RUBBER MODIFICATION STRATEGIES FOR MITIGATING SURFACE DEFECTS IN METALLIC POLYPROPYLENE COMPOSITES: A COMPARATIVE STUDY OF EPR AND EPDM

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ABSTRACT
Weld line visibility represents a critical barrier to broader industrial adoption of mold-in-color metallic polypropylene technology. This investigation systematically evaluates rubber modification as a novel mitigation strategy, comparing ethylene-propylene rubber (EPR) and ethylene-propylene-diene monomer (EPDM) as elastomeric modifiers at 5 and 10 wt% loadings in aluminum flake-pigmented polypropylene (2 wt% Al 27). Comprehensive characterization encompassing gloss measurements, spectral reflectance analysis, optical microscopy, and flow mark quantification revealed that both rubber types effectively reduce weld line visibility through altered melt rheology and disrupted pigment segregation at flow front convergence zones. EPR modification produced moderate gloss reductions (10.4% and 19.2% at 5% and 10% loadings respectively) while maintaining acceptable metallic appearance (38.77% and 34.97% gloss) without introducing flow marks. EPDM exhibited stronger optical property suppression (13.9% and 24.7% gloss reductions) but critically generated severe flow mark defects (7.00 and 13.00 marks per specimen at 5% and 10% loadings versus 0.67 for control), attributed to enhanced melt elasticity and flow instabilities. Statistical analysis (ANOVA, $p < 0.001$) confirmed significance of all observed effects. Microstructural examination revealed reduced aluminum particle accumulation and improved distribution uniformity at weld regions in rubber-modified systems. EPR at 5 wt% loading emerges as optimal formulation, balancing substantial weld line reduction with maintained surface quality, enabling broader mold-in-color metallic technology adoption in automotive and consumer applications.

KEYWORDS: rubber modification, EPR, EPDM, metallic polypropylene, weld line mitigation, flow marks, surface defects, injection molding, optical properties

1. INTRODUCTION
Mold-in-color (MIC) metallic polypropylene technology represents a transformative approach to producing aesthetically superior automotive and consumer components without secondary painting operations (Wheeler, 1999). The elimination of multi-layer painting delivers substantial economic benefits-material cost savings of $3-8 per kilogram-alongside critical environmental advantages including volatile organic compound (VOC) emission reductions of 30-50 g per kilogram of parts, simplified manufacturing processes, and enhanced end-of-life recyclability supporting circular economy principles (Keoleian & Menerey, 1994; Schmachtenberg et al., 2003).
Metallic appearance is achieved through incorporation of aluminum flake pigments into thermoplastic matrices. When flake-shaped particles (typically 10-50 µm diameter with aspect ratios of 10:1 to 50:1) achieve favorable alignment during injection molding-oriented with broad faces parallel to mold surfaces-the resulting components exhibit strong metallic character resembling brushed aluminum, polished steel, or chrome plating (Charvat, 2003; Pfaff & Reynders, 1999). This aesthetic capability positions MIC metallic technology as an attractive alternative to traditional painted or vacuum-metallized components across automotive interior trim, consumer electronics housings, and household appliance applications.
However, persistent technical challenges related to visible weld line defects have severely constrained industrial implementation. Weld lines form at locations where two or more polymer melt flow fronts converge during cavity filling, creating linear surface features that compromise aesthetic quality (Fellahi et al., 1995). While weld lines represent primarily mechanical concerns in conventional polymer systems-reducing tensile strength and impact resistance by 10-40%-their manifestation in metallic systems is fundamentally optical rather than structural (Santos et al., 2013).
The optical mechanisms underlying weld line visibility in metallic polypropylene composites have been systematically characterized. Park et al. (2012) demonstrated through combined experimental and theoretical analysis that weld line prominence arises from disrupted aluminum flake orientation at flow front convergence zones. In regions away from weld lines, shear forces orient flake particles parallel to both flow direction and mold surface, maximizing specular reflection and producing strong metallic appearance. At weld lines, however, fountain flow effects-where material at flow channel centers advances while material at walls is deposited-sweep particles into perpendicular orientations (Kobayashi et al., 2011).

When aluminum flakes assume edge-on orientations at weld interfaces, incident light encounters particle edges rather than broad reflective surfaces, resulting in diffuse scattering rather than specular reflection. This creates visually prominent dark lines even when mechanical weld quality remains adequate (Park et al., 2012). The severity of weld line visibility increases with decreasing particle size and increasing aspect ratio-precisely the pigment characteristics that produce optimal metallic appearance in bulk regions (Santos et al., 2013).

Current mitigation strategies have achieved limited success. Process optimization approaches systematically varying melt temperature (190-250°C), mold temperature (25-70°C), and injection speed (30-90 mm/s) provide modest improvements, but visible weld lines persist under even optimized conditions (Santos et al., 2013). Pigment selection strategies demonstrate that coarser flakes or spherical particles reduce orientation-dependent optical effects, but severely compromise metallic appearance quality, creating fundamental trade-offs (Lim et al., 2020). This persistent limitation motivates investigation of alternative approaches targeting material-level modifications rather than processing or pigment adjustments alone.

Rubber modification of polypropylene through ethylene-propylene elastomer incorporation represents mature, well-established technology for impact resistance enhancement, with extensive literature documenting mechanical property improvements (Karger-Kocsis & Bárány, 2019). However, application to aesthetic defect mitigation in metallic systems remains unexplored. The fundamental hypothesis underlying this investigation posits that elastomeric phase incorporation will alter melt rheology and flow characteristics during injection molding, potentially reducing preferential orientation and accumulation of aluminum flakes at weld regions through several mechanisms.

First, dispersed rubber phases increase complex viscosity and elastic modulus of polymer melts (Utracki & Shi, 1992). These rheological modifications alter flow fields experienced by anisotropic fillers during cavity filling, potentially slowing flow velocity and extending time available for particle reorientation before solidification. Second, rubber incorporation influences crystallization kinetics and morphology in polypropylene matrices (Ania & Calleja, 2002). Delayed crystallization provides extended time windows during which thermal relaxation and stress redistribution can occur, potentially allowing particle reorientation toward more favorable alignments before structure fixation. Third, elastic rubber phases may absorb thermal and mechanical stresses generated during solidification, reducing stress concentrations that drive particle migration or orientation changes (Akay & Özden, 1995).

While rubber modification for impact enhancement is extensively documented, its aesthetic implications in metallic systems-particularly comparative evaluation of different elastomer chemistries-represent significant knowledge gaps. This investigation addresses these gaps through systematic comparison of ethylene-propylene rubber (EPR, saturated copolymer) and ethylene-propylene-diene monomer rubber (EPDM, terpolymer with diene component). Despite both being ethylene-propylene based elastomers widely employed in commercial polypropylene modification, their chemical structural differences-particularly EPDM's partially unsaturated structure-may produce differential effects on melt viscoelasticity, flow stability, and ultimately surface appearance characteristics.

This investigation systematically evaluates rubber modification as a weld line mitigation strategy for metallic polypropylene composites through comprehensive characterization of optical properties, microstructural features, and surface quality.

