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The Potential of a Clinch-Lock Polymer Metal Hybrid Technology for Use in Load-Bearing Automotive Components

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In order to help meet the needs of automotive original equipment manufacturers and their suppliers for a cost-effective, robust, reliable polymer-metal-hybrid (PMH) technology which can be used for the manufacturing of load-bearing body-in-white (BIW) components and which is compatible with the current BIW manufacturing process chain, a new approach, the so-called *direct-adhesion* PMH technology, was recently proposed (Grujicic et al., *J. Mater. Process. Technol.*, 2008, 195, p 282-298). Within this approach, the necessary level of polymer-to-metal mechanical interconnectivity is attained through direct adhesion and mechanical interlocking. In the present work, a new concept for mechanical interlocking between the metal and plastics is proposed and analyzed computationally. The approach utilizes some of the ideas used in the spot-clinching joining process and is appropriately named *clinch-lock PMH technology.* To assess the potential of the clinch-lock approach for providing the required level of metal/polymer mechanical interlocking, a set of finite-element based sheet-metal forming, injection molding and structural mechanics analyses was carried out. The results obtained show that stiffness and buckling resistance levels can be attained which are comparable with those observed in the competing injection overmolding PMH process but with an ~3% lower weight (of the polymer subcomponent) and without the need for holes and for overmolding of the free edges of the metal stamping.

Keywords automotive, fabricated metal, joining

1. Introduction

In the current automotive manufacturing practice, metals and plastics are generally fierce competitors. Nevertheless, the polymer-metal-hybrid (PMH) technologies developed over the last decade are slowly changing this paradigm. Within the PMH technologies, different approaches are pursued in order to take full advantage of the two classes of materials by combining them into a singular component/subassembly. Several patented PMH design/manufacturing technologies have already proven their ability to allow the automotive original equipment manufacturers (OEMs) to engage flexible assembly strategies, decrease capital expenditures, and reduce labor required to manufacture a vehicle. The key feature of PMH structures is that the materials employed complement each other so that the resulting hybrid material can offer structural performance which is not present in either of the two constituent materials independently.

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An example of a PMH component is depicted in Fig. 1(a) and (b). The component in question is generally referred to as the *rear longitudinal beam* which connects, on the front end, to the rocker panel, on the middle to the shock tower, while at the rear end it connects to the rear cross beam. The traditional all-metal design of this component is displayed in Fig. 1(a) and includes three components: (a) main U-shape channel beam, (b) a reinforcement plate, and (c) a cover plate. The latter two components are spot welded to the first one. It should be noted that the cover plate is slightly translated in Fig. 1(a) in order to reveal the location of the reinforcing plate. The PMH rendition of the same component is depicted in Fig. 1(b). The reinforcement plate has been replaced with an injection-molded thermoplastic rib-like substructure, while the thickness of the cover plate (not shown in Fig. 1b for clarity) is reduced.

Among many technical and economic benefits offered by the PMH technologies, the following appear to be the most important:

1. reduction of the number of components;
2. production of the integrated components ready to assemble;
3. weight reduction compared to the traditional all-metal solutions;
4. additional design and styling freedom;
5. production of in-mold features like brackets, bosses, and attachment points;
6. safety improvement due to lowered center of gravity of the vehicle;
7. often a several-fold increase in the bending strength of stamped metal sections which is attributed to the ability of plastics-subcomponent to assist the metal stamping to maintain its cross-sectional properties throughout the

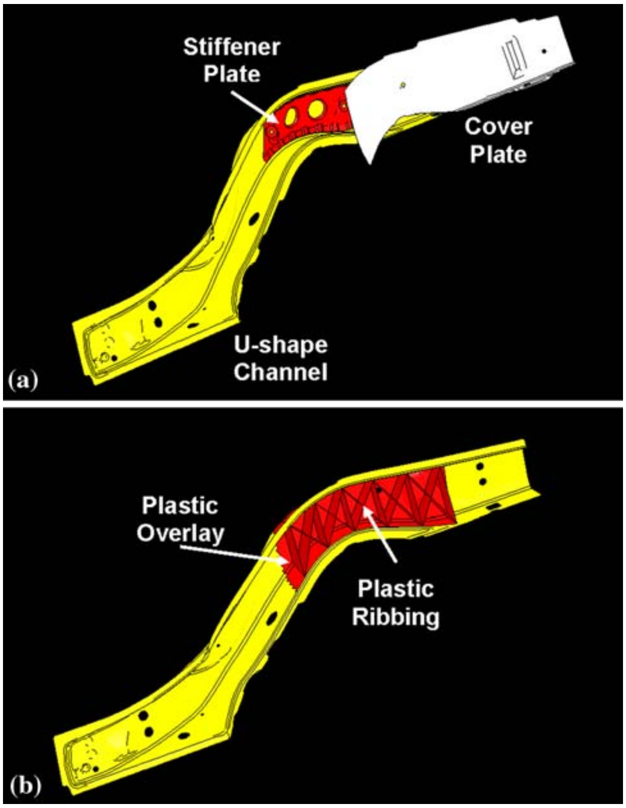

Fig. 1 An example of the (a) all-metal and (b) PMH load-bearing automotive component

loading cycle and to delay the onset of failure due to localized buckling; and

8. improved damping in the acoustic range (relative to their all-steel counterparts, often as high as four times lower initial decibel reading measured in a simple hammer-strike test).

There are three main PMH technologies currently being employed by the automotive OEMs and their tier 1 and tier 2 suppliers: (a) *injection overmolding* technologies, (b) *metal overmolding* technologies combined with secondary joining operations, and (c) *adhesively bonded* PMH technologies. Since these were reviewed in great detail in our recent work (Ref 1), they will be only briefly described in this section.

Within the *injection overmolding* technologies (Ref 2), a metal-stamping profile is placed in an injection mold and polymer (typically glass fiber reinforced nylon) is injected around the profile. The plastic wraps around the edges of the sheet metal and/or through carefully designed extruded holes or buttons. There are no secondary operations required and the drawing oils/greases do not need to be removed from the metal stamping.

Within the *metal overmolding* technologies (Ref 3), a steel stamping is placed in an injection mold in order to coat its underside with a thin layer of reinforced nylon. In a secondary operation, the polymer-coated surface of the metal insert is ultrasonically welded to an injection-molded nylon subcomponent. In this process, a closed-section structure with continuous bond lines is produced, which offers a high load-bearing capability. The hollow core of the part permits functional integration like cable housings and air or water channels.

Within the *adhesively bonded* technologies (Ref 4), glass-fiber reinforced polypropylene is typically joined to a metal stamping using an adhesive which does not require pretreating of the low-surface energy polypropylene and can be applied by high-speed robots. Adhesive bonding creates continuous bond lines, minimizes stress concentrations, and acts as a buffer which absorbs contact stresses between the metal and polymer subcomponents. Adhesively bonded PMHs also enable the creation of closed-section structures which offer high load-bearing capabilities and the possibility for enhanced functionality of hybrid parts (e.g. direct mounting of air bags in instrument-panel beams or incorporation of air or water circulation inside door modules).

