Journal of
Experimental and Theoretical Analyses

Review

Precepts for Designing Sandwich Materials

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Abstract: The demand for innovative materials has been a significant driving force in material development in a variety of industries, including automotive, structural, and biomedical. Even though a tremendous amount of research has already been conducted on metallic, polymeric, and ceramic materials, they all have distinct drawbacks when used as mono-materials. This gave rise to the development of nature-inspired sandwich-structured composite materials. The combination of strong metallic skins with soft polymeric cores provides several advantages over mono-materials in terms of weight, damping, and mechanical property tuning. With this in mind, this review focuses on the various aspects of MPM SMs (Metal/polymer/metal Sandwich Materials). The reasons for the improved qualities of MPM SMs have been discussed, as well as the numerous approaches to producing such SMs. This review shows the various possibilities of achieving such SMs in complicated forms via different shaping techniques and intends to highlight the properties of MPM SMs' remarkable qualities, the current trend in this field, and their potential to meet the demands of many industries.

Keywords: sandwich materials; bioinspired materials; tuneable properties; damping

Citation: Nayak, G.S.; Palkowski, H.; Carradò, A. Precepts for Designing Sandwich Materials. *J. Exp. Theor. Anal.* **2024**, 2, 31–45. https://doi.org/10.3390/jeta2010003

Academic Editor: Marco Rossi

Received: 28 February 2024
Revised: 16 March 2024
Accepted: 17 March 2024
Published: 20 March 2024

1. Introduction

The necessity of lightweight materials with good energy absorption, thermal insulation, and tuneable mechanical properties is relevant in automotive, defence, construction, biomedical, and other fields [1–5]. Interestingly, nature has already developed structures that contain such extraordinary properties. The human skull is comprised of two layers of hard bone (cortical bone), which are separated by spongy bone (cancellous bone). This sandwich structure of the skull is beneficial in protecting the brain against external impacts [6]. This structure has also been seen in other structures, such as the beak and wing bones of the bird, as can be seen in Figure 1, illustrating the clever design of nature to withstand high loads with minimum weight and achieve optimum capability. This inspiration led to the development of a special class of composite materials, i.e., "sandwich materials (SMs)", to fulfil the requirements of lightweight materials with a high stiffness-to-weight ratio [7]. Metal/polymer/metal (MPM) laminated sheets are one of the examples of such SMs, which are quite popular in the automotive sector [8]. It consists of hard metallic skin sheets with a polymeric core. MPM SMs provide a great possibility for the development of lightweight structures [9]. Depending on their combinations, MPM SMs have tremendous advantages compared to mono-materials in terms of lightweight [9], high acoustic and vibrational damping properties [10], great thermal insulation [11], high stiffness and strength [12], and ease of mechanical tunability [13].

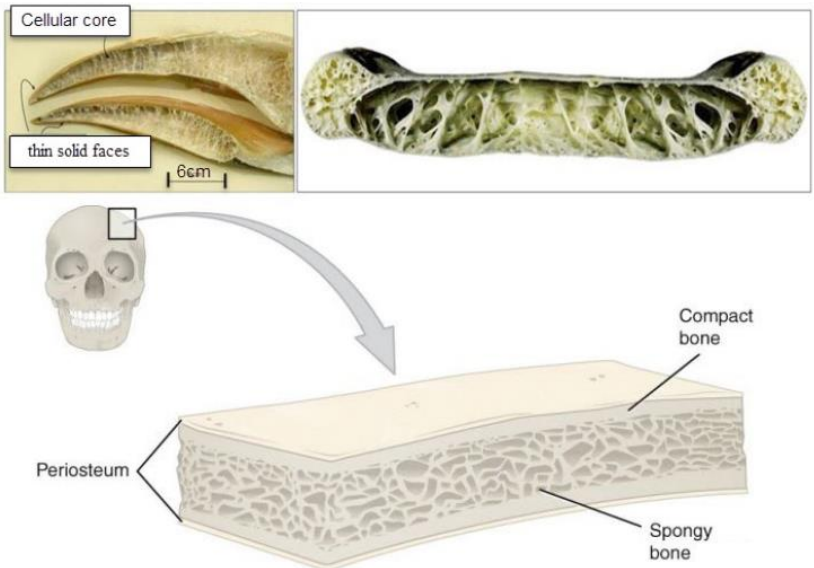

Figure 1. Examples of sandwich structures found in nature. Bird beak and wing bones composed of a cellular core and thin hard skins (**top left** and **right**); the human skull consists of compact bone skin and spongy bone as core (**bottom**) [1].