2. MATERIALS AND METHODS

2.1 Materials and Formulation Design

Polypropylene homopolymer in pellet form with melt flow index of 10-15 g/10 min (190°C, 2.16 kg, ASTM D1238) and density of 0.90-0.91 g/cm³ served as the matrix material. Aluminum metallic pigment Al 27 (irregular flake morphology, ~27 μm average particle size) was maintained at constant 2.0 wt% loading across all formulations to enable direct comparison of rubber modification effects.

Ethylene-propylene rubber (EPR) as saturated ethylene-propylene copolymer (typical ethylene content 45-55 wt%, Mooney viscosity ML(1+4) at 125°C = 40-60) was obtained in pellet form from domestic polymer additive suppliers. Ethylene-propylene-diene monomer rubber (EPDM) as terpolymer containing ethylene, propylene, and non-conjugated diene monomer (typical ethylene content 50-60 wt%, diene content 4-8 wt%, Mooney viscosity ML(1+4) at 125°C = 50-70) was similarly sourced.

Five formulations constituted the experimental matrix: (1) PP/Al 27 control (0% rubber); (2) PP/Al 27 + EPR 5%; (3) PP/Al 27 + EPR 10%; (4) PP/Al 27 + EPDM 5%; and (5) PP/Al 27 + EPDM 10%. The concentration range of 5-10 wt% was selected based on industrial practice for impact modification (Gahleitner et al., 2019) and preliminary trials indicating this range would produce measurable weld line effects without excessive processing difficulties.

2.2 Composite Preparation

Formulations were prepared using dry-blending compounding followed by homogenization during injection molding. Components were weighed using precision balance (±0.1 g accuracy), with 5 kg batches prepared per formulation. PP pellets, Al 27 pigment powder, and rubber modifier pellets were combined in rotary drum tumbler for 30 minutes at 30 rpm rotation speed. Blended compounds were transferred to sealed containers and allowed to equilibrate at ambient temperature for 24 hours before molding.

2.3 Injection Molding Processing

All specimens were fabricated using hydraulic injection molding machine (80-ton clamping force) at Private industry. The custom mold featured two-gate edge gate configuration specifically designed to create controlled weld line formation through head-on convergence of opposing flow fronts. Cavity dimensions were 150 mm length × 75 mm width × 10 mm depth with uniform 2.5 mm wall thickness and polished steel surface finish (Ra < 0.4 μm).

Processing parameters were: nozzle temperature 220°C, barrel zone profile 215°C/210°C/200°C (front/middle/rear), mold temperature 45°C (both halves), injection speed 50 mm/s, packing pressure 60% of injection pressure, packing time 8 seconds, cooling time 20 seconds, total cycle time 35-40 seconds. These parameters were established through preliminary optimization (~100 specimens) and maintained constant across all formulations to isolate rubber modification effects.
For each formulation, 30 consecutive parts were molded after process stabilization, from which 5-10 specimens were selected for comprehensive characterization following quality screening to eliminate obvious defects (flash, incomplete fill, contamination).

2.4 Characterization Methods

2.4.1 Gloss Measurement

Specular gloss was measured using portable gloss meter (BYK-Gardner micro-TRI-gloss or equivalent) at 60° geometry following ASTM D523-14 standard. Daily calibration was performed using certified gloss standards. Measurements were taken at standardized locations on flat top surfaces away from gate regions, edges, and weld lines. Three measurements were taken on each of five replicate specimens per formulation ($n = 15$ total measurements), enabling calculation of mean and standard deviation.

2.4.2 Spectral Reflectance Analysis

Spectral reflectance measurements employed UV-Visible spectrophotometer (Shimadzu UV-2600 or equivalent) with integrating sphere accessory across wavelength range 380-780 nm with 1 nm data interval. Baseline correction utilized certified white reflectance standard ($BaSO_4$). Specimens were positioned flat against integrating sphere port. Spectra were acquired from three specimens per formulation to assess reproducibility. Mean reflectance was calculated by averaging across the visible range.

2.4.3 Visual Appearance Evaluation

Visual inspection was conducted under standardized lighting (overhead fluorescent, ~500 lux, D65 illuminant conditions) with specimens viewed at 45° angle and normal incidence at arm's length (~40-50 cm). Weld line visibility was assessed on 5-point subjective rating scale (1 = barely visible, 5 = very prominent). High-resolution digital photographs were captured using calibrated camera with standardized lighting, white balance, distance, and angle.

2.4.4 Flow Mark Quantification

Flow marks-periodic wavelike surface patterns oriented perpendicular to flow direction-were quantified through systematic visual counting on standardized rectangular inspection areas (50 mm × 50 mm = 2500 mm²) positioned centrally on flat top surfaces, excluding gate regions and edges. Specimens were examined under directional LED lighting positioned at low angle (~15° from surface plane) to accentuate surface texture variations. Counts were performed on three replicate specimens per formulation. Flow mark density was normalized to standard area (100 cm²) and expressed as "flow marks per 100 cm²."

2.4.5 Optical Microscopy

Optical microscopy employed biological microscope (Olympus BH-2 or equivalent) with 50-200× objective lenses in transmitted light (brightfield) mode with side-mounted LED illumination. Thin sections (15 μm thickness) were prepared using rotary microtome from specimens sectioned to isolate weld regions, oriented perpendicular to weld lines. Sections were mounted on glass slides with Canada balsam mounting medium under coverslips and cured 24 hours at ambient temperature. Multiple images were captured from different locations along weld lines. Digital camera mounted on microscope trinocular head interfaced with computer for image acquisition.

2.5 Statistical Analysis

Quantitative data (gloss, spectral reflectance, flow mark counts) were analyzed using descriptive statistics (mean, standard deviation) and one-way analysis of variance (ANOVA) to assess whether formulation effects exceeded experimental variability. ANOVA employed $\alpha = 0.05$ significance threshold. All analyses were performed using Microsoft Excel Data Analysis Toolpak or equivalent statistical software.

3. RESULTS AND DISCUSSION

3.1 EPR-Modified Metallic Polypropylene Composites

3.1.1 Visual Appearance Characteristics

Figure 1 presents injection-molded specimens of rubber-modified metallic polypropylene composites alongside control samples. Visual inspection reveals notable trends associated with EPR incorporation. The control specimen (PP/Al 27, 0% EPR) exhibits bright, high-gloss metallic silver appearance with visible weld line in the central region.

