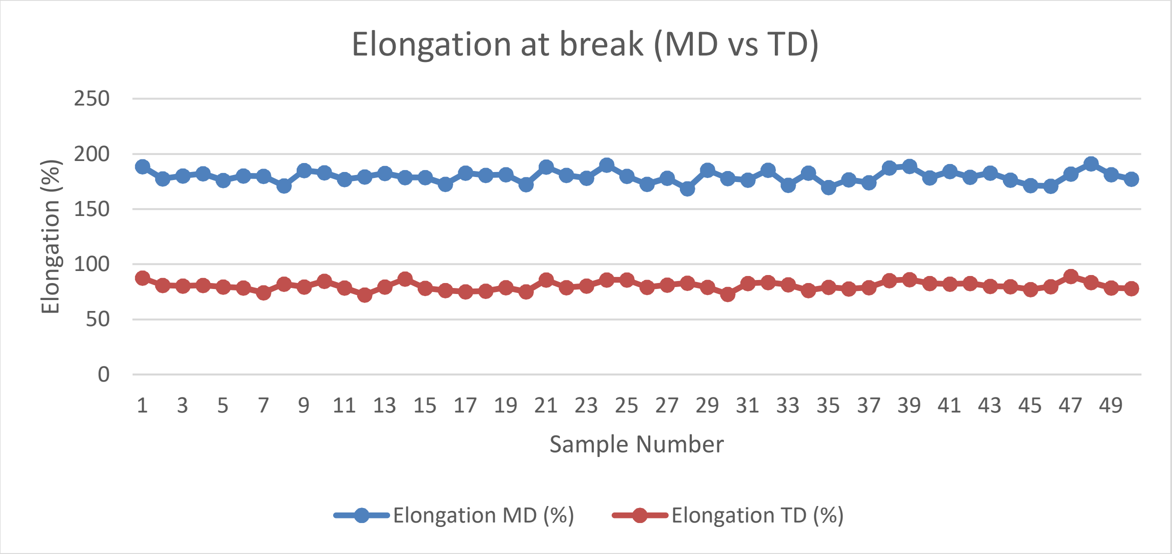


Fig. 4. Tensile strength (MD vs TD)

3.2 Elongation at Break

Fig. 5.



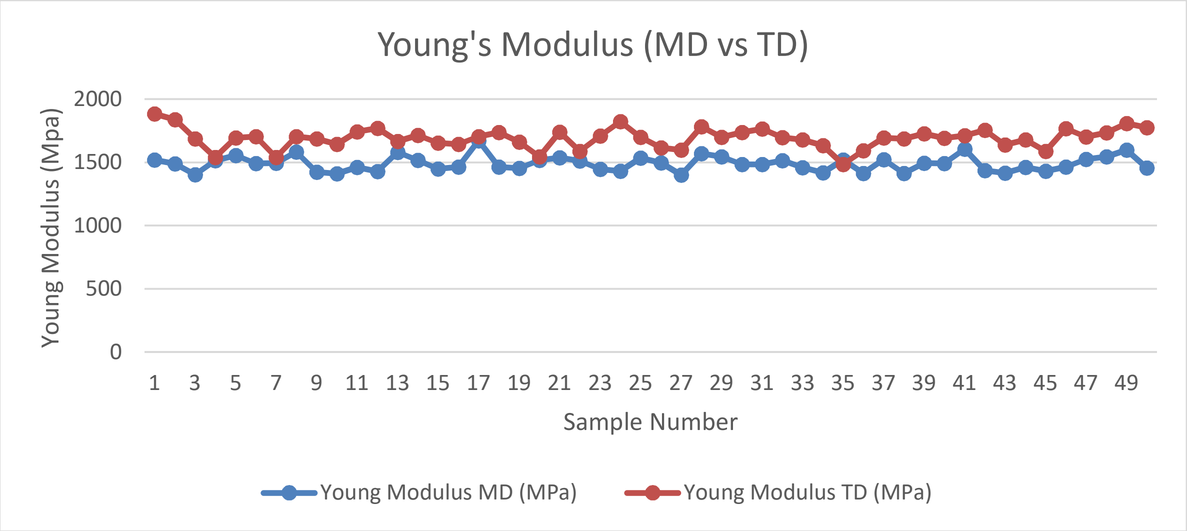
Elongation at break (MD vs TD)

This study finds that in fig. 5. the elongation at break of BOPP films exhibits significant anisotropy, whose root cause lies in differences in molecular chain mobility along the two biaxial axes: the longitudinal elongation at break reaches 170%-190%, with excellent ductility; the transverse value is only 70%-90%, as dense molecular packing raises stiffness and restricts deformation.

This study observes that when oriented polymer films under biaxial stress are stretched, the machine direction (MD) shows a higher level of reinforcement, while the transverse direction (TD) retains structural integrity and has a switchable orientation. This behavior arises because crystal rotation enables sustained elongation without any molecular breakage.

3.2.3 Young's Modulus

Fig. 6.



