Application of a Nanoclay-Polypropylene Composite to Efficient Vehicle Occupant Safety Countermeasure Design

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ABSTRACT

Polypropylene (PP) which is a thermoplastic polymer is frequently used in designing interior trim of vehicles for enhanced aesthetic appeal and perhaps additional benefits such as thermal comfort. It may be less obvious that PP-based trim panels on stiff upper body components such as A-pillars, B-pillars, headers, etc., when properly designed, can act as crucial head impact safety countermeasures during collision events. The current investigation is aimed at establishing that nanoclay-reinforced PP can provide substantially improved head impact safety as a material for automotive A-pillar trim when compared to plain PP. To this end, advanced computer-aided engineering procedures based on explicit nonlinear finite element analysis are employed in evaluating the headform impact safety performance of the present nanocomposite-based A-pillar trim panels with integrally molded fin-type ribs attached to a representative steel A-pillar component. Synthesis of nanoclay-PP composite is carried out and the mechanical behaviors of the resulting nanocomposites with various clay contents are identified through uniaxial testing of standard coupon specimens.

Keywords: Nanoclay, Polypropylene, Vehicle Interior, Head Impact Safety Countermeasure, A-pillar Trim, Finite Element Analysis

1 INTRODUCTION

Automotive components such as car interior and exterior trim, and selected under-the-hood applications are often made of thermoplastic polymers using high-throughput processes such as injection moulding. Use of polymeric materials in automotive applications presents several advantages such as reduced weight, high design flexibility, styling capabilities, superior level of integration of functionalities, and low processing costs.

Nanoclay-polypropylene (PP)-based nanocomposites have caught the attention of researchers due to their improved properties with respect to plain PP with low clay content as well as the clay serving as a valuable cost-effective additive. In general, up to 10 weight percentage of organically treated clay is added to PP polymer matrix. The addition of the nanoclay to the PP matrix increases its thermal stability, improves flame retardant properties, and most importantly enhances the mechanical properties of neat PP. Several studies have been reported on nanoclay-PP composites with various types of organoclays, clay concentrations and coupling agents [1-3].

PP has been extensively used as the material for interior trim for vehicle body components such as A- and B-pillars as well as doors. It may be less obvious that PP-based plastic trim parts along with concealed countermeasures can play an important role in reducing occupant injury during collisions. In this context, it is noted that a significant fraction of fatalities involving passengers in automobile accidents is due to severe head injury. These injuries occur when an occupant's head is struck against the interior of a vehicle during a collision of an arbitrary type [4]. In order to improve the upper interior head impact protection of occupants, an extended/amended FMVSS 201 regulation was brought into force by NHTSA (National Highway Traffic Safety Administration) in USA at the end of 1990's. In order to design countermeasures for compliance to the extended FMVSS 201 regulations for upper interior head impact safety, injection-molded plastic trims with fin-type ribs have been deployed on vehicle body components such as A-pillars in the past. Such countermeasures have been studied experimentally as well as numerically using finite element modeling and analysis. In the latter case, a validated finite element model of the featureless Hybrid III headform deployed in physical tests has been used [5].

The aim of the present study is to show that, as a material for A-pillar trim with integrally molded ribs, nanoclay-reinforced PP can deliver higher levels of head impact safety as compared to plain PP. The synthesis of the nanocomposite is carried out at first with desired percentages of nanoclay content, and injection–molded coupon specimens conforming to ASTM tensile test standards are fabricated. These coupon specimens are subjected to tensile tests in a UTM to obtain the elasto-plastic material properties of nanocomposites of different clay contents (1.5-9% by weight). Using the latter properties as input data for nonlinear constitutive modeling, an assessment of a uniform-section substitute of a typical car A-pillar made with formed mild steel panels and covered with plastic trim is carried out using simulation techniques discussed in [5]. It is shown that trim components made of nanoclay-PP composites outperform those made with plain PP by yielding lower values of HIC(d) in simulation (using an explicit LS-DYNA code) of normal headform impact on trim-covered A-pillar.

