Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 04, April-2016

Material Selection for Polymer Metal Hybrid Material Constituents for A-Pillar Design

Rindai P. Mahoso; Sagar S. Parihar
Department of Mechanical Engineering
ITM University
Gwalior, India

Abstract **– The automotive industry currently in the drive to produce lighter, safer and more efficient cars for the 21st century and beyond. One of the main ways they are seeking to achieve this is through application of new materials that can do a better job for lighter. One of the concepts that is being explored is that of Polymer Metal Hybrid materials. Although this technology has been around for quite a while it has had its challenges and has been applied in several types of body parts but has not yet been applied to safety crucial members of the vehicle body. With the advent of direct adhesion technology and the right material selection procedure the viability of Polymer Metal Hybrid parts in safety critical parts can become a reality. In this paper the researcher seeks to make a material design for a Polymer Metal Hybrid material for use in a vehicle A-pillar, which is a safety critical Body-In-White component. The material design takes into consideration carious constraints, from rollover accident loading parameters, to manufacturing parameters and adhesion parameters to design the perfect hybrid material combination for use in a possible A-pillar design. This material combination was found to be Dual Phase 980 High Strength Steel and 43% Glass Filled Polyamide 6/6 polymer bonded by direct adhesion.**

Key words – Material Selection, Polymer Metal Hybrid, A-pillar, Vehicle light-weighting, Material design

I. INTRODUCTION

The demand for lighter and stronger material solutions for automotive design problems has been at an all-time high in the 21st century mainly driven by the light-weighting trend where players in the automotive engineering industry are seeking to improve vehicle economy by reducing vehicle weight hence demand on the drivetrain [1]. Occupant safety however is still the still the biggest priority where new materials are designed and applied and it is at the highest risk during a vehicle accident and various active and passive methods have been designed to ensure safety. Of various accident modes however the rollover mode of accident has been found to be arguably the most dangerous with the highest fatality to prevalence ratio relative to other modes [2]. It has also been found that the best way to protect restrained occupants during a rollover accident is by ensuring roof integrity as this increases the chance of the occupants having their survival space. For roof integrity, the A-pillar is a crucial member as for most rollover accidents, its junction with roof header is the point of contact with the roof, with the A-pillar bearing most of the resulting load. Therefore it can be said that a failure of the A-pillar will directly result in the onset of roof crush. It is also apparent therefore that for A-pillar design, stiffness and strength are the main design aims [3] [4] [5] [6].

Vehicle Body-in-White (BIW) design however hasn't changed much in terms of favouring of steel over all other types of materials as over 90 percent of all the cars produced in the world use steel BIW [1] [7] [8] [9]. The main light-weighting trends in industry pertaining to BIW design and construction are:

- Application of advanced metals e.g. high-strength metal alloys
- Application of composite materials
- Application of hybrid materials. [10]

For A-pillar design these trends have resulted in quite a few material solutions which include HSS A-pillars, composite material A-Pillars and structural foam reinforced A-pillars, but there is always a major compromise whether in cost, weight or function. One of the emerging technologies that have not been applied to safety critical BIW structural members is Polymer Metal Hybrid (PMH) technology which fuses a composite two materials on macro scale so that their complementary characteristics yield light-weighting and performance benefits.

In the past PMH technology has been applied to several vehicle designs e.g. the front end of the 1996 Audi A6 by Ecia, Audincourt/France, the 2004 Audi A4 roof header by Lanxess and about 50 other models in several applications [11] [12]. It is to be noted however that of all the applications with information on the public domain, none of them have applied this emerging technology on safety critical BIW members which tend to be some of the heaviest members per volume on a vehicle due to steel reinforcement. This paper thus focuses on the material selection for design of a PMH material that would be developed specifically to be used to design a PMH A-pillar.