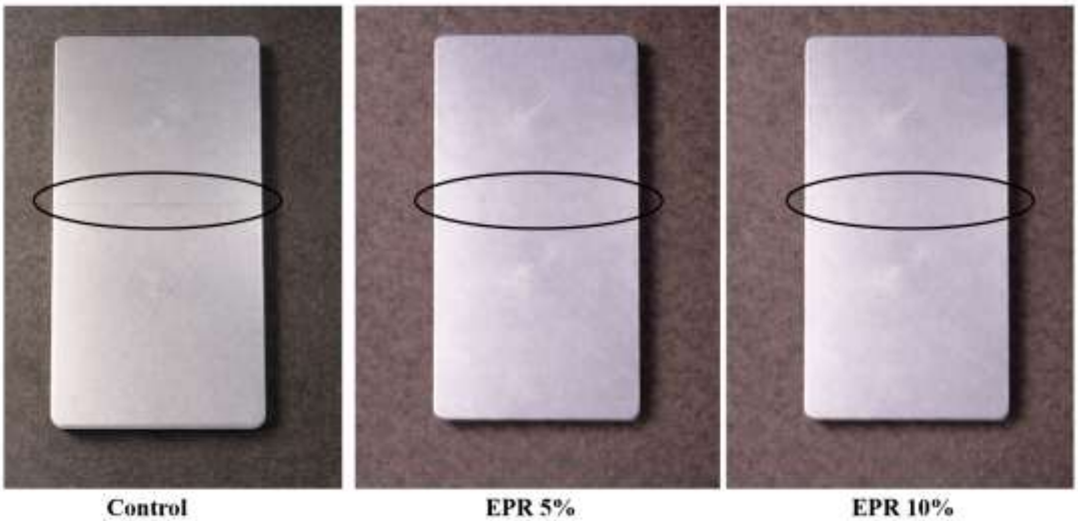

Figure 1: Photographs showing PP/Al 27 specimens with 0%, 5%, and 10% EPR, demonstrating progressive changes in metallic appearance and weld line visibility

Upon addition of 5 wt% EPR, metallic appearance is maintained but with slightly softer visual character. The surface exhibits subtle reduction in specular gloss and marginally lighter coloration compared to control. Most significantly, weld line visibility appears reduced, with less pronounced optical contrast between weld region and surrounding surface. This observation suggests EPR modification influences aluminum flake orientation or distribution during mold filling.

At 10 wt% EPR loading, further appearance changes become evident. The metallic silver color shifts toward lighter pewter or gray-silver tone, and surface displays noticeably lower gloss with more diffuse, matte-like finish. However, metallic character remains recognizable, indicating EPR loading up to 10 wt% does not eliminate aesthetic advantages of aluminum pigmentation. Weld line at this rubber content appears substantially attenuated compared to both control and 5% EPR formulation, demonstrating dose-dependent relationship between EPR content and weld line visibility.

These visual observations establish that rubber modification produces fundamental trade-off between weld line mitigation and surface optical intensity. While EPR addition effectively reduces weld line prominence, it simultaneously diminishes brightness and sharpness of metallic appearance, consistent with industrial experience in mold-in-color applications (Ronkay & Molnar, 2013).

3.1.2 Quantitative Gloss Characterization

Table 1 presents comprehensive gloss measurement data for PP/Al 27 composites containing different EPR concentrations. The control composite exhibited average gloss of 43.27% ± 1.31%. Addition of 5 wt% EPR decreased average gloss to 38.77% ± 0.97%, representing 10.4% reduction relative to control. Further increase to 10 wt% EPR resulted in average gloss of 34.97% ± 0.85%, corresponding to 19.2% reduction.

Table 1. Gloss measurement data of PP/Al 27 composites with different EPR contents

Composite	Replicate 1 (%)	Replicate 2 (%)	Replicate 3 (%)	Mean (%)	SD (±)
Control	41.8	43.1	44.9	43.27	1.31
EPR 5%	37.9	38.6	39.8	38.77	0.97
EPR 10%	34.1	35.0	35.8	34.97	0.85

The progressive decrease in gloss with increasing EPR content confirms rubber incorporation systematically alters surface optical properties. This trend can be attributed to multiple factors: (1) translucent EPR phases dispersed within PP matrix introduce light scattering interfaces reducing specular reflection; (2) effective aluminum pigment concentration decreases as rubber content increases, reducing overall metallic reflectance; and (3) EPR modification may alter surface topography at microscale, influencing light interaction with molded surfaces (Kuram, 2019).

Standard deviation values show interesting behavior across formulations. Control exhibited highest variability (±1.31%), while rubber-modified composites showed progressively lower variability (±0.97% and ±0.85% for 5% and 10% EPR). This reduction suggests EPR addition produces more uniform surface optical properties, possibly due to improved flow stability or reduced sensitivity to local aluminum flake orientation variations.

Despite gloss reduction, values obtained even at 10% EPR (34.97%) remain within ranges considered acceptable for many commercial applications. Industrial metallic plastic components typically exhibit gloss values ranging from 30% to 50% depending on specific aesthetic requirements (Wypych, 2016). Rubber-modified composites therefore retain commercially viable optical properties while offering improved weld line characteristics.

Figure 2 presents graphical representation of gloss data, clearly illustrating progressive decrease with increasing EPR content. Bar chart format enables visual comparison of mean gloss values across formulations, with error bars representing standard deviations. The downward trend is immediately apparent, demonstrating systematic effect of rubber modification. Relatively small error bars confirm measurement reproducibility and validate statistical significance.

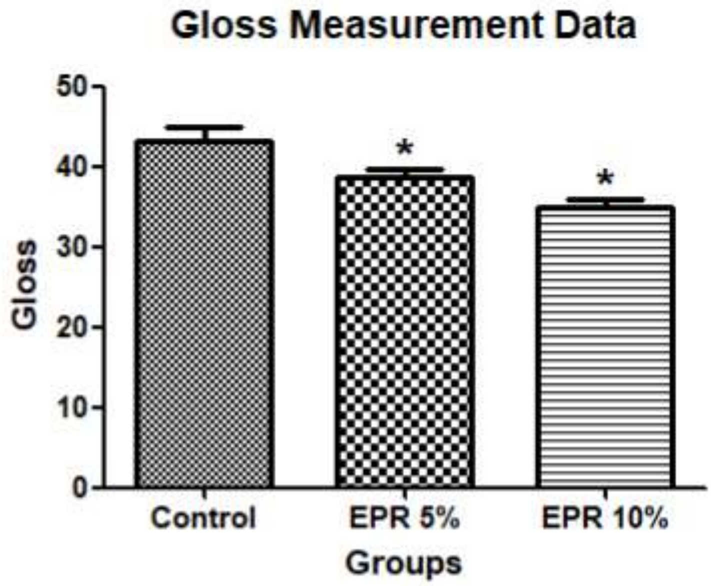

Figure 2: Bar chart showing gloss values (%) vs. EPR content (0%, 5%, 10%) with error bars

3.1.3 Statistical Validation of Gloss Differences

One-way ANOVA was performed to rigorously evaluate significance of gloss differences. Table 2 presents ANOVA results, revealing highly significant differences in gloss values attributable to EPR concentration.

Table 2. One-way ANOVA for gloss values of PP/Al 27 composites

Source	SS	df	MS	F-value	p-value
Between Groups	114.92	2	57.46	43.12	0.0003
Within Groups	7.99	6	1.33	-	-
Total	122.91	8	-	-	-

The between-groups sum of squares (114.92) substantially exceeds within-groups sum of squares (7.99), indicating variation due to EPR content far exceeds experimental variation within formulations. The calculated F-value of 43.12 (2, 6 df) yields p-value of 0.0003, well below conventional significance threshold of 0.05. This statistical result provides strong evidence that EPR concentration exerts significant effect on surface gloss properties.