2 SYNTHESIS OF NANOCOMPOSITE

2.1 Materials used

Isotactic polypropylene (Repol H110MA) possessing a melt flow index of 11 g/10 min at 230°C under 2.16 kg load was obtained from Reliance Polymers India. Nanoclay (Crysnano 1010), a natural montmorillonite modified with quaternary ammonium salt, was procured from Crystal Nanoclay Pvt. Ltd. Pune, India.

2.2 Formulation and preparation of PP-nanoclay composite test samples

PP granuals (of a total mass of 30 g) were at first added to the mixing chamber of a torque rheometer (Haake PolyLab QC) preheated to 150°C. 30 g of oven-dried nanoclay was then added to the mixing chamber. After thorough mixing for sufficient time, the blend was removed and cooled to room temperature. The resulting lumps of nanoclay-PP mixture, constituting the ‘master batch’, were later palletized into approximately 3 mm sized pallets using a Fritsch Pulverisette 25 laboratory cutter which were now ready for formulating the nanocaly-PP composite specimens with varying percentages (in the range of 1.5-9% by weight) of nanoclay. It is noted that the master batch had a 1:1 ratio of PP and nanoclay. Additional nanoclay was added to a chosen amount of pallets from the master batch and dry-blended to arrive at a given percentage of nanoclay (between 1.5-9% by weight) in the composite mixture. The dry mixture was then fed into the inlet hopper of a co-rotating twin-screw extruder and heated through several stages ranging from 165ºC-180ºC. The usage of the twin-screw extruder ensured a homogeneous compounding of PP and nanoclay in an efficient manner resulting into a nanocomposite which has been later labeled as PPNx here (x being the percent concentration of nanoclay by weight varying from 1.5 to 9). The nanocomposite was recovered from the twin-screw extruder in the form of a molten extrudate which was guided into a standard cold water stranding bath. The cooled strands were chopped into pellets, dried and stored in sealed plastic bags. The compounded pallets of nanoclay-PP composites were finally molded into standard ASTM-type dog-bone specimens using a 60 ton L&T Demag make microprocessor-controlled, closed-loop injection molding machine.

2.3 Uniaxial tensile tests

Uniaxial tensile tests were conducted in accordance with the ASTM D638 [6] standard with Type I specimens. During the tests, the crosshead speed was set at 50 mm/min. Deflection was recorded with a strain gauge type extensometer having a 50 mm span. All tests were performed on a 10 kN Shimadzu universal testing machine. Five replicates were tested for each composition.

3 HEADFORM IMPACT SAFETY

3.1 Extended FMVSS 201 regulation

The FMVSS 201 safety regulation stipulates that HIC (d), an acronym for Head Injury Criterion (dummy), should not exceed 1000 when a featureless free-motion Hybrid III headform is impacted with the center of its forhead zone at a speed of 15 mph on any valid target belonging to the upper interior of a vehicle. An A-pillar of a vehicle represents a stiff body component which can give rise to unacceptably high values of HIC(d) unless sufficiently protected with a countermeasure such as a plastic trim with integrally molded internal ribs. In the current study, a representative uniform-section A-pillar component earlier considered in [5] is chosen for the assessment of the trim shown in Figure 1(a) from the viewpoint of head impact safety. Comparisons are made for trim made of plain PP as well as various nanocomposites discussed in section 2.2. The objective of providing the trim with ribs as a protection for head impact safety is to allow the absorption of impact kinetic energy of a test headform through deformation of trim and ribs such that the headform does not contact the A-pillar inner metallic surface and the peak deceleration of the headform remains at a desirable level. A cross-sectional view of the A-pillar component studied along with the protective trim and ribs is given in Figure 1(b). The finite element model of the upright A-pillar component and positioned headform for striking an apex point on the trim surface in a normal manner so as to represent a worst-case impact scenario is shown in Figure 2.