II. MATERIAL DESIGN CONSTRAINTS

The A-pillar's purpose on a vehicle roof structure is to ensure reasonable structural support to the roof at the foremost end, to provide a support structure for the windshield and to form part of the closure for the doorframe of the front doors. As the roof is a major part of the vehicle aesthetic and aerodynamic design, it is usually oriented at acute angles to the horizontal. Therefore when designing an A-pillar a great number of design considerations need to be taken into account and when designing one from a PMH material, the selection of material is key and is to be used has to be done carefully to make sure the materials match well with manufacturing and operational conditions as well as matching the crashworthiness standards [1] [13].

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 04, April-2016

The general production principle for a PMH part involves a formed, perforated sheet metal part is placed in an injection mould as the insert and an appropriate polymer is injected around it [14]. The resulting hybrid material ideally should exhibit performance characteristics of the two materials. Metal forming and injection moulding are two of the most economical serial production methods hence this technology has the potential of cutting the implementation and manufacturing costs subject to proper material and process design [15] [16] [14].

Some of the benefits promised by using PMH materials for BIW members include:

- Weight reduction compared to the traditional all-metal solutions
- Increased bending strength of stamped metal sections by reduction of failure due to localised buckling by maintaining of member cross-section because of the polymer reinforcement
- Recyclability of the PMH parts as the materials can be separated readily in one step and fed back directly into the production cycle
- Reduction of part complexity by using shorter processes and less subcomponents in an assembly
- Safety improvement due to lowered centre of gravity of the vehicle
- Improved damping in the acoustic range relative to all-steel components
  [14] [17] [18]

Applying concepts of computational materials design and science, where we use integrated targeted materials process–structure and structure–property models create material solutions for specific engineering needs, it will be possible to design the PMH material to suite our very specific bill for a suitable A-pillar material. [19] [20] Mixing these concepts up with optimisation tools to take care of the different parameter trade-offs that need to be taken into consideration will ensure that the material selection is a success. For that, a number of constraints and parameters need to be taken heed of, these are discussed in the subsequent sections.

A. *Manufacturing parameters*

For a PMH material to be employed successfully in BIW manufacture, the impact it has on the current day manufacturing system needs to be minimised. This can be a major issue as the current vehicle manufacturing process poses its own challenges to the design and manufacture the PMH component. Most pronounced of these hurdles are in the welding and paint shop treatments. Therefore thermal dimensional stability is key for the material and processes used for polymer-metal adhesion as the part needs to withstand the intense local heat of the spot welding procedures and endure the +130°C curing procedure of the paint shop without losing part integrity. Chemical stability is also very important because the part will also be exposed to oils, E-coat primer and paint during its period in the paint shop.

B. *Operational parameters*

Researches have shown that for a part to be used in load carrying BIW components, the adhesion strength should have a minimum value of at least 10MPa. It has been shown that any adhesion strength higher than that value does not yield any recognisable performance benefits [11].

C. *Design parameters*

In the 21st century, any material design procedure needs to ensure or at the very least embrace environmental design. This ensures that products are made in a sustainable manner with viable end of life disposal strategies. Therefore for material selection and chosen adhesion method, a sustainable and environment friendly life cycle needs to be ensured [21] [22] [23].

D. *General materials requirements*

Therefore in line with the parameters pointed out, the desired polymer characteristics for a good PMH part include:

- Good impact strength and stiffness
- Low viscosity melt
- Low density
- Resistance against oil, grease and detergent
- Reasonable cost
- Low thermal expansion
- Low thermal conductivity

And on the other hand the desired metal characteristics for the PMH parts match those for normal BIW manufacturing and these are:

- High strength and stiffness
- Ductile behaviour
- Low coefficient of thermal expansion
- Good deep drawing
- Reasonable cost

III. MATERIAL SELECTION

All through the considerations in the material design procedure, the criteria to be used for selection generally be:

- Individual material strength and heat performance characteristics
- Metal-polymer adhesion strength
- Compatibility with upstream and downstream BIW manufacturing processes
- Material and processing cost