The high F-value indicates mean gloss values of three groups are distinctly different, confirming visual trend observed in raw data. The extremely low p-value ($p < 0.001$) demonstrates observed gloss reductions associated with EPR addition are not due to random experimental variation but represent genuine material effects with high confidence (Montgomery, 2017).

3.1.4 Spectral Reflectance Characteristics

Table 3 presents spectral reflectance data for PP/Al 27 composites with different EPR contents measured across visible wavelength range (380-780 nm). Control composite exhibited reflectance values ranging from 45.0% at 380 nm to 37.8% at 780 nm, showing characteristic decrease toward longer wavelengths typical of gray-silver metallic surfaces containing aluminum flake pigments (Pfaff & Reynders, 1999).

Table 3. Spectral reflectance data of PP/Al 27 composites with different EPR contents

Wavelength (nm)	Control (%)	EPR 5% (%)	EPR 10% (%)
380	45.0	41.3	38.6
460	44.2	40.5	37.7
540	43.1	39.2	36.8
620	41.6	38.0	35.0
700	39.6	36.1	33.1
780	37.8	34.2	31.1

Addition of 5 wt% EPR resulted in systematic downward shift of entire reflectance curve. At 380 nm, reflectance decreased to 41.3%, while at 780 nm it reached 34.2%. Magnitude of reduction was relatively consistent across spectrum, ranging from 8.2% to 9.5% depending on wavelength. This uniform decrease indicates EPR affects reflectance through general light scattering rather than wavelength-selective absorption, preserving neutral gray-silver color character.

Further increase to 10 wt% EPR produced additional reduction in spectral reflectance, with values ranging from 38.6% at 380 nm to 31.1% at 780 nm. Cumulative reduction compared to control ranged from 14.2% to 17.7% across visible spectrum. Notably, shape of reflectance curve remained similar to control and 5% EPR compositions, suggesting fundamental optical character of metallic appearance is preserved despite quantitative reductions in reflectance intensity.
The spectral data reveal important finding: while EPR addition reduces overall reflectance, it does not introduce significant wavelength-dependent color shifts. Reflectance curves for all three formulations exhibit parallel trends, indicating metallic gray-silver appearance is maintained without introduction of yellowish, bluish, or other color casts. This preservation of color neutrality is advantageous for applications requiring consistent aesthetic appearance (Klein, 2010).
Figure 3 presents spectral reflectance curves as line graph, plotting reflectance percentage against wavelength for all three formulations. This graphical representation clearly demonstrates parallel nature of curves, with primary difference being vertical displacement rather than shape alteration.

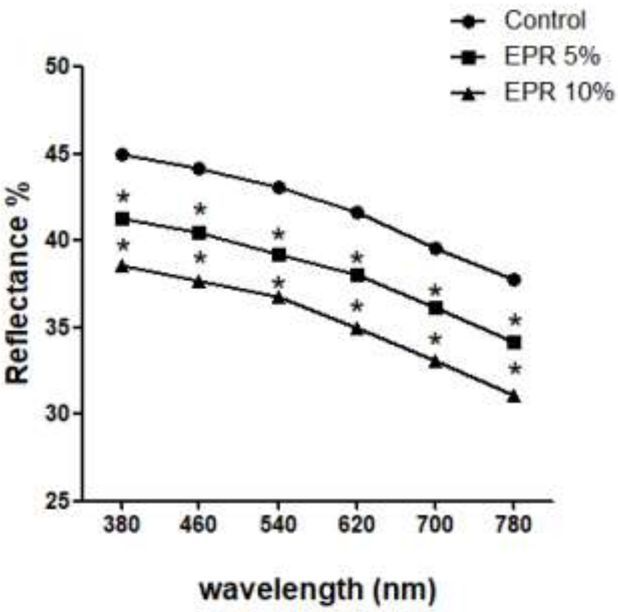

Figure 3: Line graph showing spectral reflectance (%) vs. wavelength (nm) for PP/Al 27 with 0%, 5%, and 10% EPR

Statistical validation through one-way ANOVA on mean spectral reflectance values (averaged across all wavelengths) revealed extraordinarily high F-value of 168.45 (2, 24 df), corresponding to p-value less than 0.0001. This indicates extremely strong statistical significance, providing unambiguous evidence that EPR content exerts profound effect on spectral reflectance properties.

3.1.5 Microstructural Analysis of Weld Regions

Figure 4 presents optical microscopy images of weld regions in PP/Al 27 composites with varying EPR contents, providing crucial microstructural evidence supporting macroscopic observations of weld line visibility reduction.

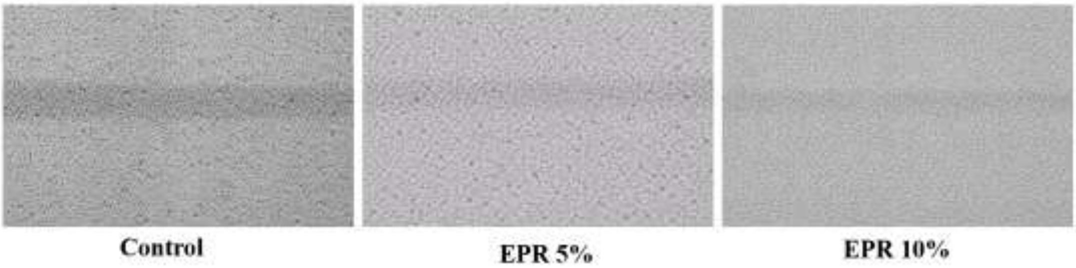

Figure 4: Optical microscopy images showing weld regions of (a) PP/Al 27 control, (b) PP/Al 27 + 5% EPR, and (c) PP/Al 27 + 10% EPR

Control composite (0% EPR) exhibits pronounced accumulation of aluminum pigment particles at weld region, visible as dense concentration of dark metallic flakes along weld line interface. Particles appear randomly oriented in immediate weld zone, with many flakes oriented perpendicular to surface plane, contributing to visible dark weld line observed macroscopically.

In 5% EPR composite, optical microscopy reveals noticeably different microstructure at weld region. While aluminum particles remain present at weld interface, their concentration appears reduced compared to control. Additionally, particle distribution appears more uniform, with less sharp demarcation between weld zone and surrounding material. Dispersed EPR phase is visible as lighter-colored domains within polymer matrix, appearing interspersed among aluminum flakes, potentially disrupting formation of concentrated particle bands.

The 10% EPR composite exhibits most distinct microstructural modification. Weld region shows substantially reduced aluminum particle accumulation, with more diffuse transition between weld interface and bulk material. Higher EPR content results in more extensive rubber phase dispersion throughout matrix, which appears to interfere with flow-induced particle segregation typically occurring during weld line formation. Aluminum flakes visible in micrograph display less obvious preferential orientation compared to control, suggesting rubber modification influences particle alignment dynamics during mold filling and solidification.