3.2 Estimation of head injury

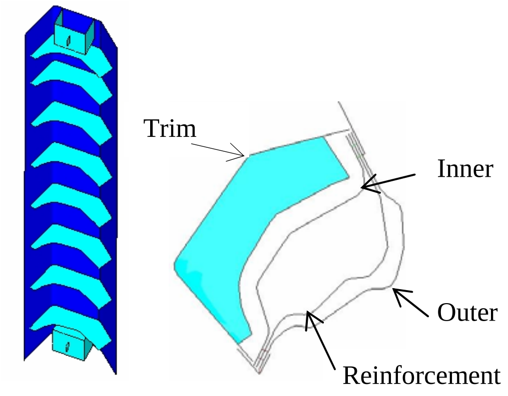
In test conditions as dictated by the FMVSS 201 regulation, a tri-axial accelerometer is placed at the CG (center of gravity) of the test headform and the resultant translational deceleration recorded is used to compute HIC(d) according to the following relations [7, 8]:

$$HIC(d) = 0.75446 HIC + 166.4 \qquad (1)$$

where, free motion HIC is given as

$$HIC = \left\{ \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \frac{\ddot{x}}{g} dt \right]^{2.5} (t_2 - t_1) \right\}_{\max} \qquad (2)$$

In Equation (2), $\ddot{x}$ is the instantaneous acceleration, g is the acceleration due to gravity, and $0 \leq t_1 \leq t_2 \leq t_f$, where, the final time t_f corresponds to the condition $\ddot{x} = 0$, i.e. when a striking headform looses contact with the target being impacted. Generally speaking, t_f will not exceed 36 ms.



(a) (b)

Figure 1: (a) Trim with ribs; (b) Cross-section of A-pillar component covered with ribbed trim

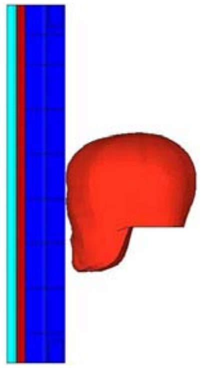


Figure 2: Finite element model of a Hybrid III headform striking normally an A-pillar component covered with trim

4 RESULTS AND DISCUSSIONS

4.1 Mechanical characterization

Mechanical properties were evaluated in the uniaxial tests conducted with plain PP as well as nanocomposites with different percentages of nanoclay content. The objectives for these tests were to confirm the anticipated enhancements in common mechanical properties such as tensile modulus and strength of PP reinforced with nanoclay, as well as to generate input data for headform impact simulation. The true stress with respect to true strain curves obtained in typical uniaxial tests for specimens made of plain PP and PPNx are given in Figure 3. For a given clay content (i.e. 0% for PP and x% for PPNx), five samples were tested to ascertain repeatibility of test results. The samples were found to yield consistent test results as can be seen in Figure 4 for the nanocomposite with 3% clay content (i.e. PPN3). From an examination of the stress-strain data given in Figure 3, it was found that the elastic modulus rose appreciably from 1.8 GPa for plain PP to 2.75 GPa for PPN9 (implying an increase of 53%). A noticeable increase in tensile strength was also observed for nanoclay-reinforced PP. The stress-strain behaviors in Figure 3 indicate that tensile strength reaches a maximum for a nanoclay content of 3% (starting with 35.4 MPa for plain PP and increasing to 40.3 MPa, i.e. an increase of 13.8%); any further increase in clay content actually leads to a slight deterioration in tensile strength but is still quite above that of plain PP.

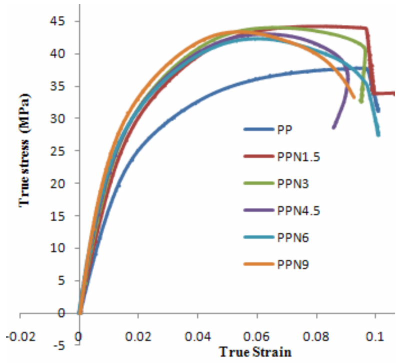


Figure 3: True stress with respect to true strain curves for various concentrations of nanoclay

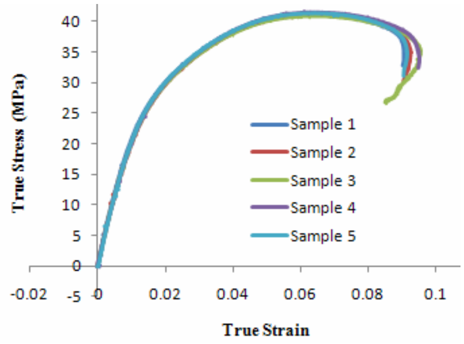


Figure 4: True stress with respect to true strain curves for 3% nanoclay concentration (i.e. five samples of PPN3)