Due to these factors, the focus of this evaluation is on MPM SMs, with particular attention given to various facets of these materials and the rationale underlying their behaviour. In light of their remarkable superiority to mono-materials across multiple industries, numerous facets of SMs have been examined recently [4,5,14–18]. The initial section of this review examines the potential routes to attaining MPM SMs and then proceeds to explain the rationale behind their remarkable mechanical, thermal, and vibrational characteristics. Subsequently, it delves into the potential fabrication techniques for MPM SMs and the associated failure risk. A review of the diverse characteristics of the MPM SMs has been provided in the sections that follow.

2. MPM SMs Fabrication Routes

To start with, a viable method is necessary to achieve MPM SMs that can carry out the desired application. To fulfil that need, some manufacturing techniques are available that can be applied to the fabrication of MPM SMs. There are three possible ways to join metals with polymers: mechanical, chemical, or physical force [19,20]. Based on these possibilities, the available techniques are discussed in the following sections.

2.1. Mechanical Fastening

Dissimilar materials, such as metals and polymers, can be joined by the application of interlocking to hold them together via this technique in Figure 2. This interlocking can be provided via rivets, bolts, screws, etc., or by forming processes [20,21]. The geometric parameters and the materials used for joining the parts play a big role in the structural integrity of this technique, as any joint that is not designed properly can act as a damage initiator in the structure [22].

This technique has advantages in terms of simplicity, minimal surface preparation, and ease of joining. For transport applications, this approach is generally favoured during the manufacturing process on account of its straightforward installation, removal, and inspection [23]. However, this kind of joining always leads to stress concentration on the metallic part and can cause material damage, and if the joint is not properly sealed, it can lead to a fissure between the materials. Along with that, the interlocking medium also means an undesired additional weight [21,24,25]. In this type of joint, core buckling, shear cracking, delamination, and tensile rupture are the primary modes of failure [26].

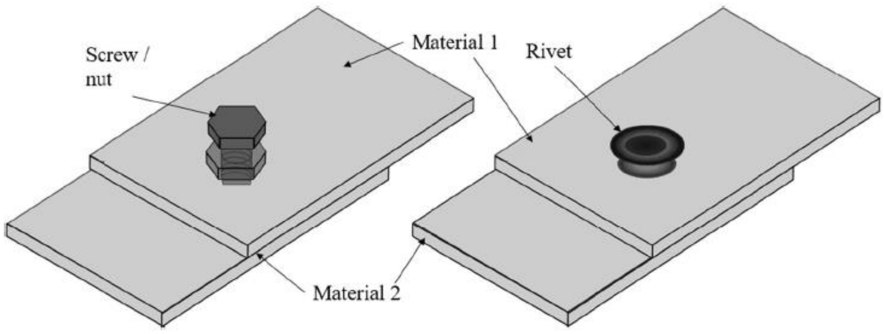

Figure 2. Metal/polymer joining via mechanical joining using a screw or nut (**left**) and a rivet (**right**) [21].

2.2. Adhesive Bonding

This is one of the most commonly used techniques for MPM SM preparation, given its ease of production and good bonding properties [8,27–29]. The general methodology for this technique, along with its application in the automotive sector, can be seen in Figure 3. This technique generally requires the application of pressure and heat to join prepared metal skins to polymeric cores using adhesive layers [8,14,30,31]. The curing of the adhesive layer at the interlayer provides the adhesion strength in the MPM SMs [25]. Various surface preparation routes can be applied to improve the metal/polymer bonding. It can be carried out mechanically by brushing, grit blasting, or grinding to increase the anchorage possibilities [32,33]. Chemical treatments such as electrochemical etching, anodisation, and the addition of adhesive promoters can all be used to improve adhesion [34,35]. Moreover, it can also be accomplished physically using techniques such as laser treatment, corona treatment, or plasma treatment [36–38]. In a recent study, X. Zou et al. demonstrated that laser significantly improved the bonding between DP590 steel and carbon fibre-reinforced plastic (CFRP) via laser treatment [36]. They found an increase of 299% in the shear strength of the DP590-CFRP-DP590 SMs, where laser treatment was applied to improve the adhesive bonding between DP590 and CFRP.