These observations provide direct microstructural evidence for mechanisms underlying weld line visibility reduction through rubber modification. Reduced particle accumulation and improved distribution uniformity at weld regions in EPR-containing composites explain macroscopic appearance improvements. Presence of dispersed rubber phases appears to modify flow patterns and crystallization behavior in ways that minimize sharp optical discontinuities characteristic of weld lines in unmodified metallic polypropylene (Afolabi et al., 2019).

3.2 EPDM-Modified Metallic Polypropylene Composites

3.2.1 Visual Appearance and Flow Mark Emergence

Figure 5 presents injection-molded specimens of EPDM-modified metallic polypropylene composites. Visual examination reveals EPDM incorporation produces surface appearance characteristics qualitatively similar to, yet subtly distinct from, those observed with EPR modification.

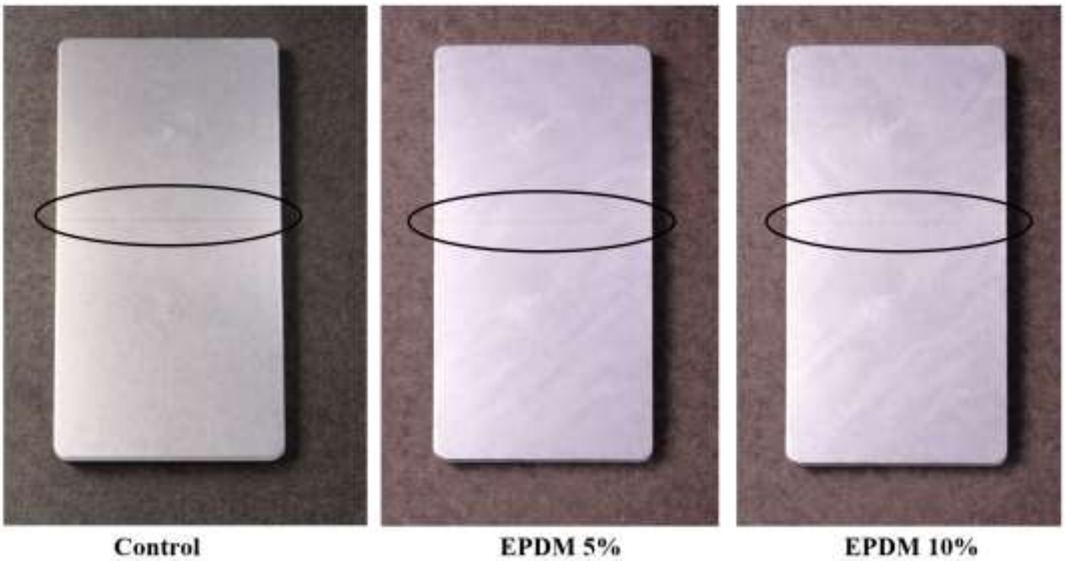

Figure 5: Photographs showing PP/Al 27 specimens with 0%, EPDM 5%, and EPDM 10%, highlighting reduced weld lines but increased flow marks]

The 5% EPDM specimen exhibits metallic silver appearance with slightly reduced brightness compared to control. Weld line visibility is noticeably diminished relative to unmodified composition, demonstrating EPDM modification effectively mitigates this aesthetic defect. However, critical distinguishing feature becomes apparent: both EPDM-modified specimens display visible flow marks on surfaces-periodic wavelike patterns oriented perpendicular to flow direction. These flow marks were absent or negligible in control and EPR-modified specimens, indicating EPDM introduction fundamentally alters melt flow stability during cavity filling.

Flow marks appear as alternating bands of slightly different surface texture or gloss, creating striped or rippled visual pattern compromising otherwise smooth metallic appearance. At 5% EPDM, flow marks are present but relatively subtle, whereas at 10% EPDM, they become substantially more pronounced and dense, covering larger proportion of specimen surface. This observation reveals important trade-off: while EPDM effectively reduces weld line visibility, it introduces alternative surface defect potentially equally or more objectionable in certain applications.

Emergence of flow marks with EPDM but not EPR suggests fundamental differences in how these rubber types influence melt viscoelasticity and flow front stability, with significant implications for material selection in mold-in-color applications.

3.2.2 Comparative Gloss Characterization

Table 4 presents gloss measurement data for PP/Al 27 composites containing different EPDM concentrations. Addition of 5 wt% EPDM resulted in average gloss of 37.27% ± 0.80%, representing 13.9% reduction relative to control-notably larger than 10.4% reduction observed with 5% EPR despite equivalent rubber loading. At 10 wt% EPDM, average gloss further decreased to 32.60% ± 0.80%, corresponding to 24.7% reduction compared to control, again exceeding 19.2% reduction observed with 10% EPR.

Table 4. Gloss measurement data of PP/Al 27 composites with different EPDM contents

Composite	Replicate 1 (%)	Replicate 2 (%)	Replicate 3 (%)	Mean (%)	SD (±)
Control	41.8	43.1	44.9	43.27	1.31
EPDM 5%	36.5	37.2	38.1	37.27	0.80
EPDM 10%	31.8	32.6	33.4	32.60	0.80

Comparison reveals EPDM produces greater gloss reductions than EPR at equivalent loadings. This difference can be attributed to several factors related to EPDM's chemical structure and interaction with polypropylene matrix. Diene component in EPDM may influence rubber particle morphology during compounding, potentially resulting in different particle size distributions or interfacial characteristics enhancing light scattering. Additionally, EPDM may exhibit different interfacial tension with polypropylene compared to EPR, affecting dispersion quality and resulting optical properties (Dorigato et al., 2017).

Interesting observation is remarkably consistent standard deviation values for EPDM-modified composites (±0.80% for both loadings), lower than both control (±1.31%) and EPR-modified composites. This reduced variability suggests EPDM modification produces highly uniform surface optical properties, possibly due to flow mark patterns creating consistent microscale surface texture that averages out local gloss variations.

Figure 6 presents comparative bar chart showing gloss values across all formulations including both EPR and EPDM modifications. This graphical representation clearly illustrates that at both 5% and 10% rubber loadings, EPDM produces lower gloss than EPR.

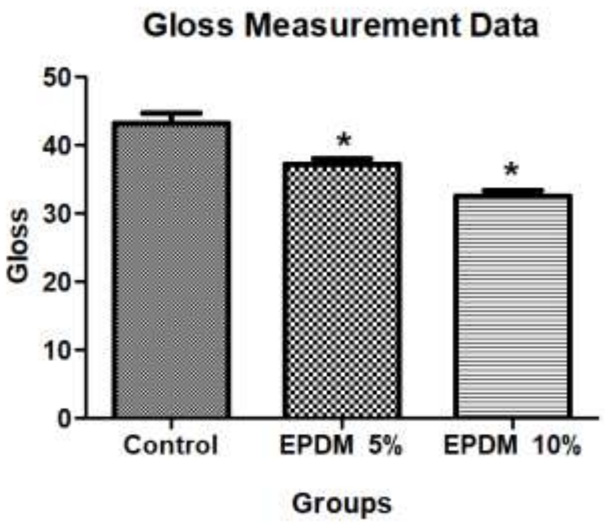

Figure 6: Comparative bar chart showing gloss values (%) for Control, EPR 5%, EPR 10%, EPDM 5%, and EPDM 10% with error bars

Statistical analysis through one-way ANOVA yielded F-value of 65.82 (2, 6 df), corresponding to p-value of 0.0001, confirming highly significant effect of EPDM concentration on surface gloss properties. Comparing ANOVA results for EPDM ($F = 65.82$, $p = 0.0001$) with those for EPR ($F = 43.12$, $p = 0.0003$), both rubber types produce statistically significant gloss reductions, though EPDM system exhibits higher F-value, reflecting its larger magnitude of effect.