4.2 Head impact safety assessment

A finite element model of the actual Hybrid III headform was used [5] for the assessment of various trim material compositions. The model had an outer vinyl skin covering a thick amd relatively rigid aluminum skull. The outer skin was modeled with solid elements and viscoelastic material properties (using material type 6 In LS-DYNA). The headform inner (representing skull) was modeled with Belytschko-Lin-Tsay shell elements. The various sheet metal parts of the A-pillar component were meshed with similar shell elements. The constitutive behaviors of both the mild steel-based A-pillar parts and PP-based trim with ribs were defined with elasto-plastic material properties (using material type 24 In LS-DYNA). The headform in Figure 2 was given an initial velocity of 15 mph (i.e. 6.7 m/s) in accordance with FMVSS 201 stipulation.

The headform deceleration responses obtained after impact analysis of A-pillar when trim with ribs was used as a countermeasure are shown in Figure 5. These time-histories of deceleration corresponded to trim made of plain PP and nanocomposites labeled as PPNx. A careful scrutiny of Figure 5 reveals that peak decelartion is lower for nanocomposites when compared to plain PP. To further elucidate the beneficial effect of nanoclay reinforcement of PP especially when integral fin-type ribs are present behind trim, computed deceleration responses are presented in Figure 6 for plain PP and PPN9 for trim with and without ribs. It is clearly seen in the latter figure that the magnitude of peak deceleration is lowest for trim with ribs assumed to be made of PPN9. The values of HIC(d) yielded by the responses in Figure 5 are given in Table 1 and the improved headform impact safety performance resulting from the reinforcement of plain PP with nanoclay is observed. Although all cases appear to meet the HIC(d) threshold of 1000, trim made of PPN9 would potentially provide the highest safety margin with a HIC(d) of 681 which is an improvement of 23% when compared to plain PP.

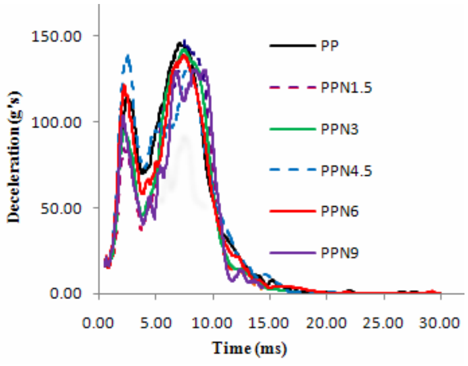


Figure 5: Predicted deceleration response curves for A-pillar trim with ribs made of plain PP and five cases of PPNx

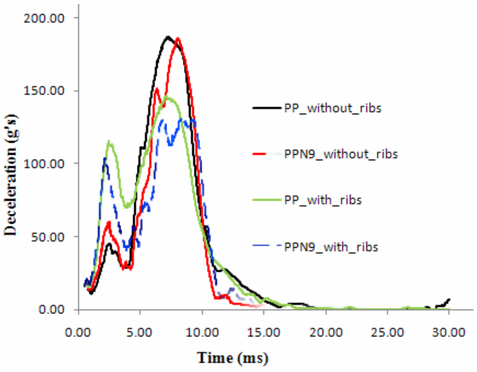


Figure 6: Predicted deceleration response curves for A-pillar trim with and without ribs made of plain PP and PPN9

Table 1: Predicted values of HIC(d) for trim with ribs made of plain PP and PPNx

Trim Material Composition	HIC(d)
PP (Plain)	890
$PPN_{1\text{-}5}$	781
PPN_3	761
$PPN_{4\text{-}5}$	815
PPN_6	782
PPN_9	681

5 CONCLUSIONS

Using an advanced simulation-based technique, the current study has established the efficacy of nanoclay-reinforced PP as a higher performing material relative to plain PP for an automotive A-pillar trim from the viewpoint of head impact safety. Other highlights include synthesis of the present nanocomposite and identification of its mechanical properties for various clay contents in a UTM.

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