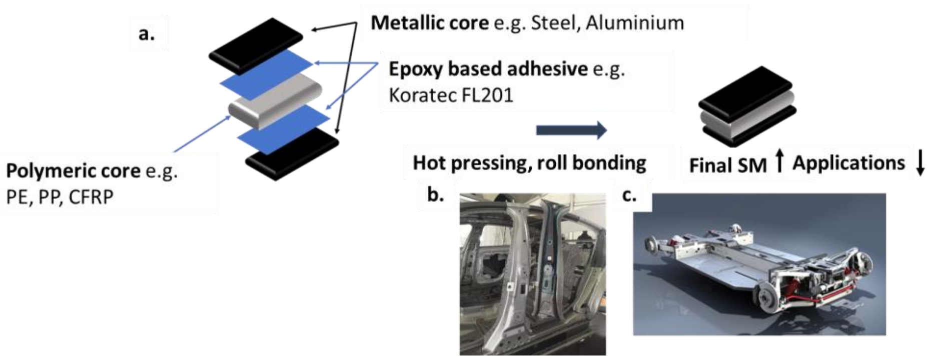

Figure 3. SMs production via adhesive bonding. (**a**) General components in SMs and processing routes; (**b**) application of SMs in preparation of B-inner reinforcement for BMW 7 series (G12) [39]; (**c**) application of SMs in a car (Inrekor, Poole, UK) [40].

Due to the excellent adhesion between metal and polymer via this technique, it is highly favoured in the automotive and aircraft industries [41,42]. This technique can also be used for the preparation of biocompatible MPM SMs for biomedical applications; however, the problem lies in the preparation route, as generally cytotoxic epoxy-based adhesives are used in this technique [27,43,44]. Moreover, adhesion via epoxy resins also carries the risk of deterioration with time due to moisture [45]. Thus, to apply this technique further for biomedical applications, a biocompatible adhesive/bonding condition is required.

2.3. Biocompatible Hybrid Joining

To achieve a biocompatible joining between metals and polymers, Reggente et al. [13,46] developed a novel strategy that can be used to prepare biocompatible MPM SMs. In this study, grafted polymers were used as adhesives, and the interpenetration of grafted and bulk polymers via fusion bonding was used to provide the necessary bonding required for processing. In this study, a "grafting from" technique was initially used to graft PMMA on Ti surfaces (Figure 4). Subsequently, Ti-PMMA-Ti SMs were prepared by joining PMMA-grafted Ti and bulk PMMA via hot-pressing. The pull-off studies of these SMs showed excellent adhesion strengths between the Ti and PMMA (20–25 MPa).

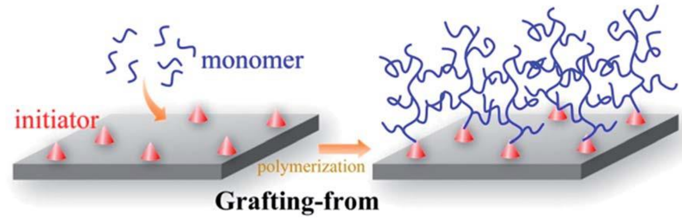

Figure 4. Schematic of *grafting from* technique for immobilising polymers on metallic surfaces [47].

Fusion bonding differs from adhesive bonding in that the adhesion strength, in this case, is developed due to the diffusion of chain segments across the interface [48,49], whereas in adhesive bonding, the chemical bonding of dissimilar materials at the interface, e.g., metal to polymer, provides the adhesion [48]. Fusion bonding is composed of two stages: (1) the intimate contact between interfacial surfaces, followed by (2) the autohesion process, i.e., the interdiffusion of the molecular chains across the interface [50,51].

Fusion bonding is illustrated in Figure 5. Intimate contact is the mechanism that happens at the initial stage (t = 0). It leads to direct and perfect contact between two polymer interfaces. At this stage, the two surfaces are pressed together. By providing a temperature above the glass transition temperature (T_g) of the polymer along with sufficient pressure, the surfaces start to have viscoelastic deformation, get in contact, and become wet [50,52–54]. Thus, the achievement of full intimate contact is dependent on both temperature and pressure [55,56].

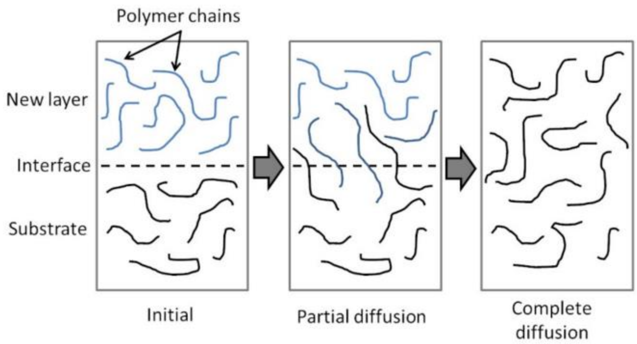

Figure 5. Stages in the autohesion phenomenon [57].