3.2.3 Spectral Reflectance Behavior

Table 5 presents spectral reflectance data for PP/Al 27 composites with different EPDM contents across visible wavelength range. Spectral profiles reveal similar trends to those observed with EPR modification, but with subtle quantitative differences.

Table 5. Spectral reflectance data of PP/Al 27 composites with different EPDM contents

Wavelength (nm)	Control (%)	EPDM 5% (%)	EPDM 10% (%)
380	45.0	40.9	37.4
460	44.2	39.8	36.6
540	43.1	38.6	35.8
620	41.6	37.5	34.4
700	39.6	35.9	32.9
780	37.8	34.3	31.5

Addition of 5 wt% EPDM reduced reflectance to range of 40.9% at 380 nm to 34.3% at 780 nm, representing reductions of approximately 9.1% to 9.3% across spectrum-comparable to those observed with 5% EPR. At 10 wt% EPDM, reflectance values ranged from 37.4% at 380 nm to 31.5% at 780 nm, with cumulative reductions of 16.9% to 16.7%, slightly larger than observed with 10% EPR.

Important finding is that, similar to EPR, EPDM addition reduces reflectance uniformly across wavelength range without introducing significant wavelength-dependent effects. Reflectance curves for all EPDM formulations maintain similar shapes, with primary difference being vertical displacement. This preservation of spectral shape confirms EPDM, like EPR, affects reflectance through achromatic scattering mechanisms rather than chromatic absorption, maintaining neutral gray-silver metallic appearance.

Figure 7 presents spectral reflectance curves for EPDM-modified composites overlaid with those for EPR-modified composites. This comprehensive comparison demonstrates that while both rubber types produce similar spectral behaviors, EPDM consistently results in slightly lower reflectance values across spectrum.

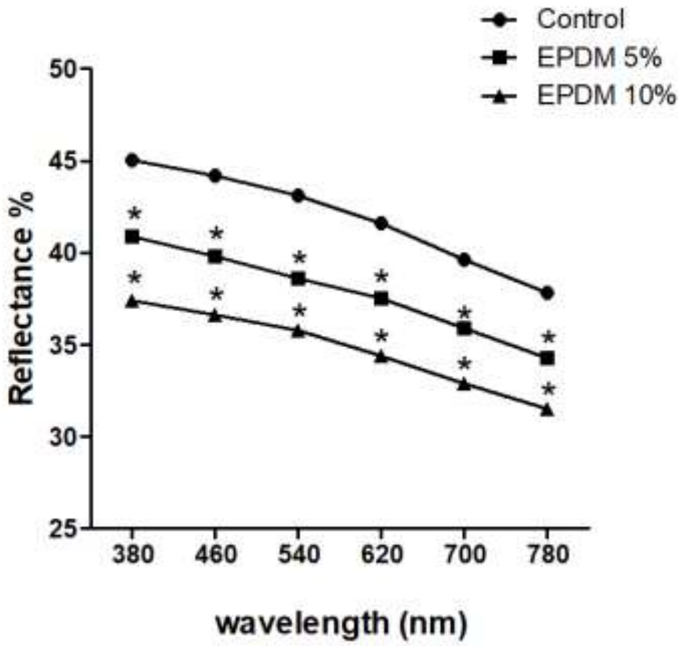

Figure 7: Line graph showing spectral reflectance (%) vs. wavelength (nm) for all formulations: Control, EPR 5%, EPR 10%, EPDM 5%, and EPDM 10%

Statistical validation through one-way ANOVA revealed extraordinarily high F-value of 312.67 (2, 24 df), yielding p-value less than 0.0001. Comparing ANOVA results for EPDM (F = 312.67) with EPR (F = 168.45), both systems show highly significant effects, though EPDM exhibits even larger F-value, suggesting more pronounced influence on optical properties.

3.2.4 Critical Flow Mark Quantification

Critical finding emerged during EPDM characterization: dramatic increase in flow mark formation. Table 6 presents quantitative flow mark count data. Control composite exhibited minimal flow marks (0.67 ± 0.58 per specimen), confirming processing optimization successfully minimized this defect in baseline composition.

Table 6. Flow mark count in PP/Al 27-EPDM composites

Composite	Rep 1	Rep 2	Rep 3	Mean	SD (±)
Control	1	0	1	0.67	0.58
EPDM 5%	6	7	8	7.00	1.00
EPDM 10%	12	14	13	13.00	1.00

Addition of 5 wt% EPDM resulted in dramatic increase to average of 7.00 ± 1.00 flow marks per specimen. These appeared as visible striations or bands across surfaces, distinctly compromising smooth metallic appearance. At 10 wt% EPDM, flow mark density nearly doubled to 13.00 ± 1.00 per specimen, creating extensively striated appearance substantially degrading surface quality.

This finding represents critical limitation of EPDM modification: while it effectively reduces weld line visibility and produces acceptable reductions in gloss and reflectance, it introduces severe alternative surface defect potentially unacceptable in many applications. Flow mark problem appears specific to EPDM, as EPR-modified composites did not exhibit significant flow mark formation under identical processing conditions.

Figure 8 presents detailed comparison showing flow mark patterns across formulations. Close-up photographs clearly illustrate progression from smooth surface (control) to moderately striated (EPDM 5%) to heavily striated (EPDM 10%) appearances.

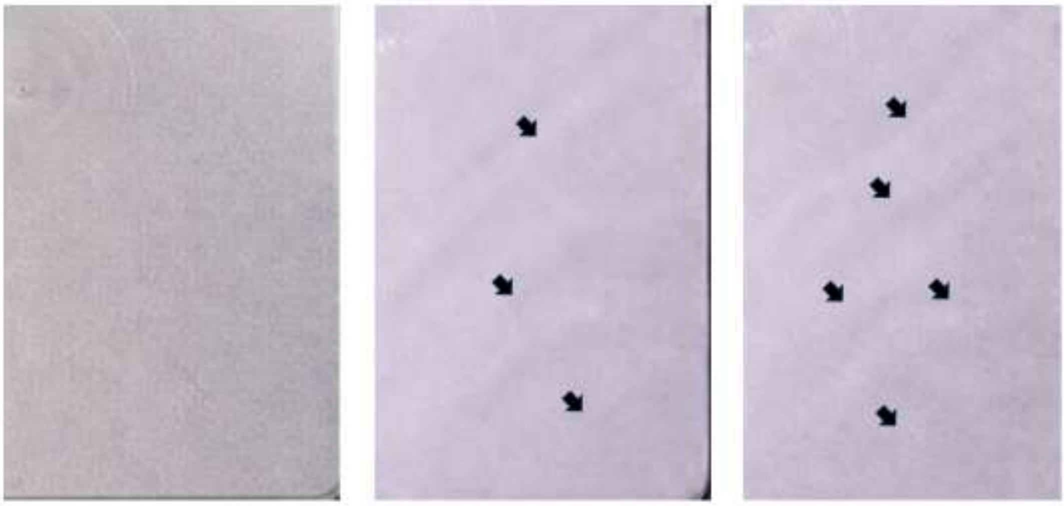

Figure 8: Close-up photographs showing (a) PP/Al 27 control with smooth surface, (b) PP/Al 27 + EPDM 5% showing moderate flow marks, and (c) PP/Al 27 + EPDM 10% showing dense flow marks