A. *Adhesion method*

The first design decision to be made was on the polymer-metal adhesion mechanism. In current research on PMH technology, this is the issue that takes centre stage because for all the advantages promised by PMH technology to

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 04, April-2016

become a possibility, the strength and reliability of this bond need to be guaranteed. Depending on intended use many methods can be thought of but for BIW application, only a handful show prospects of viability and these include:

- Mechanical joining in injection over-moulding and metal over-moulding technology [14] [15] [24]
- Surface undercut technology [15]
- Adhesively-Bonded Polymer-Metal-Hybrid Structures [11] [15]
- Primed-metal surfaces for enhanced polymer adhesion [11] [24]
- Technologies based on chemical modifications of the injection-moulding thermoplastic
- Chemical modifications of polymer for enhanced adhesion [11]
- Direct Adhesion PMH Technology [11]

After a comparison of the given methods, the selected method for this paper is the direct adhesion method. In this method the required level of adhesion strength is attained through the infiltration of the polymer melt into the micron-size surface asperities of the metal insert surface and upon cooling, interlocking occurs. This mechanism of direct bonding evades the high cost of adhesives and primers, the surface processing costs of surface undercutting and the localised stresses of mechanical joining and overmoulding. Direct adhesion allows the direct application of the injection moulding in the least possible steps. However this method requires the selection of a polymer that has the ability to bond to metals in an efficient and effective manner.

B. Polymer selection

The selection of polymer for use is reduced to thermoplastics as the desired manufacturing method is injection moulding and recyclability is a requirement.

Therefore looking at the thermoplastics available on the market, the candidates that stand out for the application are polyphthalamide, polycarbonate and glass fibre reinforced polyamide (nylon)

As can be shown from Table II, polyamide is the clear choice as it ticks the boxes for the best stiffness and strength performance through the relatively high elastic modulus and strength values. It has also been shown to have lower cost on the marker and availability. Polyamide also possesses the amide group in its polymer structure which aids in its direct adhesion to metals, through the breaking of the carbon-oxygen double bond and the subsequent diffusion of oxygen into the metal and formation of carbon-metal bond [25]. Therefore the best form of polyamide will be the form of nylon 6/6 as it has a higher amide group presence in its polymer backbone. This poses as a significant advantage over the other materials especially in line with direct adhesion. Polyamide has been shown to produce good direct adhesion to steel components in the range of 40MPa in perfect conditions [11]. To maximise the stiffness and strength the highest rating of glass filling on the market can be chosen to maximise structural performance. A good example of such a material would be the FORMPOLY N66GF43, which has 43% glass fibre reinforcements in the nylon matrix.

The major drawback with nylon however is with its sensitivity to moisture hence care during manufacture and operation is crucial. This would have to be a major design consideration in application.

C. Metal selection

Metals have always been the material of choice in BIW construction during car manufacture and the three main metals that have been used extensively as bases for alloys used in the automotive industry are steel, aluminium and magnesium. As these metals are already in use in the automotive industry, the conditions for thermal stability and chemical stability concerning the BIW manufacturing process need not be considered for the following analysis.

TABLE I: METAL CANDIDATE COMPARISON

Material	Elastic Modulus (GPa)	Yield Strength (MPa)	Coefficient of Thermal Expansion (°C^{-1})
Aluminium 6111	70	150	23.5Exp-6
Magnesium AZ91D	45	165	27.3Exp-6
Steel DP600	210	330	13Exp-6

TABLE II: POLYMER MATERIAL CANDIDATE COMPARISON

Material	Elastic Modulus (GPa)	Yield Strength (MPa)	Heat Deflection Temperature (°C)	Chemical stability (known sensitivities)	Cost ($/m^3)
GF Polyamide	10	190	250	Water	3540
Polyphthalamide	2.1	69	120	strong acids; oxidizing agents	9640
GF Polycarbonate	5.5	70	280	aromatic solvents	4454