While the PMH technologies discussed above have been widely used in the manufacturing of various nonstructural and load-bearing automotive components, they, nevertheless, display some significant shortcomings. Among such shortcomings, the ones most frequently cited are the following:

1. The injection overmolding technologies rely on the presence of holes and free edges in the metal stamping in order to attain the needed polymer-to-metal interlocking. These holes may compromise the structural integrity of the stamping while edge overmolding of the stamping is often restricted.
2. In the case of adhesively bonded PMHs, the adhesive cost, long curing time and limited ability of the adhesive to withstand aggressive chemical and thermal environments encountered in the paint-shop during body-in-white (BIW) pretreatment and E-coat curing may create defective PMH components.
3. The *metal overmolding* and the *adhesively bonded* PMH technologies involve secondary (joining) operations which are accompanied with additional cost.

Consequently, alternative lower cost PMH technologies for structural load-bearing BIW components which are compatible with the BIW manufacturing process chain are being sought. One such technology, which has been the subject of our recent work (Ref 1, 5), is the so-called *direct-adhesion* PMH technology in which joining between the metal stamping and the polymer subcomponents is attained through their direct contact, adhesion, and mechanical interlocking. No holes and free edges are required and a structural adhesive is not used (Ref 1, 5). The following main potential advantages offered by this technology have been identified:

1. Polymer-to-metal adhesion strengths (20-30 MPa) comparable with those obtained in the case of thermo-setting adhesives are feasible but only at a small fraction of the manufacturing cycle time.
2. The shorter cycle time and the lack of use of an adhesive allow for more economical PMH-component production.
3. Unlike the adhesive-bonding technology, joining is not limited to simple and noninterfering contact surfaces.
4. Reduced possibility for entrapping air in undercuts of a complex surface.
5. No holes for the formation of interlocking rivets are required and, hence, structural integrity of the part is not compromised.
6. Overall reduction in the constraints placed upon the design complexity of the PMH component.

As implied by its name, the direct-adhesion PMH technology relies (at least partly) on polymer-to-metal adhesion to attain the required level of mechanical connectivity between the two materials. In our previous work (Ref 5), various possible polymer-to-metal adhesion mechanisms (such as microscale mechanical interlocking, metal-substrate priming, chemical modifications of the plastics, etc.) were reviewed with respect to suitability and potential for use in the direct-adhesion PMH technology. It was found that each of the adhesion mechanisms suffers from some shortcomings with respect to either the BIW load-bearing PMH-component performance or durability or with respect to the BIW manufacturing process chain. Consequently, it was concluded that (millimeter length-scale) mechanical interlocking between metal stamping and the polymer subcomponent is required to attain the full potential of the direct-adhesion PMH technology. In the present article, a novel approach for polymer/metal interlocking is proposed and studied computationally. The approach utilizes some of the concepts used in clinch-joining processes and is appropriately named *clinch-lock PMH technology*. The computational analysis involves a series of finite-element based calculations aimed at assessing the feasibility and the potential of this technology for use in BIW load-bearing direct-adhesion PMH technology.

This article is organized as follows. In Sect. 2.1 and 2.2, brief overviews are provided of the basic concepts of clinch joining and clinch-lock joining, respectively. Details pertaining to the fabrication of a single dovetail-shaped indentation/impression in the metal stamping by a punching process are discussed in Sect. 2.3. Fabrication of a single polymer/metal clinch-lock joint by injection molding is presented in Sect. 2.4. The procedure and the results pertaining to the finite-element analyses of the load-bearing capability of the clinch-lock joints are given in Sect. 2.5. The potential of the clinch-lock joining technology for fabrication of the PMH load-bearing BIW components is discussed in Sect. 3. The key conclusions resulting from the present work are summarized in Sect. 4.

2. Problem Formulation and Computational Analysis

2.1 Fundamental Aspects of Clinch Joining

As mentioned earlier, the clinch-lock PMH technology proposed in the present work utilizes some of the concepts inherent to the clinch joining (more specifically to spot clinching) of sheet metal. Consequently, a brief overview of spot clinching is provided in this section, while emphasizing the aspects of this mechanical joining process which are utilized in the clinch-lock PMH technology.

Clinching is a sheet-metal mechanical fastening method which relies on plastic deformation to form a mechanical interlock between the sheets and does not require any consumables. Two basic clinching methods are generally used (Ref 6):

1. The older method, often referred to as a *clinched or lanced lock*, shears the metal sheets, forcing the top sheet through slits in the bottom sheet. This method is primarily used for metals with less ductility, such as hardened aluminum alloys or high-strength steels, or where there is a considerable thickness or ductility difference between the sheets being joined. A schematic of the shear-clinched joint is displayed in Fig. 2(a).
2. The second method, called a *spot or round clinch*, produces no hole or slits but simply deforms metal sheets so that the bottom sheet locks around the top one, like a circular dovetail joint. This joint is often preferred because of its neater appearance and leak resistance. The following basic stages are involved in the *spot clinching* process: (a) the sheets are clamped between a die and a blank-holder; (b) the punch locally pushes/draws the sheets into the die cavity; (c) the sheets are squeezed between the punch and die expelling material outward, which results in the formation of an interlocking button that holds the sheets together. A schematic of the spot-clinched joint is displayed in Fig. 2(b).

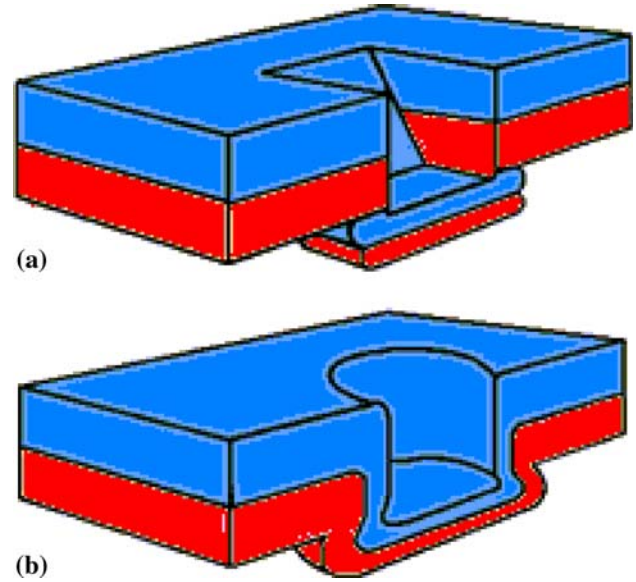

Fig. 2 A schematic representation of (a) the shear clinching and (b) the press (spot) clinching processes

In the present work, the concept of spot clinching is utilized but for a single metal sheet (i.e. metal stamping) to produce circular dovetail impressions/indentations for polymer-rib interlocking. A more detailed discussion of this approach is provided in the next section.