Once intimate contact is achieved, the polymer chains start interdiffusion due to Brownian motions [50,58]. At some intermediate time (t > 0), the polymer chains partially diffuse across the interface and get entangled with neighbouring molecular chains on the other side of the interface. Eventually, after a longer period of time ($t = t_\infty$), the complete interpenetration and entanglements of polymer chains are achieved, and the interface can no longer be differentiable to the bulk polymer [48]. As autohesion is dependent on the time-dependent thermal activity of the polymer chains, it is a time- and temperature-dependent mechanism [51,54,58–60].

This study opened a pathway to achieve biocompatible SMs, where the biocompatible polymer with a selectable thickness can be grafted on metallic surfaces and subsequently used in the function of an adhesive [61–63].

3. Traits of MPM SMs

In this section, the thermal, acoustic, mechanical, and formability properties of the MPM SMs are discussed, explaining the reasons behind their extraordinary properties. Along with that, the conditions that lead to failure in MPM SMs are also illustrated in the later part.

3.1. Thermal Properties

Apart from excellent strength-to-weight ratios, MPM SMs also have an advantage in terms of thermal insulation. With a proper selection of core material and its thickness, the thermal insulation of MPM SMs can be significantly improved [4,18,64,65]. The heat flow through an MPM SM cross-section can be seen in Figure 6. The temperature T_1 from the heat source gets decreased to T_2 during the process of transferring through the MPM SM due to the insulation effect of the core. Assuming the average temperatures in the skins are T_{s1} and T_{s2}, respectively, the average temperature in the core (T_c) is as follows [7]:

$$T_c = \frac{T_{s1} + T_{s2}}{2} \quad (1)$$

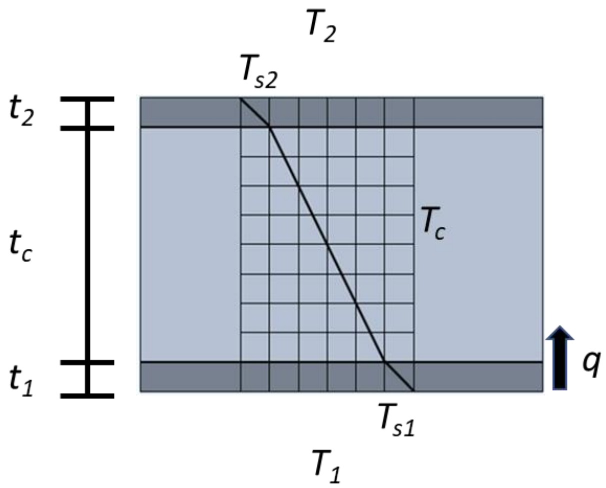

Figure 6. Schematic of the temperature field across the MPM SM cross-section.

The heat loss per unit area (q) through the cross-section is equal to the thermal transmittance (k) multiplied by the temperature difference:

$$q = k(T_1 - T_2) \quad (2)$$

where q is positive in the positive direction of heat transfer and k is the thermal transmittance of the cross-section.

In the general case of the heat flow through the body along the cross-section, (t) obeys *Fourier's law*, and q can be calculated via the following equation [66]:

$$q = -\lambda \frac{(T_2 - T_1)}{t} \quad (3)$$

where λ is the thermal conductivity of the material at a given temperature, and t is its thickness.

However, as for the general MPM SMs, thin skin metallic sheets are used, exhibiting a high thermal conductivity as compared to the thicker polymeric core with a significantly lower thermal conductivity. The q can be simplified to the following [7]:

$$q \approx \frac{(T_1 - T_2)\lambda_c}{t_c} \tag{4}$$

where λ_c is the thermal conductivity of the core and t_c *is* the thickness of the core.

Thus, with the help of a thick core of low thermal conductivity, a significant improvement in thermal insulation can be achieved. This advantage has been significantly used in the aerospace industry, as MPM SMs have been used in several components of space vehicles to provide thermal protection [67]. In a recent study, the thermal conductivity of the SS304 steel-Bakelite (Al1050) SMs was investigated [64]. A tremendous decrease in thermal conductivity was found for the SS304-Al1050 SMs. Where the thermal conductivity of SS304 was 41.31 W/m·K, it decreased to 2.93 W/m·K. This illustrates the potential of these MPM SMs in manufacturing car bodies to protect passengers from intense sunlight. In another study, the possibility of different sandwich panels for thermal protection in ships was studied via the finite element method (FEM) [68]. Steel, aluminium, and glass fibre/epoxy were used as possible skin sheets, where the core consisted of polystyrene (PS) in all cases. In this study, steel-PS-steel SMs demonstrated the best thermal loading performance.