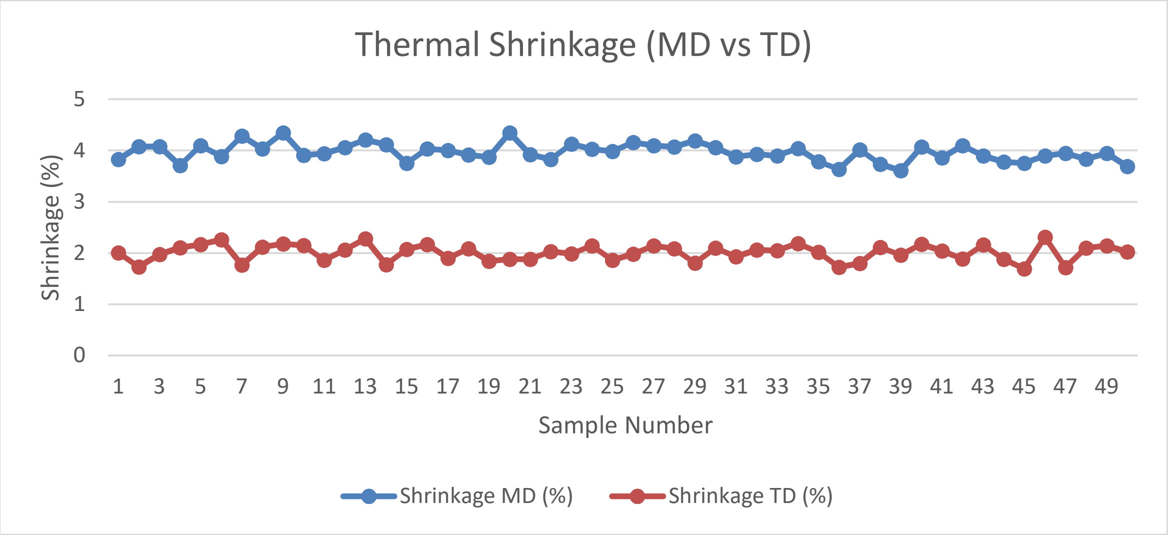
Young's Modulus (MD vs TD)

In fig. 6. the 40μm BOPP film tested in this study adopts its Young's modulus to characterize the film's stiffness and resistance to elastic deformation. Its modulus in the machine direction (MD) is

1400–1600 MPa, while its modulus in the transverse direction (TD) is 1600–1800 MPa. The higher TD modulus arises from elevated orientation and crystallinity during the production stretching stage, which enhance the film's rigidity. The lower MD modulus endows the film with better flexibility and extensibility. The modulus measurements of the samples in this study are reliable, which stems from the uniform performance of the films, and the films can adapt to application scenarios that require a simultaneous balance of stiffness and flexibility.

3.3 Thermal Shrinkage

Fig. 7.



Thermal Shrinkage (MD vs TD)

This study used heat shrinkage tests to measure the glass transition and melting behavior of 40 µm-thick BOPP films. After holding the test samples at 120°C for 5 minutes, we recorded a longitudinal shrinkage rate of 3.8%–4.2% and a transverse shrinkage rate of 1.8%–2.2%, with stable bidirectional dimensional changes.

This study elaborates on the molecular mechanism corresponding to the difference in longitudinal and transverse shrinkage of BOPP films, clarifies the influence of biaxial orientation on shrinkage rate, and corroborates processing consistency based on calorimetric test results of 50 samples. Its controllable high-temperature shrinkage performance can meet the core requirements of the two major downstream applications of printing and labeling.

3.4 Thickness and Density Measurements

3.4.1 Thickness Analysis

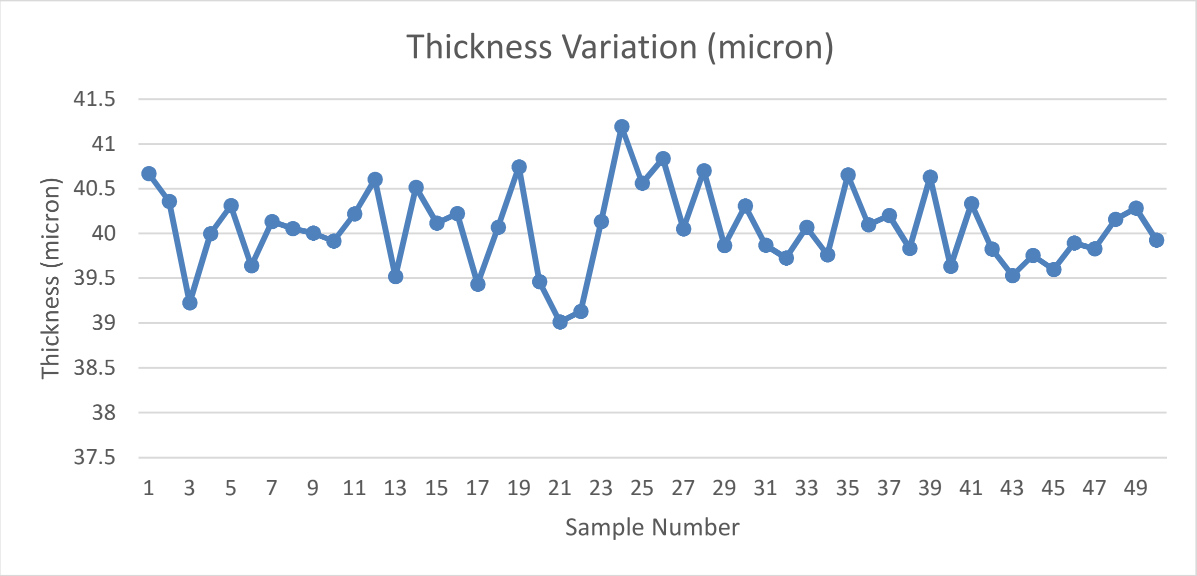


Fig. 8.