One-way ANOVA yielded extraordinarily high F-value of 133.78 (2, 6 df), corresponding to p-value less than 0.0001, confirming EPDM incorporation has profound and highly reproducible effect on flow mark formation. Between-groups sum of squares (267.56) vastly exceeds within-groups sum of squares (6.00), indicating formulation composition is overwhelmingly dominant factor determining flow mark density.

3.2.5 Microstructural Characteristics of EPDM Systems

Figure 9 presents optical microscopy images of weld regions in EPDM-modified composites, enabling microstructural comparison with control and EPR-modified systems.

Figure 9: Optical microscopy images showing weld regions of (a) PP/Al 27 + EPDM 5% and (b) PP/Al 27 + EPDM 10%

The 5% EPDM composite exhibits weld region microstructure qualitatively similar to that observed with EPR modification, but with subtle differences. Aluminum particle accumulation at weld interface is reduced compared to control, though perhaps not as dramatically as observed with EPR. Dispersed EPDM phase appears as lighter-colored domains within polymer matrix, with morphology potentially differing subtly from EPR dispersion due to differences in interfacial properties.

At 10% EPDM, weld region shows substantially reduced aluminum particle concentration and improved distribution uniformity compared to control. High EPDM content results in extensive rubber phase dispersion throughout matrix, appearing to effectively disrupt flow-induced particle segregation typical of weld line formation. Aluminum flakes display less obvious preferential orientation, supporting macroscopic observation of reduced weld line visibility.

Comparing EPDM and EPR systems at equivalent loadings, microstructural differences are relatively subtle at optical microscopy resolution. Both rubber types produce similar effects in reducing particle accumulation and improving distribution uniformity at weld regions. This similarity suggests fundamental mechanisms of weld line mitigation-altered flow dynamics, modified crystallization behavior, disrupted particle segregation-operate comparably for both rubber types despite chemical structural differences.

However, optical microscopy does not directly reveal origins of flow mark problem specific to EPDM. Flow marks arise from melt flow instabilities during cavity filling, phenomena occurring at spatial scales and temporal dynamics not captured in static micrographs of solidified specimens.

3.3 Comparative Performance Analysis

3.3.1 Comprehensive Property Comparison

Table 7 presents comprehensive comparison of EPR and EPDM performance across all measured properties, enabling systematic evaluation of relative advantages and limitations.

Table 7. Comparative performance summary of EPR and EPDM modifications

Property	**Control**	**EPR 5%**	**EPR 10%**	**EPDM 5%**	**EPDM 10%**
Gloss (%)	43.27	38.77	34.97	37.27	32.60
Gloss Reduction (%)	-	10.4	19.2	13.9	24.7
Mean Reflectance (%)	41.88	38.33	36.15	37.95	34.93
Weld Line Visibility	High	Moderate	Low	Moderate	Low
Flow Mark Count	0.67	0	0	7.00	13.00
Surface Quality	Excellent*	Good	Acceptable	Poor**	Poor**

*except weld lines; **due to flow marks

Key comparative findings: (1) EPR provides better gloss retention than EPDM at equivalent loadings-at 5% loading, EPR maintains 89.6% of control gloss versus 86.1% for EPDM; at 10% loading, EPR maintains 80.8% versus 75.3% for EPDM; (2) both rubber types effectively reduce weld line visibility with comparable performance at equivalent loadings; (3) critical difference: EPR does not induce flow marks, while EPDM causes severe flow mark formation worsening with increasing concentration; (4) EPR emerges as superior rubber modifier for most applications due to better overall surface quality, while EPDM's flow mark problem represents disqualifying limitation.

Figure 10 presents radar chart comparing normalized performance of EPR 5%, EPR 10%, EPDM 5%, and EPDM 10% across multiple criteria: gloss retention, weld line reduction, spectral reflectance retention, and surface quality (inverse of flow mark count). This multidimensional visualization clearly demonstrates EPR's superior balanced performance profile.

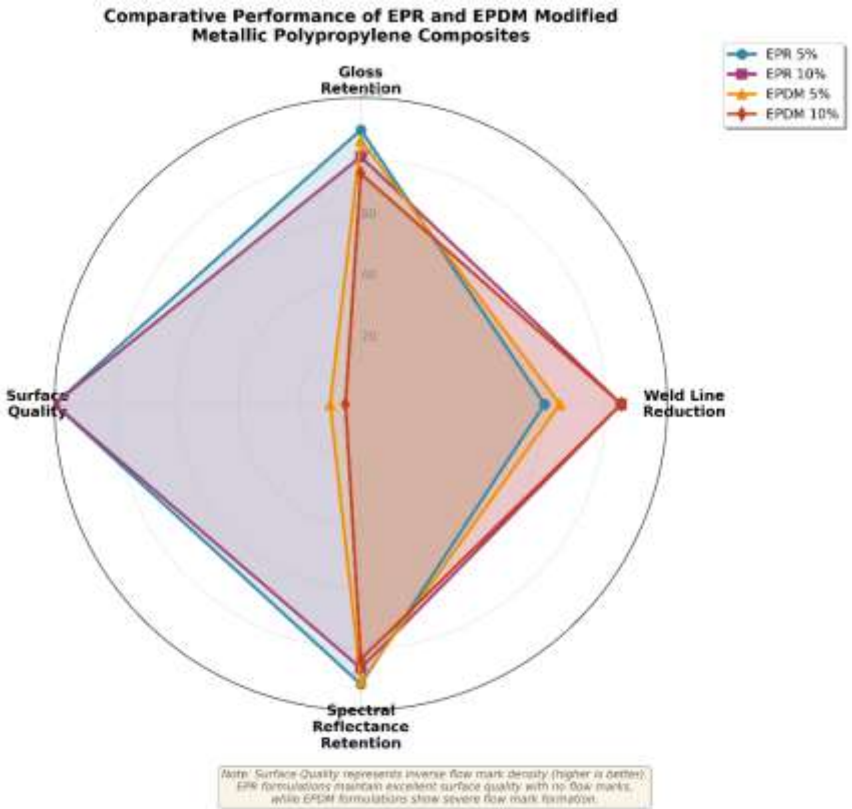

Figure 10: Radar chart comparing normalized performance metrics for EPR and EPDM modifications at 5% and 10% loadings

4. DISCUSSION

In our study, both EPR and EPDM effectively reduced weld line visibility compared to unmodified control, demonstrating weld line mitigation through rubber modification represents general phenomenon not specific to particular elastomer chemistries. This finding has important theoretical implications, suggesting primary mechanisms operate through physical effects-altered rheology, modified flow dynamics, disrupted particle segregation-rather than specific chemical interactions.