Despite magnesium's 75% and aluminium's 50% weight saving advantages over steel components, steel still holds its ground in the automotive industry today. Iron and steel still form the critical elements of BIW structures for the vast majority of vehicles and the prime reason for their use is their inherent capability to absorb impact energy in a crash situation and predictable failure modes. This, in combination with the good formability, a quality magnesium doesn't have; joining capability, a challenge with aluminium to this day; and material availability, makes steel remain a reasonable choice for BIW design.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 04, April-2016

Recent years have seen steady increases in the use of HSS, many versions of which are referred to as high-strength low-alloy steels that have been shown in American Iron and Steel Institute (AISI) Ultralight Steel Auto Body (ULSAB) project to be achieve an overall weight saving as high as 19% through reduction of the wall thickness of structures. Austenitic Stainless Steels are another type of steel being used, these are highly strain rate sensitive therefore member made from it possess rigidity and therefore crashworthiness. One such advanced steel is the Dual Phase 600 High Strength Steel (HSS) which was used for the purposes of comparison above which has the same mechanical specifications as the steels used in a number of mid-range sedan A-pillars [1] [7] [9] [10] [26].

For these very reasons in this study we retain the services of steel for our material selection. However as has been noted, steel is being produced in many forms and many highly customised grades can be found. Even in automotive steels the selection range is wide, therefore an assessment needs to be done to select the optimal grade of steel for use in a PMH A-pillar design.

D. PMH pair selection

The material selection of steel is to be optimised to find the best suited grade of automotive steel to be used as the metal insert for the PMH material since for steels stronger is not always better.

The automotive steel candidates to be assessed the HSS grades generally used in the manufacture if the safety critical components of the motor vehicle BIW are chosen. The chosen four candidates are the Dual Phase steels of 600MPa, 780MPa, 980MPa and a 1500MPa Ultra HSS as found in common automotive engineering practise.

This assessment will be based on a simulation run in ANSYS Workbench where we intend to assess the strength of a prototypical PMH member using the different steel grades. The prototypical member is an Erlanger-Trager type composite beam that will have the same bounding box dimensions of a mid-size saloon A-pillar of 100mm in width and thickness and 800mm length. The design will have a metal insert frame of 1mm thickness and an orthogonal polymer ribbing reinforcement which will be is 3mm thick.

The simulation will be a non-linear axial buckling simulation. This test setup is chosen because axial strength is one of the major loading modes of the rollover accident as most forces act compressively during loading. For purposes of this simulation, contact debonding was not used and the bond between polymer and metal was set to “no separation” to ensure assessment of the influence of changing metal grade only. The nonlinear material models used for the simulations are given below:

TABLE III: MATERIAL MODEL FOR 43% GLASS FIBRE REINFORCED POLYAMIDE 6/6

Property	Value
Density	1480 kg/m^3
Bilinear Isotropic Hardening	
Yield Strength	190MPa
Tangent Modulus	9.4Gpa
Isotropic elasticity	
Young’s Modulus	14GPa
Poisson’s Ratio	0.35
Bulk Modulus	15.56GPa
Shear Modulus	5.19GPa

TABLE IV: MATERIAL MODELS FOR HIGH STRENGTH AUTOMOTIVE STEELS

Common to all steels	
Density	7850 kg/m3
Young’s Modulus	200GPa
Poisson’s Ratio	0.3
Bulk Modulus	175GPa
Shear Modulus	80.8GPa
Dual Phase 600 HSS	
Bilinear Isotropic Hardening	
Yield Strength	330MPa
Tangent Modulus	14.7GPa
Dual Phase 780 HSS	
Bilinear Isotropic Hardening	
Yield Strength	450MPa
Tangent Modulus	25GPa
Dual Phase 980 HSS	
Bilinear Isotropic Hardening	
Yield Strength	700MPa
Tangent Modulus	47GPa
1500 Ultra HSS	
Bilinear Isotropic Hardening	
Yield Strength	1100MPa
Tangent Modulus	50GPa