2.2 Clinch-Lock PMH Technology

The basic idea behind the clinch-lock PMH technology proposed in the present work is to first produce shallow millimeter-size impressions/indentations within the metallic stamping using a simple stamping process. Such impressions are next used to anchor the subsequently, injection-molded plastic ribs to the metal stamping. To ensure an effective metal/polymer interlocking, the indentations should possess a *dovetail* shape (similar to the one observed in spot clinching). A schematic of the final-stamping/plastic-rib joint is given in Fig. 3(a). The joint provides effective metal/polymer connectivity by at least two distinct mechanisms: (a) mechanical interlocking and (b) enhanced adhesion due to an increased metal/polymer contact surface area. In addition, the impressions

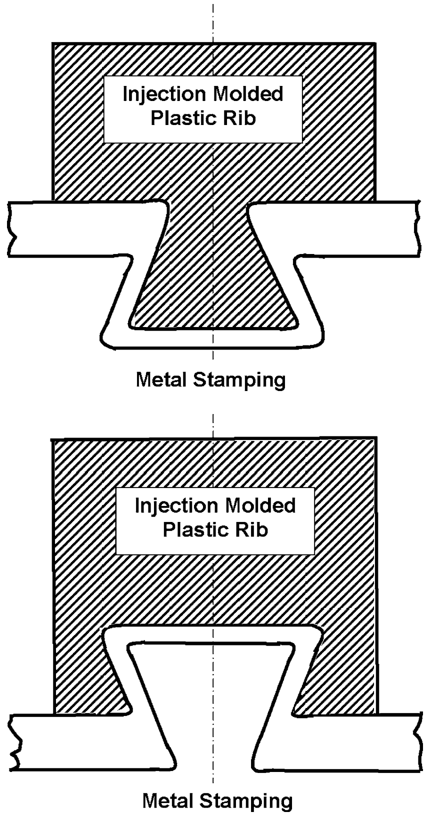

Fig. 3 Schematics of two types of clinch-lock concepts analyzed in the present work. Please see text for details

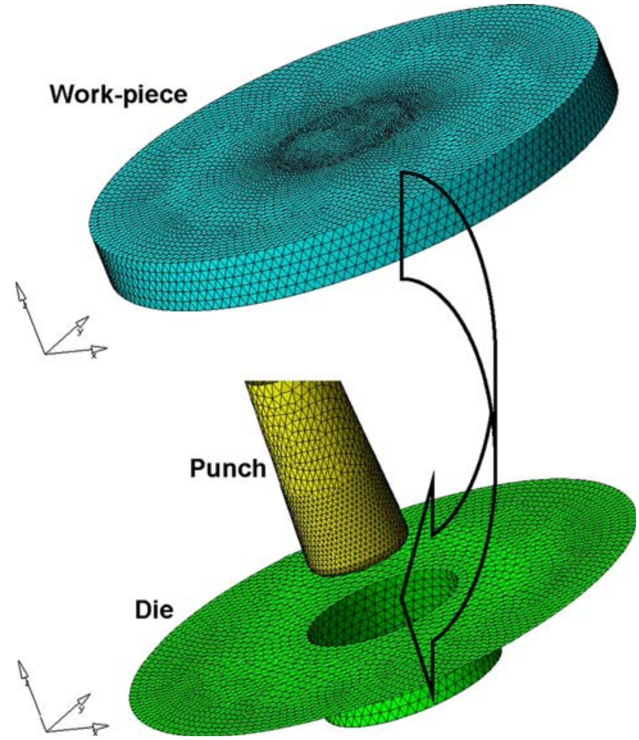

Fig. 4 Finite-element models for the workpiece punch die used in the computational analysis of metal-stamping indentation formation

can be filled with adhesion promoters/primers to further enhance polymer-to-metal adhesion strength. In Fig. 3(b), an alternative method of polymer/metal clinch locking is presented, in which the plastic is injected around the metal-stamping protrusion instead of into the metal-stamping impression. The potentials of both of these methods in the PMH technology for load-bearing BIW components are explored in the present work.

2.3 Computational Analysis of Indentation Formation

The first step in the clinch-lock PMH technology is the production of a series of indentations in the metallic stamping for plastic-rib interlocking. In this section, a brief description is given of the computational finite-element analysis used to analyze the formation of such indentations through the use of a tool set consisting of a punch (in the shape of a truncated cone) and a circular die (with a dome-shaped bottom). A finite-element mesh model for the workpiece and the tools is depicted in Fig. 4. Since the analysis carried out in the present work concerns the formation of a single indentation, the metallic stamping is represented by a circular disc with a radius of 5 mm. Furthermore, since the sheet-metal thickness is assumed to be 1 mm and the nominal indentation radius is also set to 1 mm, the workpiece (the circular disc-shaped metal stamping) is modeled as a solid part. Conversely, the punch and the die are modeled as rigid shell parts.

The workpiece and the tools were initially designed as geometric models using CATIA V.5 R16 CAD program (Ref 7) and subsequently meshed using HyperMesh preprocessing program (Ref 8). In a typical analysis, the workpiece is discretized using 82332 tetrahedron solid elements while the punch and the die are discretized using 3651 and 5425 triangular shell elements, respectively. A friction coefficient of 0.15 is assumed to exist at the workpiece/punch and workpiece/die contact surfaces. The motion of the die is fully constrained. In a typical analysis, no constraints are imposed onto the disk-shaped workpiece, while a normal velocity of 1 m/s is assigned to the punch.

The indentation-formation process is simulated using ABACUS/Explicit computer program (Ref 9). The workpiece is assigned the typical mechanical properties of a dual-phase steel with the following thermo-mechanical properties: Young's modulus, $E = 210$ GPa, Poisson's ratio, $\nu = 0.3$, yield strength, $\sigma_y = 350$ MPa, linear strain-hardening tangent modulus, $h = 600$ MPa, linear thermal expansion coefficient, $\alpha = 12.4 \times 10^{-6}$.

An example of the typical results obtained in this portion of the work is displayed in Fig. 5(a)-(d), wherein the evolution of the indentation is shown. To reveal the details of indentation formation, a vertical cut through the axis of the punch/die is used in Fig. 5(a)-(d). The results displayed in Fig. 5(a)-(d) clearly reveal the formation of a dovetail-shaped indentation, which is critical for effective metal/plastic mechanical interlocking. A preliminary analysis involving ad hoc variation of a number of punch and die geometry parameters revealed that more pronounced dove shape can be obtained than the one displayed in Fig. 5(a)-(d). However, optimization of the indentation-formation process with respect to attaining the maximum extent of dovetail geometry while enabling an easy removal of the workpiece from the die was not carried out in the present work.