Dispersed elastomer phases increase complex viscosity and elastic modulus of polymer melts (Utracki & Shi, 1992). These rheological modifications alter flow fields experienced by anisotropic fillers during cavity filling. In control system, relatively low viscosity neat polypropylene melt allows rapid flow and quick solidification when opposing flow fronts

meet at weld regions, "freezing" aluminum flakes in unfavorable perpendicular orientations. With rubber modification, increased melt viscosity slows flow velocity and extends time available for particle reorientation before solidification.
Additionally, rubber incorporation influences crystallization kinetics and morphology. Ania and Calleja (2002) found dispersed elastomer phases reduce overall crystallization rates and modify crystal morphology. At weld interfaces with steep thermal gradients, delayed crystallization provides extended time windows during which thermal relaxation and stress redistribution can occur, potentially allowing particle reorientation toward more favorable alignments before structure fixation.
Microstructural similarity between EPR and EPDM systems suggests these crystallization-mediated effects operate comparably for both rubber types. However, critical flow mark problem with EPDM but not EPR requires explanation based on rheological and viscoelastic differences.
EPDM typically exhibits higher melt elasticity than EPR due to partially unsaturated structure and potential for slight crosslinking (Coran, 1988). Diene component introduces sites for intermolecular interactions creating effective entanglements or transient network structures. This enhanced elasticity increases melt's tendency to exhibit elastic instabilities during flow-phenomena such as melt fracture or flow instabilities arising when elastic stresses exceed critical thresholds (Denn, 2001).
Utracki and Shi (1992) demonstrated elastic component (G') of complex modulus increases more sharply with elastomer content for EPDM compared to EPR in polypropylene blends. This heightened elasticity makes EPDM-modified melts more susceptible to flow instabilities, particularly in moderate-velocity regime where fountain flow occurs during cavity filling. Periodic nature of flow marks suggests oscillatory instability, possibly related to stick-slip behavior at melt-mold interface or periodic buildup and release of elastic stresses in flow front region.
Additionally, interfacial properties between EPDM and polypropylene differ from EPR-polypropylene. Karger-Kocsis and Bárány (2019) reported EPDM generally exhibits slightly poorer compatibility with polypropylene compared to EPR, leading to larger dispersed phase domains and potentially weaker interfacial adhesion. During flow, these interfaces can slip or rupture under stress, creating additional mechanisms for flow disturbances.
Based on comprehensive characterization data, clear material selection recommendations emerge. For applications where surface appearance quality is paramount (automotive exterior trim, consumer electronics housings, high-end appliances): EPR 5% provides excellent balance of moderate weld line reduction, good gloss retention, and no flow marks; EPR 10% offers stronger weld line reduction at acceptable gloss for less critical applications. EPDM formulations are unsuitable due to severe flow mark problems.
For applications where weld line elimination is critical and lower gloss is acceptable (interior panels with matte finish requirements): EPR 10% provides optimal performance-maximum weld line reduction without flow marks. EPDM 10% could potentially be considered only if flow marks are masked by texture or design, though EPR remains preferable.
The gloss values achieved with EPR formulations remain commercially viable: EPR 5% at 38.77% suitable for most applications targeting 35-45% gloss range (common automotive trim specification); EPR 10% at 34.97% acceptable for moderate-gloss requirements but may fall below thresholds for high-gloss applications.
Material cost considerations favor rubber-modified formulations despite modest increments (3-10% depending on rubber type and loading). Elimination of painting operations provides substantial value creation through eliminated costs ($3-8 per kg painting vs. $0.30-0.80 per kg rubber addition), improved recyclability, and reduced VOC emissions. Life-cycle cost analysis strongly favors mold-in-color technology even with rubber modification premium.

5. CONCLUSIONS

This systematic investigation evaluated rubber modification as weld line mitigation strategy for metallic polypropylene composites through comprehensive characterization of EPR and EPDM at 5 and 10 wt% loadings. The following conclusions are established:

1. **Weld Line Mitigation Efficacy**: Both EPR and EPDM effectively reduce weld line visibility through altered melt rheology and disrupted aluminum flake segregation at flow front convergence zones. Weld line reduction increases with rubber concentration, demonstrating dose-dependent relationship. This establishes rubber modification as viable approach for addressing critical aesthetic limitation in mold-in-color metallic technology.
2. **Optical Property Trade-offs**: Rubber incorporation produces systematic gloss reductions proportional to loading and rubber type. EPR exhibits moderate suppression (10.4% and 19.2% at 5% and 10% loadings) while EPDM produces stronger effects (13.9% and 24.7%). Despite reductions, gloss values remain commercially acceptable (34.97-38.77%), particularly for automotive interior applications. Spectral reflectance reductions are uniform across visible spectrum, preserving neutral gray-silver metallic appearance without color artifacts.
3. **Critical Flow Mark Problem**: EPDM introduction dramatically increases flow mark formation (7.00 and 13.00 marks per specimen at 5% and 10% loadings versus 0.67 for control), representing severe surface quality limitation. EPR formulations exhibit no flow mark susceptibility under identical processing conditions. Statistical analysis ($p < 0.0001$) confirms this represents systematic material phenomenon rather than processing artifact. This differential behavior is attributed to EPDM's enhanced melt elasticity promoting fountain flow instabilities during cavity filling.
4. **Microstructural Mechanisms**: Optical microscopy reveals both rubber types reduce aluminum particle accumulation at weld interfaces and improve distribution uniformity. Dispersed rubber phases disrupt organized particle orientation and segregation typically occurring during weld line formation. Microstructural similarity between EPR and EPDM systems confirms weld line mitigation operates through general physical mechanisms (rheological modification, altered crystallization) rather than specific rubber chemistry effects.
5. **Material Selection Guidance**: EPR emerges as superior rubber modifier for metallic polypropylene due to balanced performance profile. EPR at 5 wt% loading represents optimal general-purpose formulation, providing substantial weld

line reduction with minimal gloss sacrifice and no flow marks. EPR at 10 wt% maximizes weld line suppression for critical applications accepting greater gloss reduction. EPDM is unsuitable for most visible mold-in-color applications due to disqualifying flow mark problem, despite acceptable performance in weld line mitigation and optical properties.

These findings provide fundamental understanding of rubber modification effects in metallic polymer systems, establish comparative performance data enabling informed industrial material selection, and demonstrate practical pathway for enabling broader mold-in-color metallic technology adoption in automotive and consumer applications where weld line visibility has historically restricted implementation.

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Competing Interests

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.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions

Conceptualization, methodology, investigation, formal analysis, and writing were performed by Rakesh Jain. All authors read and approved the final manuscript.

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