3.2. Damping Properties

The primary mechanism for dissipation of energy in MPM SMs is the contraction and extension of the viscoelastic core as they are flexed [69,70]. As the MPM SM plate undergoes flexural vibration, the core is constrained to shear (Figure 7). This shearing action of the core causes the vibration energy to be dissipated as heat energy. The *EI* (product of Young's modulus and the moment of inertia) of the MPM SMs also plays a major role in damping vibration or sound energy. A higher *EI* of the MPM SMs leads to higher damping performance as more energy is required to vibrate them [71].

On the basis of the type and structure of the core material, various theoretical models have been developed to predict the damping behaviour of MPM SMs [69,70,72–75]. This damping behaviour can be measured in terms of acoustic or vibration damping.

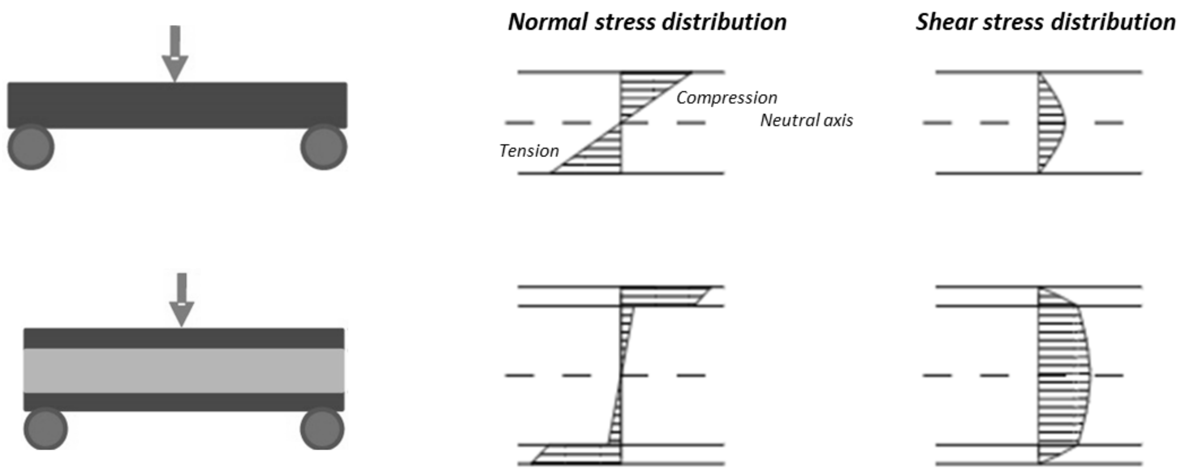

Figure 7. Stress distribution comparison between mono-material and MPM SM panels during bending. Mono-material has a linear distribution of compressive stresses on the upper side and tensile stresses on the lower side, with a parabolic distribution of shear stresses. In MPM SMs, the skins carry tensile and compressive stresses, with the core carrying the shear stresses [76].

Generally, the damping loss factor (η) is used to determine the damping behaviour of a material. It can be measured by determining the response of the material to any vibration via the half-power bandwidth method [77]. The thickness, Poisson's ratio, and density of the core material can significantly influence the damping performance of the MPM SMs [77–79]. With a thicker core, a Poisson's ratio closer to 0.5 (soft materials), and a low-density core material, the damping performance of SMs is significantly improved. Due to these advantages, MPM SMs have been extensively used in the automotive, aerospace, and marine sectors for their energy absorption potential [5,70]. In a recent study, M. Harhash et al. [80] investigated the potential of galvanised Steel–Polyolefin (PP/PE) SMs for crash box applications. In this study, the crashbox behaviour resembled that of pure steel. This showed the potential of lightweight alternatives for steel parts in automotive applications, which can reduce the weight of cars and decrease fuel consumption without compromising the quality of the car. As an interesting alternative, the work performed by J. Zhang et al. showed the possibility of the application of metal foams as cores for energy absorption applications [81–84]. In a simulation study of the energy absorption of a monolithic aluminium alloy (Al) sheet, one layer of Al-Al foam-Al SMs and two layers of Al-Al foam-Al SMs were compared [81]. It has been found out that even though for extremely low impulse, Al sheets performed better than SMs, with an increase in impulse, SMs have better energy absorption behaviour, whereas, with an even further increase in impulse, two layers of Al-Al foam-Al SMs supersede one layer of Al-Al foam-Al SMs in performance.