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 04, April-2016

The prototypical member used in the simulation is shown below:

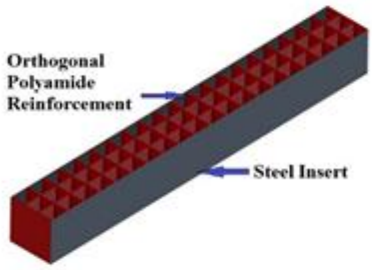

Figure 1: Prototypical Erlanger-Trager type member

IV. SIMULATION RESULTS

It can be noted that since the materials are of the exact same elastic modulus, and the tested members are same dimensions in all simulation runs, the stiffness will remain the same since stiffness k, is:

$$k = AE/L \quad (1)$$

Therefore the stiffness performance will not be assessed. The main focus will be to assess which material combination yields to the highest loading value. The simulation runs produced the following set of results

Table V: NONLINEAR AXIAL LOADING RESULTS FOR ORTHOGONAL AUTOMOTIVE STEEL GRADES SELECTION

Insert material	Axial buckling load (N)
Dual Phase 600 HSS	35300
Dual Phase 780 HSS	39270
Dual Phase 980 HSS	43850
1500 Ultra HSS	45000

As can be noted, changing the metal insert material gives a distinct increase in axial performance dependant on the increase in tensile strength rating as was the expected case. On this basis alone it would be the natural choice to choose the highest tensile strength rating steel. However it can also be noted that the axial performance benefits from the increase in tensile strength reduces as after the Dual Phase 980 steel grade.

V. DISCUSSION

Given the fact that the 1500MPa rating steel yields the best results, it can also be noted that with high strength steels, manufacturability decreases, cost per kg increases and availability decreases as the tensile strength rating increases. And in light of this with the given decrease in performance gain, it is the researcher's recommendation to select the 980MPa rated dual phase steel for the material combination as it offers the best gains in performance with some saving on manufacturing costs and material costs.

VI. CONCLUSIONS

Therefore the PMH material designed for application in an A-pillar design is a direct adhesion polyamide-steel hybrid made of Dual Phase 980 HSS and 43% glass filled Nylon 6/6. The next step in this research would be to