Thickness Variation (micron)

In fig. 8. the measured average thickness of the samples was approximately 40µm, with a thickness standard deviation of around 0.5µm. No large-scale outliers were detected in thickness fluctuations, which proves that the film formation process is uniform and stable. The films meet the required standards for mechanical and printing properties, can support applications ranging from ton-scale mass production to gram-level precision use cases, and are suitable for precision label scenarios that demand strict dimensional tolerance requirements. This verifies the reliability of these films for industrial applications.

3.4.2 Density Analysis

This study conducted density tests on BOPP films, with the original purpose of assessing the material's homogeneity and structural integrity. The core measured data in fig. 9., which include an average density of 0.90 g/cm³ and a standard deviation of approximately 0.005 g/cm³, align with the conventional expected values for polypropylene. Combined with observations from visualized dot plots, the density of all tested samples is evenly distributed with minimal fluctuation. This confirms that molecular stacking is highly consistent across the entire area of the films, and their composition is stable. This consistency and stability ensure predictable mechanical and thermal behaviours, fully meet the reliability and uniformity requirements for large-scale label production, and are suitable for industrial application scenarios.

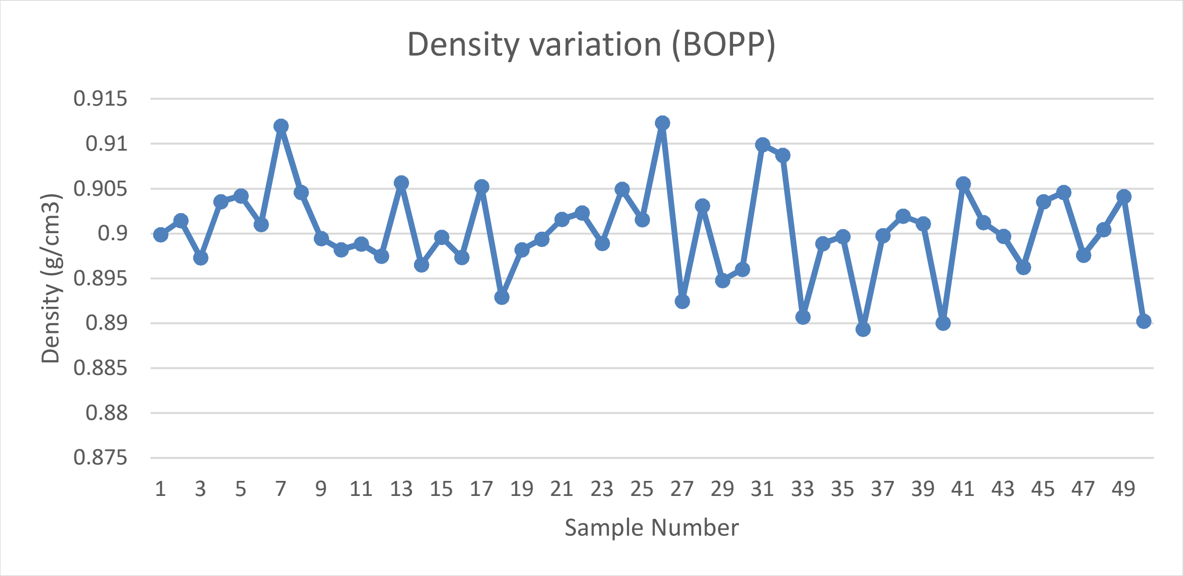


Fig. 9.

Density variation (BOPP)

Conclusion

The research team of this paper conducted a full characterization study of the thermomechanical properties of 40μm BOPP films intended for label applications. We adopted four categories of testing methods—dynamic mechanical analysis (DMA), tensile testing, heat shrinkage rate measurement, and thickness and density testing—to systematically obtain full-dimensional core performance data of the film. These data include its viscoelastic variation patterns, differences in tensile properties between the MD (machine direction) and TD (transverse direction), its heat shrinkage rate in a 120°C environment, as well as the control level of thickness and density tolerances during mass production. Based on the above quantitative test results, this study concludes that this BOPP film is fully feasible for industrial application in the label sector, and can adapt to the harsh high-speed, high-temperature conditions of demanding label application scenarios. Follow-up research will advance optimization along two specific paths: first, performance upgrading via material modification; second, quality improvement via process parameter optimization, while also exploring the potential to implement sustainability-focused research.

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