3.3. Mechanical Properties

Each constituent in the MPM SMs, i.e., skins, core, and interface, plays an intrinsic role in the overall mechanical properties of the structure [85,86]. The outer metallic skins, supposedly thin and of high strength, carry the loads and absorb the outward energy. The interface between skin and core offers good adhesion between skin and core to ensure smooth transmission of load from skin to core. The polymeric core plays the role of a low-density filler with sufficient stiffness to stabilise the skin layers under load. It also needs to have the necessary durability to handle processing and service conditions.

For MPM SMs, there are two established models to estimate the mechanical properties on the basis of the load direction (Figure 8). The mechanical properties of the SMs, such as Young's modulus (*E-modulus*), yield strength (Y), ultimate tensile strength (UTS), and density (ρ), can be calculated for the Voigt model using the rule of mixtures (*ROM*) formula:

$$X = f_1 X_1 + f_2 X_2 \tag{5}$$

where X is the mechanical property (E, Y, UTS, or ρ) of the MPM SM, and X_1 and X_2 are the same mechanical properties of the constituents (skin and core). f_1 and f_2 correspond to the volume fractions of the respective constituents [7,87].

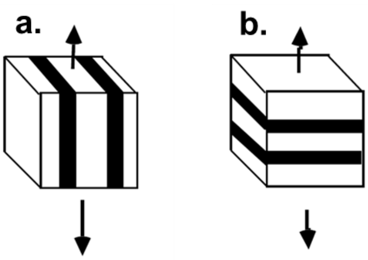

Figure 8. Voigt and Reuss models. (**a**) Voigt model, where the orientation of sandwich constituents is parallel to the applied load. (**b**) Reuss model, where the orientation of sandwich constituents is perpendicular to the applied load [88].

On the contrary, the *E-modulus* in the Reuss model is approximated via the inverse rule of mixture (IROM) [7,87,89]:

$$\frac{1}{E} = \frac{f_1}{E_1} + \frac{f_2}{E_2} \tag{6}$$

The application of ROM has been found to be successful in predicting the mechanical properties of MPM SMs [13,28,29]. In the study performed by J. G. Liu et al. [28], an excellent correlation was found for the engineering stress–strain curve determined via experiments and the results obtained by ROM for Al (AA5005)—PP SMs (Figure 9).

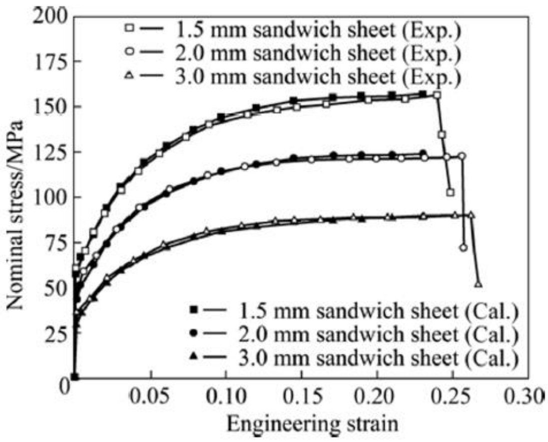

Figure 9. Comparison of engineering stress–strain curves obtained via experiment and ROM for AA5005-PP SMs [28].

However, to achieve the ideal tensile properties obtained via ROM for the MPM SMs, the bonding conditions need to be considered. In a recent study, the effect of interfacial adhesion on the tensile properties of Steel–Polyamide 6 (PA6) SMs was investigated [90]. It was found that as the adhesion strength approached perfect bonding, the tensile strength of the MPM SMs clearly followed the *E-modulus* predicted by ROM.

In the biomedical field, the major problem with metallic implants such as Ti is its *stress shielding* problem due to its high *E-modulus* [91,92]. With the help of MPM SMs, this problem can be solved, and the desired *E-modulus* can be easily achieved by adjusting the skin-to-core ratio.

Another aspect of the MPM SMs is the influence of their structure on their stiffness to bending, i.e., flexural rigidity (*EI*). For symmetric SMs with the dimensions illustrated in Figure 10, the *EI* of the MPM SM can be calculated using Equation (7) [93]:

$$EI = \frac{1}{12} E_s b (t^3 - c^3) \tag{7}$$

where E_s is the modulus of elasticity of the skin. It should be noted that this equation is valid for the condition where the modulus of elasticity of the core is (E_c) << E_s, which is generally the case for MPM SMs.