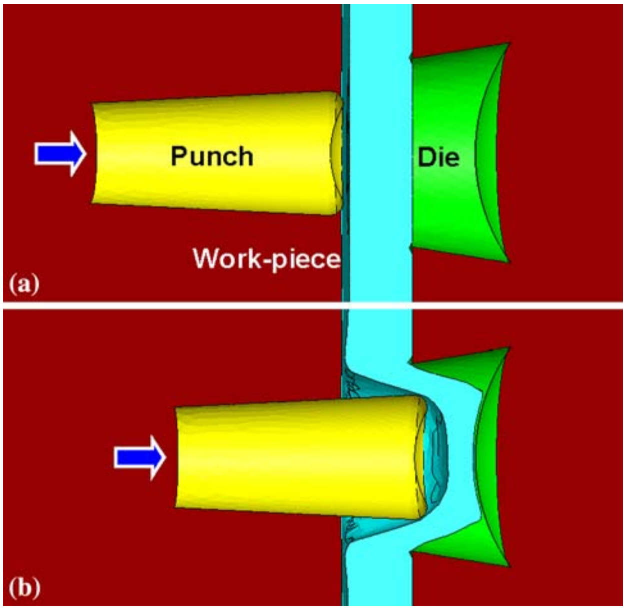

Fig. 5 Temporal evolution of the metal-stamping indentation formation

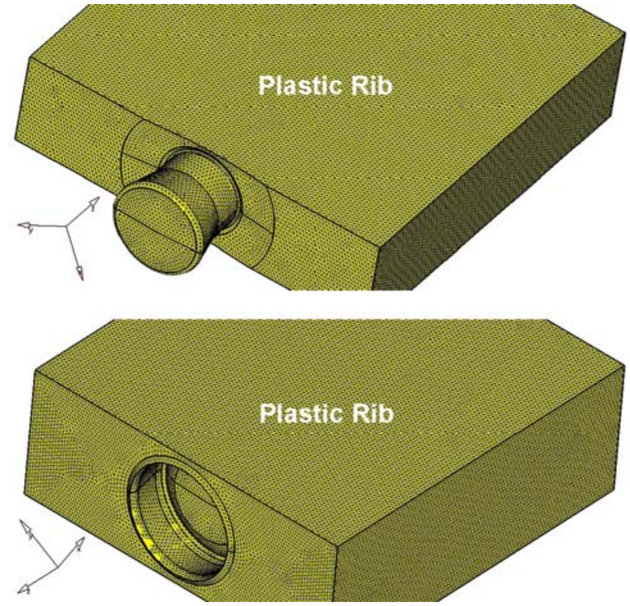

Fig. 6 Typical finite element models for the injection-mold cavities used in the computational analyses of fabrication of the two clinch-lock concepts by injection molding

2.4 Injection Molding of a Single Plastic Rib

The next step in the computational analysis of the clinch-lock PMH technology is injection molding simulations of a plastic rib whose bottom is anchored by the plastics injection molded into the dovetail-shape indentations in the metallic stamping or by overmolding the dovetail-shape protrusion of the metallic stamping. Toward that end, the final configuration of the circular disk workpiece shown in Fig. 5(d) is next used to construct the geometrical model for a single-rib injection-molding mold cavity with the workpiece acting as a metal insert in the mold. This was accomplished by exporting the finite-element mesh for the workpiece displayed in Fig. 5(d) as an .igs solid model file from HyperMesh into CATIA. Upon the creation of a solid model for the mold cavity, the model is meshed (using 400,000 tetrahedron elements) in HyperMesh and exported as an .udm input file for injection-molded analysis within Moldflow Plastics Insight 6.1 (Moldflow, for brevity) (Ref 10).

Typical finite-element models for the injection-mold cavities used in the analysis of the two clinch-lock concepts are displayed in Fig. 6(a) and (b), respectively.

The injection-molding analysis included the following stages: (a) determination of the optimal location of the injection port(s), (b) mold filling with fiber orientation distribution analysis, (c) material packing, (d) mold cooling, and (e) part ejection. Since very detailed descriptions of all these steps were given in our recent work (Ref 1), they will not be repeated here. The descriptions provided in Ref 1 include the definitions of all governing differential conservation and evolution equations, all material-model equations, definitions of all initial and boundary conditions and the necessary details pertaining to the numerical procedures used to carry out the injection-molding simulations. As mentioned above these details will not be reiterated upon in the present work. Merely, the locations of the injection ports are indicated in Fig. 7(a) and (b), and the rheological and thermo-mechanical properties of Durethan BKV 130 H2.0 (a 30 wt.%

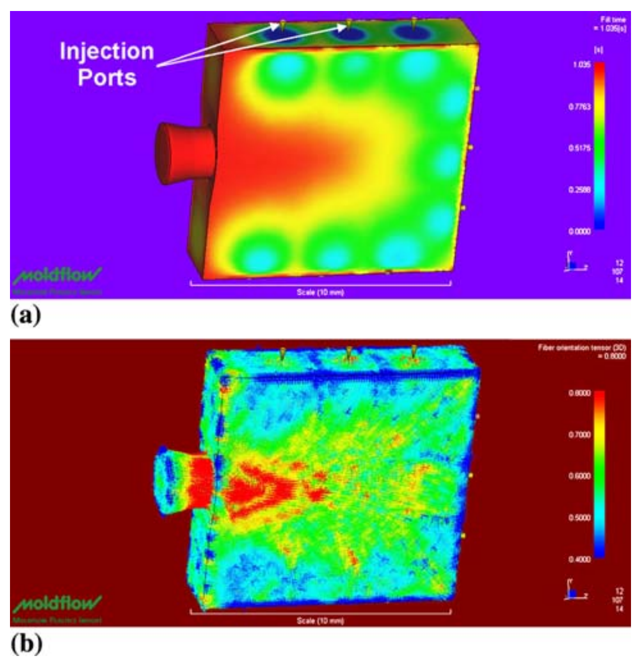

Fig. 7 An example of the results obtained in the computational analyses of fabrication of a single polymer/metal clinch-lock joint by injection molding: (a) fill time and (b) glass-fiber orientation distribution

glass-fiber filled Nylon 6, elastomer-modified and heat-age resistance enhanced) are provided below. This thermoplastic material is most widely used in the fabrication of injection- and metal-overmolded PMH components.

The following rheological and thermal properties of Durethan BKV 130 H2.0 were used in the injection molding mold-filling, material-packing and part cooling analysis: the viscosity is shear-rate and temperature-dependent and was defined using the cross-WLF model as presented in our previous work (Ref 1), specific heat, C_p = 1909 J/kg·K, thermal conductivity, k = 0.14 W/m·K, glass transition temperature, T_{trans} = 479.0 K. Likewise, the following thermo-mechanical properties were used in the finite-element analysis of the PMH component in-mold stress and post-ejection warping development: Young's modulus, E = 7 GPa, Poisson's ratio, v = 0.4, yield strength, σ_y = 150 MPa, linear strain-hardening tangent modulus, h = 100 MPa, linear thermal expansion coefficient, $\alpha = 4 \times 10^{-5}$. It should be noted, however, that the thermo-mechanical properties for Durethan BKV 130 H2.0 given above pertain to the properties of this material in its as-received (isotropic) condition. The actual properties used in the thermo-mechanical analyses were both anisotropic and non-uniform throughout the part and were obtained by combining the mold-filling results pertaining to the local orientation of the glass fibers with a rule-of-mixture computational scheme for determination of the effective (two-phase) material properties. A more detailed account of this procedure can be found in our previous work (Ref 1).

An example of the results obtained in the single-rib injection-molding analysis carried out in the present work is shown in Fig. 7(a) and (b). In Fig. 7(a), a field (contour) plot for the fill time is displayed. It should be noted that in order to represent a typical plastic melt flow pattern in the neighborhood of a typical clinch-lock joint, wherein the melt can arrive at the joint from several possible directions, nine injection ports (three per each of the three sides of the rib) are used in the injection molding analysis. The locations of these ports are denoted in Fig. 7(a) and (b) using cone-shaped symbols.