REFERENCES

[1] E. Ghassemieh, "Materials in Automotive Application, State of the Art and Prospects," in *New Trends and Developments in Automotive Industry*, M. Chiaberge, Ed., Rijeka, INTECH, 2011, pp. 365-394.
[2] K. M. Dobbertin, M. D. Freeman, W. E. Lambert, M. R. Lasarev and S. S. Kohles, "The relationship between vehicle roof crush and head, neck and spine injury in rollover crashes," *Accident Analysis and Prevention (Elsevier)*, vol. 58, p. 46– 52, 2013.
[3] R. Pathare, M. Mirdamadi and O. Bijjargi, "Roof crush enhancement incorporating structural body enhancement systems," Dow Automotive, 2009.
[4] B. Pipkorn , J. Lundström and M. Ericsson , "Safety and vision improvements by expandable A-pillars," *International Journal of Crashworthiness*, vol. 17, no. 1, pp. 11 - 18, 2012.
[5] M. I. U. Haq, A. Anand, T. Nasir and D. Singh, "Design Considerations for Safety in Automobiles: A System Approach," *International Journal of Mechanical Engineering and Research*, vol. 3, no. 6, pp. 583-588, 2013.
[6] S. U. Ryu, W. Jin, Y. C. Shin, K. S. Bae and K. B. Lee, "Study of Optimal Body Structural Design for Coupe-Type Vehicles in Rollover Events," in *23rd International Technical Conference on the Enhanced Safety of Vehicles (ESV)*, Seoul, South Korea, 2013.
[7] P. K. Mallick, "Advanced materials for automotive applications: An overview," in *Advanced Materials in Automotive Engineering*, J. Rowe, Ed., Woodhead Publishing, 2012, pp. 5-27.
[8] E. R. Fuchs, F. R. Field, R. Roth and R. E. Kirchain, "Strategic materials selection in the automobile body: Economic opportunities for polymer composite design," *Composites Science and Technology*, vol. 68, p. 1989–2002, 2008.
[9] P. Urban and R. Wohlecker, "Advanced automotive body structures and closures," in *Advanced Materials in Automotive Engineering*, Woodhead Publishing, 2012, pp. 230-253.
[10] C. Lauter, J. Niewel, B. Siewers, B. Zanft and T. Tröster, "Crashworthiness of Hybrid Pillar Structures Consisting of Sheet Metal and Local CFRP Reinforcements," in *15th International Conference on Experimental Mechanics*, Porto, Portugal, 2012.
[11] M. Grujicic, V. Sellappan, M. A. Omar, N. Seyr, M. Erdmann and J. Holzleitner, "An overview of the polymer-to-metal direct-adhesion hybrid technologies for load-bearing automotive components," *Journal of Materials Processing Technology*, 2007.
[12] C. Korson and D. Stratton, "An integrated roof module concept: Plastic-metal hybrid and polyurethane composite technology," Lanxess Corporation; Bayer Material Science LLC.
[13] W. Tan, B. G. Falzon and M. Price, "Predicting the crushing behaviour of composite," *International Journal of Crashworthiness*, vol. 20, no. 1, pp. 60-77, 2015.
[14] Lanxess Corporation, "Application Information: Hybrid Components in Series Production," [Online]. [Accessed 15 November 2015].
[15] S. Müller, M. Brand, K. Dröder and D. Meiners, "Increasing the Structural Integrity of Hybrid Plastics-Metal Parts by an Innovative Mechanical Interlocking Effect," *Materials Science Forum*, Vols. 825-826, pp. 417-424, 2015.
[16] A. Jäschke and U. Dajek, "Roof-frame design using hybrid technology," LANXESS Deutschland GmbH, Leverkusen, 2004.
[17] E. Mangino, J. Carruthers and G. Pitarresi, "The future use of structural composite materials in the automotive industry," *International Journal of Vehicle Design*, vol. 44, no. 3-4, pp. 211-232, 2007.
[18] M. Grujicic, "Injection over molding of polymer-metal hybrid structures," *American Journal of Science and Technology*, vol. 1, no. 4, pp. 168-181, 2014.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 04, April-2016

[19] C. J. Kuehmann and G. B. Olson, "Computational materials design and engineering," *Materials Science and Technology*, vol. 25, no. 4, pp. 472-478, 2009.

[20] Materials Science and Engineering Expert Committee, "Computational Techniques, Methods and Materials Design," European Science Foundation, Strasbourg, 2011.

[21] Modern Plastics, Modern plastics handbook, C. A. Harper, Ed., Lutherville: McGraw-Hill, 1999.

[22] GE Plastics, GE Engineering Thermoplastics Design Guide, GE Plastics.

[23] C. Maier , Design Guides for Plastics, Tangram Technology Ltd., 2009.

[24] R. Klein, K. Burlon, C. Meyer, M. Gallei, M. Appold and M. Rehahn, "Novel Coupling Agents as Adhesion Promoters Between Thermoplastics and Metal," in *Euro Hybrid Materials and Structures*, Stade, Germany, 2014.

[25] H. Imai , K. Kondoh, T. Izawa and J. Umeda, "Interfacial Structure Analysis on Direct Bonding Metals to Plastics," *Transactions of JWRI*, vol. 44, no. 1, pp. 23-26, 2015.

[26] V. O. Mérida, X. A. Ripoll, M. Ferstl, A. Z. Ruiz and V. Clua, "Applying new blow-forming processes to obtain new structural componentsfor automotive industry: A-pillar," in *15th International Congress On Project Engineering*, Huesca, 2011.