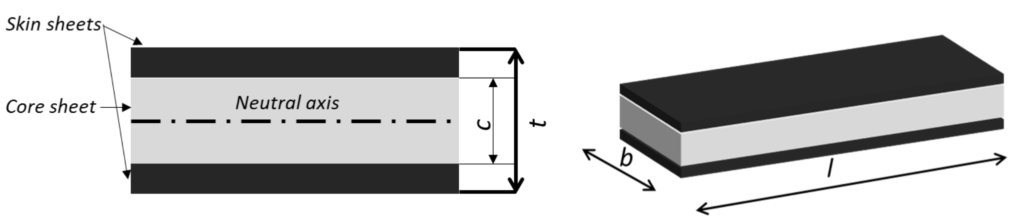

Figure 10. Dimensions of a symmetric SM for the determination of the *EI*.

The separation between the skin plates and the adhesion plays a key role in determining the *EI* of the MPM SMs. As can be seen from Equation (7), the higher the separation between skin sheets (the thicker core), the higher the *EI* of the SM. Along with that, without any adhesion, *EI* would vanish as each part would bend according to its separate neutral axis. This reasoning that provides extraordinary properties to MPM SMs in terms of *EI* is known as the *sandwich effect* [7,94]. Given this effect, for approximately the same weight as the skin material, the addition of a light core between the two halves of the skin can lead to tremendous improvement in *EI*, showing the extraordinary benefits of MPM SMs (Figure 11).

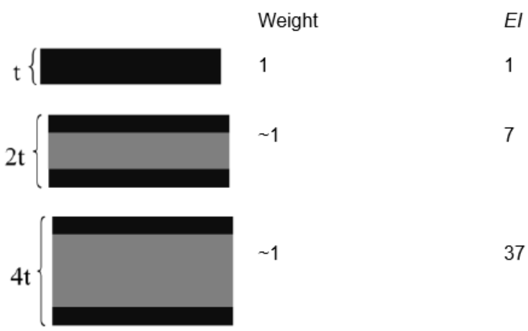

Figure 11. Comparison between mono-materials and MPM SMs in terms of weight to *EI* ratio [95].

3.4. Formability of MPM SMs

To obtain MPM SM in any desired shape, they need to have an acceptable formability. The extreme differences in the mechanical properties of metal and polymer sheets make the forming of these materials a complicated task. Several studies have been performed to understand the behaviour of these materials. In the study performed by M. Harhash et al., the strain hardening exponent (n) of the 316L stainless steel–(polypropylene-polyethylene) SMs decreased as compared to steel sheets due to the contribution of the soft core [27]. This was also seen in the recent study performed by Forcellese et al. [96], where the n value of an IF steel-PP-PE SM was found to be lower in comparison to the IF steel. Due to this reason, the formability of this MPM SM was also lower than that of the IF steel sheet. It has also been found that the formability of SMs can be improved by applying a polymeric core with a higher n value [28].

The adhesion between the metal/polymer interface also plays an important role in the formability of MPM SMs. Where a low adhesion can lead to debonding during the forming operation, a too-strong adhesion can also limit formability by preventing smooth sliding between the layers [97,98]. During the forming process of MPM SMs, the yielding in the skin sheets is compensated by the shearing of the core; the shear strength of the core needs to be proportional to the yield strength of the skin sheets to prevent the delamination of the MPM SMs [99]. Moreover, as the metal/polymer interfacial adhesion is generally negatively influenced by temperature, formability also tends to decrease if performed at higher temperatures [100,101]. Thus, for forming MPM SMs at higher temperatures, the polymer and adhesion conditions need to be carefully evaluated.

The deep drawability of the MPM SMs has been investigated in several studies [2,95,102–104]. MPM SMs have a higher tendency to wrinkle compared to monolithic metal sheets [103]. The blank holding force (F_{BH}) plays an important role in the successful deep drawing of MPM SMs. Where a high F_{BH} can lead to cracking of the outer metallic skin sheets, the risk of wrinkling increases with decreasing F_{BH} [105]. Thus, F_{BH} needs to be properly calibrated to obtain the desired results. However, the tendency to fail also increases with increasing thickness of the polymeric core [104]. With increasing thickness of the core, the tendency for cracking of the outer core also increases, as it leads to a higher thickness reduction of that part.

To minimise these problems, incremental sheet forming (ISF) can also be used for MPM SMs. In ISF, sheets are deformed progressively via localised plastic deformation using small round hemispherical deforming tools to achieve the final shape. This way, ISF allows the possibility of shaping sheets into complex forms, which can open the possibilities of MPM SMs in biomedical, aeronautical, and various other fields [106–108]. In recent studies, the formability of MPM SMs has been found to be better via ISF as compared to conventional sheet forming techniques like deep drawing [109,110]. However, the forming potential of MPM SMs is found to be 30–50% of the same-sized sheet made completely of metallic skin [111,112].