The orientation of glass fibers used as reinforcements in the polymeric (nylon 6) material is displayed as a contour plot in Fig. 7(b). The fiber-orientation plot depicted in Fig. 7(b) reveals the probability for the fiber axis to be aligned with the local 1st principal direction (defined by a line connecting the first and the second node of a finite element at hand). The orientation distribution of fibers affects the extent of orthogonality of the reinforced plastic material (i.e. a random orientation of the fibers gives rise to an isotropic material while perfectly aligned fibers yield an orthotropic material). As mentioned earlier, the fiber orientation results are combined with a micromechanics-based homogenization analysis (implemented in Moldflow), to determine the local effective mechanical and thermal properties of the two-phase (polymer + glass fibers) material. These properties are exported into ABAQUS/Standard and used to carry out a series of finite-element analyses of the mechanical response of a single polymer/metal clinch-lock joint when subjected to tensile and shear loads. These analyses are further discussed in the next section.

2.5 Structural Mechanics Analysis of a Single Metal/Plastics Clinch-Lock Joint

Once the final shape of the PMH assembly consisting of a single circular disk-shaped metal stamping with a dovetail-shaped indentation/protrusion and a matching single plastic rib is completed, a quasi-static structural mechanics analysis is carried out in order to quantify the load-bearing capability of the metal/plastics clinch-lock joint. Toward that end, the finite-element geometry of the plastics rib attained at the end of injection-molding simulations as well as the associated spatial distributions of the plastics material mechanical properties are exported to ABAQUS/Standard. This was done using in-house developed script file (written in MATLAB (Ref 11)) which reads the Moldflow .xml results files and translates them into an .imp file consistent with the ABAQUS/Standard input file syntax. To complete the ABAQUS/Standard input files, meshed geometry for the metallic stamping (with a dovetail-shaped indentation/protrusion) is added, as well as the metal-stamping material properties and the boundary/loading conditions. Simple quasi-static loading is applied in the present work which tests the ability of the metal/polymer clinch-lock joint to withstand either a normal tensile or a shear load is tested. In each case, a load versus displacement curve is recorded and the onset of joint failure recorded.

An example of the computational results obtained in the quasi-static finite-element mechanical testing analysis of the single polymer/metal clinch-lock joints is displayed in Fig. 8(a)-(c). The results displayed in Fig. 8(a) and (b) show the spatial distribution of von Mises stress in a plane passing through the axis of the joint for the cases of tensile and shear loading, respectively. The associated load versus displacement traces are shown in Fig. 8(c). For both loading cases, the load increases to a peak value (corresponds to the initiation of joint failure) and then begins to drop (as a result of further progress of joint failure). The shear load versus shear displacement results like the ones displayed in Fig. 8(c) are averaged over different shear directions in order to obtain the mean response of a single polymer/metal clinch-lock joint to shear. This was done separately for both configurations of the clinch-lock joint; that is, the one based on an impression in the metal stamping and the other based on a projection in the metal stamping. It should be noted that Fig. 8(a)-(c) contain only the results for the case of the metal stamping containing an impression.

The procedure described above yielded normal and (mean) shear load versus displacement relations for a single clinch-lock joint. They are used in the next section in which the load-bearing capability of a prototypical PMH load-bearing automotive BIW component is investigated. Due to a large number of clinch-lock joints needed to attain polymer-to-metal interconnectivity, the joints could not be modeled explicitly. Instead, the presence of a joint at a given location of the polymer/metal interface will be represented by the interfacial elements whose mechanical response will be derived using the normal shear load versus displacement relations for a single clinch-lock joint.

3. Application of the Clinch-Lock PMH Technology to Load-Bearing Automotive Components

The computational structural mechanics analysis discussed in the previous section enabled determination of the basic (tensile and shear) load versus displacement relations for a single metal/polymer joint of either of the two clinch-lock concepts. In this section, a comprehensive finite-element analysis is carried out to ascertain the potential of the clinch-lock PMH technology for use in load-bearing BIW components. The potential of this technology is assessed by comparing it with the well-established injection-overmolding PMH technology (the technology in which metal/polymer interconnection is attained through the formation of interlocking rivets and overmolded edges). This comparison is carried

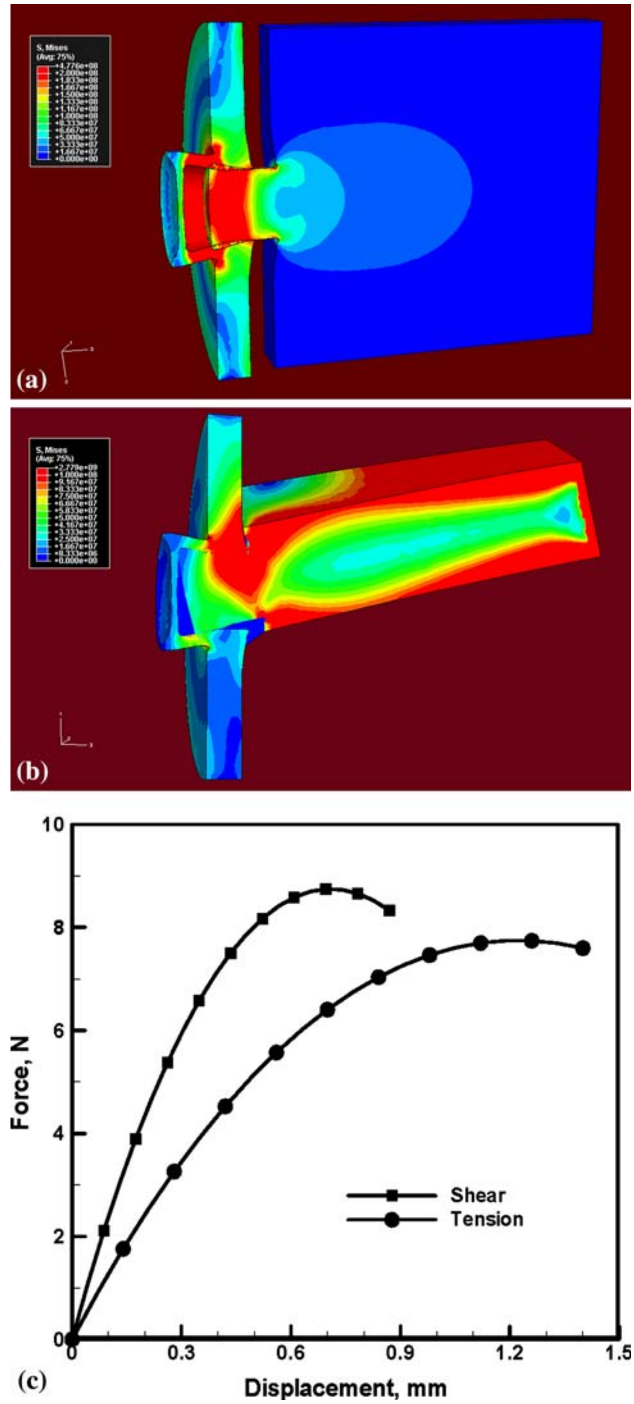

Fig. 8 An example of the results obtained in the computational analyses of tensile- and shear-load bearing capabilities of a single metal/polymer clinch-lock joint: (a, b) contour plots showing spatial distribution of the von Mises equivalent stress; (c) the corresponding load versus displacement curves

out by conducting a set of parallel analyses of the ability of the two (i.e. the injection-overmolding and the clinch-lock) technologies to delay the onset of buckling in a prototypical BIW load-bearing PMH component when subjected to a bending load. The prototypical BIW load-bearing PMH component used in the present work is displayed in Fig. 9(a) and (b). The model displayed in Fig. 9(a) is based on injection-overmolding technology while the one displayed in