3.5. Failure Conditions for MPM SMs

The failure conditions of MPM SMs are critical to understanding and evaluating their performance for forming possibilities and applications. Generally, there are four modes of failure in MPM SMs (Figure 12). During loading, the sandwich may fail due to (a) yielding or fracture of the skin, (b) wrinkling of the skin sheet under compression, (c) fracture of the core due to insufficient shear strength, (d) skin-core layer debonding because of a weak bond or too high shear stresses. These failures are dependent on the loading conditions as well as the materials' properties and the dimensions of the MPM SMs.

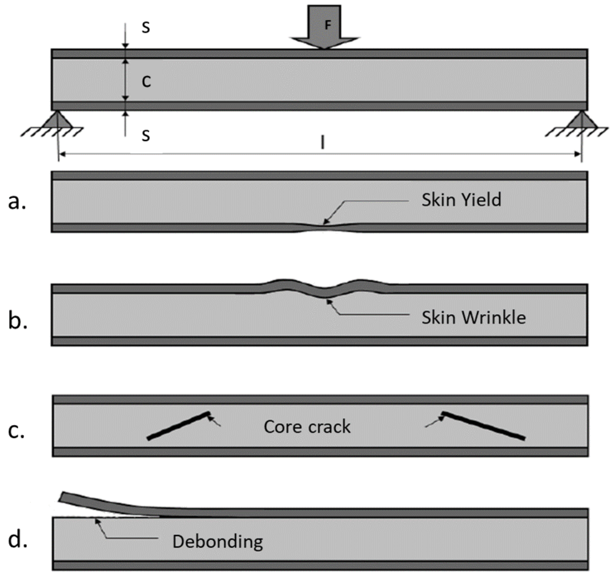

Figure 12. Failure modes of SMs under loading. (**a**) skin yielding; (**b**) skin wrinkling; (**c**) core cracking, (**d**) debonding. S: the thickness of skin sheets; C: the thickness of core; F: the applied force; l: the length of the specimen.

Skin yielding generally occurs due to the excessive tension on the bottom skins during the bending process. Skin yielding is generally replaced by wrinkling of the top skin if the shear stiffness of the core is considerably lower than the *E-modulus* of the skin sheets in its perpendicular direction. This is generally the case where the core is too thin or anisotropic, such as in honeycomb structures [113]. The core in the MPM SMs primarily bears the shear loading. Thus, insufficient shear strength of the core leads to core failure while loading. This is one of the most common failures seen in MPM SMs [7,114]. Skin-core delamination of MPM SMs is generally caused by impact loading. The huge difference in mechanical properties between the metal and polymer leads to peeling at the interface, and if the interface cannot bear the peel forces, debonding occurs [115]. This leads to a significant decrease in the stiffness of the MPM SMs, making them susceptible to buckling under in-plane compression [116].

4. Discussion

The purpose of the current review is to provide a short summary of the various aspects of MPM SMs. The general pathways to achieving these SMS have been discussed in this study. The combination of dissimilar materials, i.e., metals and polymers, can be achieved in various different ways. On the one hand, it can be simply performed with mechanical fastening, or it can be performed in a more complicated manner, such as adhesive bonding or biocompatible hybrid joining. The implementation of the technique is solely based on the intended application of the MPM SMs.

Moreover, the various aspects of the MPM SMs have also been discussed in this study. These materials have extraordinary advantages in so many different fields, which makes them excellent candidates for various applications. The thermal and energy absorption properties of the polymers, when combined with the hard metallic skins, can solve problems not only in automotive fields but, as the latest literature suggests, also in aeronautics and even in the biomedical field.

However, the formability of these materials has always been a challenging task. As it is mentioned in various publications, the dissimilarity in the properties of the materials needs a careful evaluation of the forming technique to be applied for shaping these materials. Nonetheless, recent research in the ISF of MPM SMs shows great promise in developing viable techniques to construct complicated structures from them.

Thus, the current trends definitely predict a high demand for MPM SMs in various different fields, which makes further investigation into the aspects of these materials an important and challenging task for researchers.

Author Contributions: Conceptualisation, A.C., G.S.N. and H.P.; methodology, G.S.N.; writing—original draft preparation, G.S.N.; writing—review and editing, A.C. and H.P.; supervision, A.C. and H.P. All authors have read and agreed to the published version of the manuscript.

Funding: German Research Foundation: DFG, grant no. PA 837/47-1, and French Research Foundation: ANR, grant no. ANR-18-CE92-0056.

Conflicts of Interest: The authors declare no conflicts of interest.

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