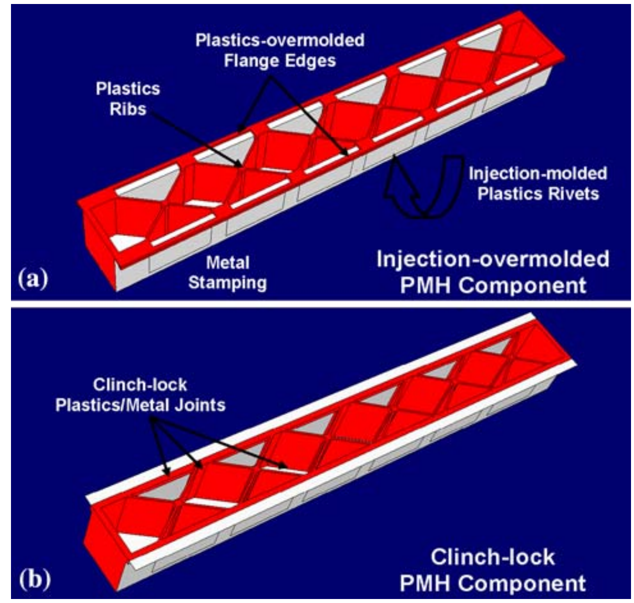

Fig. 9 A prototypical PMH load-bearing automotive component produced by the (a) injection-overmolding and (b) clinch-lock technologies

Fig. 9(b) corresponds to the clinch-lock PMH joining technology. In the case of the injection overmolded technology, the plastic penetrates the holes at the bottom of the U-shape metal stamping and forms locking buttons and, in addition, it wraps around the U-shape end and flange edges. In the case of the clinch-lock PMH joining technology, polymer/metal interlocking is attained through the use of dovetail-shaped impressions/protrusions in the metal stamping located along the contact surfaces between the plastic ribs and the metal stamping while no holes or overmolding of the edges was required.

3.1 Injection Mold-Filling and Material-Packing Analyses

Before the structural-mechanics finite-element analysis of the buckling resistance of a prototypical BIW load-bearing components produced by injection-overmolding (Fig. 9a) and clinch-lock (Fig. 9b) PMH technologies can be carried out, the fiber orientation distributions throughout the plastic subcomponents (and their effect on the mechanical properties of glass-fiber reinforced plastic) had to be determined. This was done by carrying out the injection mold-filling and the material-packing analysis analogous to those discussed in Sect. 2.4. However, in the present case, the mold cavity for the entire plastic subcomponents (as denoted in Fig. 9a, b) was used instead of the mold cavities for a small fraction of a single rib associated with the given polymer/metal clinch-lock joint. Two injection points were used in the present injection-molding analysis, one placed at the second and the other placed at the fifth X-shape inter-rib crossings (Fig. 9a, b). Except for these minor differences the injection-molding analysis carried out in this section followed essentially the same steps as the ones discussed in Sect. 2.4.

In the injection-molding analysis carried out in the present work, it was assumed that a Netstal commercial injection-molding machine Model 4200H-2150 is used with the following specifications: (a) The injection unit – maximum machine

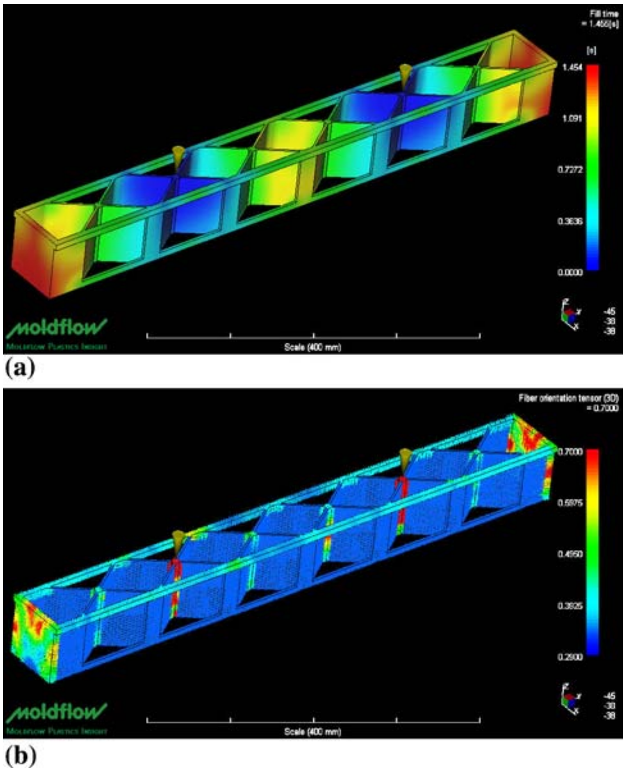

Fig. 10 An example of the results obtained in the computational analyses of fabrication of a prototypical PMH component by injection molding: (a) fill time and (b) glass-fiber orientation distribution

injection stroke = 248 mm, maximum machine injection rate = 5024 cm^3/s, machine screw diameter = 80 mm; (b) The hydraulic unit – maximum machine hydraulic pressure = 17.5 MPa, intensification ratio = 10.0, machine hydraulic response time = 0.2 s; and (c) The clamping unit – maximum machine clamp force = 3800 ton. Also, the injection molding is assumed to be done under the following process parameters: *filling stage*—melt temperature = 563 K, injection rate = 400 cm^3/s, velocity/pressure switchover at 99% volume filled; *packing stage*—time = 10 s, pressure = 80 MPa; *cooling stage*—mold surface temperature = 363 K, ejection temperature = 458 K, fraction of solid phase at ejection = 1.0; *mold material*—tool steel P20; *thermoplastics material*—Durethan BKV 130 H2.0 (an elastomer-modified Nylon 6 filled with 30 wt.% of glass fibers and heat-age stabilized).

An example of the typical results obtained in the PMH-component level injection-molding analysis is displayed in Fig. 10(a) and (b). The results displayed in Fig. 10(a) show a contour plot of the fill time and reveal that a balanced-flow condition has been attained, i.e. the locations in the mold cavity which are filled last are filled essentially at identical times. Attainment of the balanced-flow condition is critical from the standpoint of minimizing (undesirable) post-ejection component-warping effects.

The results displayed in Fig. 10(b) show the spatial orientation distribution of glass fibers. As discussed in Sect. 2.4, this information is used to compute the local effective mechanical properties of the two-phase (polymer-matrix reinforced with glass fibers) material, which are needed in the structural mechanics analysis discussed in the next section.

3.2 Structural Mechanics Analysis of Buckling Resistance of PMH Load-Bearing Components

Once the spatially dependent mechanical properties of the glass-fiber reinforced nylon 6 are computed and imported in ABAQUS/Standard, a set of structural mechanics analyses was carried out in order to investigate the potential of the two PMH technologies (i.e. the injection-overmolding and the clinch-lock PMH technologies) to delay the onset of buckling in the metal stamping when subjected to a bending load. In the finite-element computational analyses carried out in this section, adhesion between the polymer and the metal is neglected and a delay in the onset of buckling of the metal stamping is assumed to be induced by lateral constraints imposed onto the metal stamping by the plastic ribs where these constraints are the results of direct mechanical contact and interlocking between the two materials. In the case of the injection-overmolding technology, there is only one 5 mm-diameter circular hole at the bottom face of the metal stamping per each X-shape rib structure (Fig. 9a). Consequently, a detailed solid model for the plastic subcomponent can be used within which each plastic rivet is modeled explicitly. In sharp contrast, the number of polymer/metal joints in the prototypical load-bearing PMH component produced by the clinch-lock joining technology (Fig. 9b) is extremely large, joints have a complicated geometry, and their size is quite small. Consequently, the clinch-lock joints could not be modeled explicitly in the finite-element analysis of buckling resistance of the PMH component produced by the clinch-lock joining technology. Instead, each polymer/metal clinch-lock joint is replaced by a rectangular-shaped *adhesion patch* (typically a 2 mm-edge-length quadratic region within which polymer and metal are joined using special interfacial-cohesion elements). This approach was used successfully in the recent work of Grujicic and co-workers (Ref 12) and all the necessary details regarding its formulation and implementation can be found in this reference.

In the finite-element analysis of mechanical response and buckling resistance of the BIW load-bearing components displayed in Fig. 9(a) and (b) when subjected to a bending load, the flanged U-shape metal stamping is represented using ca. 30,000 three-node triangular shell elements. The injection-molded plastic rib-like structure is represented using ca. 90,000 and ca. 80,000 four-node tetrahedron elements in the injection-overmolding and clinch-lock joining PMH technologies, respectively. The adhesion patches were modeled using six-node interfacial cohesion elements whose (normal and shear) traction versus separation relations are derived using the load versus displacement relations for a typical single plastics/metal clinch-lock joint obtained in the previous section. All adhesion patches were taken to be rectangular in shape, to have identical 2-mm length and a width equal to the local thickness of the plastic rib which is being connected to the metal stamping.

Material properties for the metallic stamping are set equal to the ones for dual-phase steel as listed in Sect. 2.3, while those for the plastics were obtained by combining the fiber-orientation distribution results of the injection-molding analyses presented in the previous section for the prototypical PMH component with a micromechanical model for determination of the effective material mechanical properties. Specifically, while the initial glass-fiber reinforced thermoplastic material was isotropic, fiber reorientation during mold filling and material packing stages of the injection-molding process rendered the material heterogeneous and orthotropic. The finite-element level orthotropic material properties were determined using the aforementioned micromechanical model within Moldflow and exported to ABAQUS/Standard. A detailed account of this procedure can be found in our previous work (Ref 1).

As discussed earlier, the PMH component analyzed in the present work is a prototypical load-bearing automotive BIW component which usually fails by buckling test. The main objective of hybridization of the metal stamping in such a component using different technologies (e.g. injection overmolding, clinch-lock joining, etc.) is thus to delay the onset of buckling. In addition, the stiffness is enhanced which makes a positive contribution to the overall rigidity of BIW. To assess the effectiveness of the clinch-lock joining PMH technology in enhancing buckling resistance and stiffness of the prototypical PMH load-bearing component, a simple three-point bending mechanical test is simulated using ABAQUS/Standard quasi-static structural-mechanics analysis. Toward that end, the bottom end edges of the metal stamping are constrained in the vertical direction and the middle section (of the metal stamping only) displaced in the downward (negative z) direction. The width of the PMH component at its half-length is monitored, along with the applied load, to detect the moment of elastic instability, i.e. buckling. The load at which an abrupt increase in the width of the PMH component is observed is denoted as the component buckling resistance, while the slope in the corresponding vertical load versus vertical deflection plot is used as a measure of the component stiffness.

Typical results obtained in the three-point mechanical testing analysis are displayed in Fig. 11(a)-(d). Spatial distributions of the von Mises equivalent stress at the moment of buckling for the PMH component fabricated using the injection overmolding and the (metal-stamping impression based) clinch-lock joining PMH technologies are displayed in Fig. 11(a) and (b), respectively. A comparison between the two PMH technologies relative to the buckling resistance of the prototypical PMH component fabricated using the two technologies is displayed in Fig. 11(c), in which the width of the midsection of the PMH component is displayed as a function of the applied load. The instance of buckling is characterized by a sudden increase in the component width. The results displayed in Fig. 11(c) clearly show that the PMH component fabricated using the clinch-lock technology possesses comparable buckling resistance to that of the same component fabricated using the well-established injection-overmolding technology. It should be further noted that the weight of the clinch-lock PMH component is about 97% of the injection-overmolded component.

Figure 11(d) shows the vertical load versus vertical deflection results. Since the slope of the two curves displayed in Fig. 11(d) is comparable, it appears that stiffness of the PMH component processed using the two technologies is also comparable and that, as mentioned above, the use of the clinch-lock joining technology results in an ~3% lighter component.

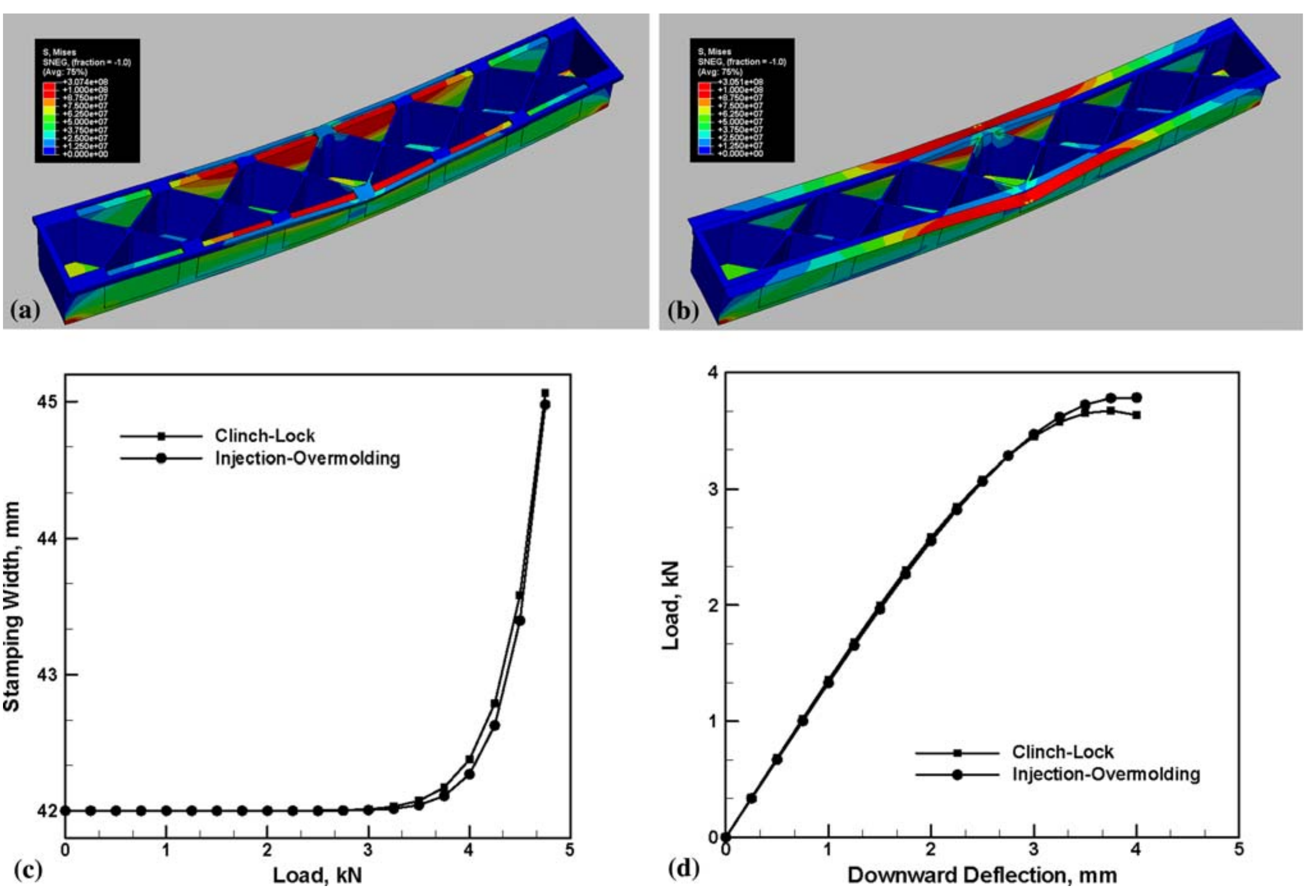

Fig. 11 An example of the von Mises stress spatial distribution results obtained in the computational analyses of three-point bending of the prototypical PMH load-bearing component fabricated using (a) the injection-overmolding process and (b) clinch-lock joining technology; (c) the corresponding stamping width versus load and (d) load versus displacement curves

The computational analyses of the mechanical performance of the prototypical PMH load-bearing BIW component considered in this section were applied to both types of the clinch-lock joining concepts, i.e. to the concept based on impressions within the metal stamping and the one based on projections on the metal stamping. In all the analyses carried out, it was found that the clinch-lock joining concept based on impressions made in the metal stamping outperforms the alternative concept.

3.3 Brief Discussion

As mentioned earlier, the objective of the present work was to assess suitability and potential of a newly developed clinch-lock joining PMH technology for use in load-bearing automotive BIW components. The main requirements placed on this technology in the present work were that: (a) no holes are created in the metallic stamping, (b) metal-stamping flanges cannot be used for polymer/metal interlocking, and (c) the performance of a prototypical PMH component with respect to its buckling resistance and stiffness is improved or, at least, maintained at the level attained with the PMH injection-overmolding technology. The results obtained in the present work are quite encouraging and suggest that all the requirements listed above are met. However, for a new PMH technology to be adopted by the automotive OEMs and the suppliers, an additional set of requirements has to be satisfied. Among such requirements the most critical ones appear to be (a) the compatibility of the new PMH technology with the BIW manufacturing process chain, (b) reliability and long-term durability, and (c) amenability to disassembly and recycling at the end of life of the vehicle. These additional requirements that the clinch-lock joining technology must meet will be addressed in our future correspondence.

4. Summary and Conclusions

Based on the results obtained in the present work, the following main summary remarks and conclusions can be drawn:

1. A new PMH technology for load-bearing automotive BIW components is proposed. The technology is based on the formation of dovetail-shaped metal/plastics joints and is appropriately named the "clinch-lock joining" PMH technology.
2. The main advantages of the new technology over the existing competing PMH technologies are that no holes in the metal stamping or overmolding of stamping flanges are required and no expensive low-energy substrate surface energy adhesive is needed to obtain the required level of polymer/metal mechanical interconnectivity.
3. A series of injection-molding and quasi-static mechanical simulation analysis is carried out in order to obtain a preliminary assessment of the suitability and the potential of the clinch-lock joining PMH technology for use in the manufacture of load-bearing BIW components.
4. While the preliminary results are quite encouraging and suggest that the new technology can successfully compete with the well-established injection-overmolding PMH process, further validation work is identified which should be carried out in order to ensure the compatibility of the clinch-lock technology with the BIW manufacturing process chain, reliability and durability of the PMH component as well as the ease of disassembly, material segregation and recycling at the end of the vehicle life.

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References

1. M. Grujicic, V. Sellappan, G. Arakere, N. Seyr, and M. Erdmann, Computational Feasibility Analysis of Direct-Adhesion Polymer-to-Metal Hybrid Technology for Load-Bearing Body-in-White Structural Components, *J. Mater. Process. Technol.*, 2008, **195**, p 282–298
2. O.J. Zoellner and J.A. Evans, Plastic-Metal Hybrid. A New Development in the Injection Molding Technology, *ANTEC 2002 Annual Technical Conference*, San Francisco, CA, 1-4, 2002
3. Plastic-Metal Hybrid Material, http://www.hbmedia.net/polymotive/polymotive/2003/01/articles/frontend1.shtml
4. D. Recktenwald, Advanced Adhesives Foster Hybrid Structures, *Machine Des.*, 2005, **77**(21), p 124–126
5. M. Grujicic, V. Sellappan, M.A. Omar, N. Seyr, and M. Erdmann, An Overview of the Polymer-to-Metal Direct-Adhesion Hybrid Technologies for Load-Bearing Automotive Components, *J. Mater. Process. Technol.*, 2008, **197**, p 363–373
6. V. Hamel, J.M. Roelandt, J.N. Gacel, and F. Schmit, Finite Element Modeling of Clinch Forming with Automatic Remeshing, *Comput. Struct.*, 2000, **77**, p 185–200
7. CATIA, Version V5R16, Dassault Systems, www.3ds.com, 2007
8. HyperMesh, Version 8.0SR, Altair Engineering Inc., www.altair.com, 2007
9. ABAQUS, Version 6.6, User Documentation, Dassault Systems, www.3ds.com, 2006
10. Moldflow Plastics Insight Version 6.1, User Documentation, Moldflow Corporation, Framingham, MA, 2006
11. MATLAB, *The Language of Technical Computing*, 7th ed., The Math Works Inc., Massachusetts, 2006
12. M. Grujicic, V. Sellappan, B. Pandurangan, G. Li, M. Erdmann, and J. Holzleitner, Computational Analysis of Injection-Molding Residual-Stress Development in Direct-Adhesion Polymer-to-Metal Hybrid Body-in-White Components, *J. Mater. Process. Technol.*, 2008, **203**, p 19–36