

## **Bonded metal-plastic composite structures - the future of lightweight, cost-effective performance**

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### **ABSTRACT**

With continued increases in energy costs, the trend towards weight reduction and fuel economy in the automotive industry will further grow in importance in the coming years. However, increased safety and performance are demands on which the consumer is also not willing to compromise. This paper presents a viable technology, complimentary to metals, for structural applications where stiffness, impact resistance and functional integration are combined to form a cost effective, lightweight solution. The paper examines the use of metal-plastic composite structures as a means to reduce weight while maintaining or improving performance. The metal is used where the high stiffness and strength can be exploited, while the plastic composite gives a balance of stiffness and impact resistance and enables functional integration through the formation of complex shapes in the moulding process. The combination allows the optimisation of the performance and function, per unit weight, of the application, by balancing the contribution of the metal and the plastic composite.

Polypropylene (PP)-based composites have high potential for usage in many structural applications in cars, due to the cost effectiveness combined with a good balance of properties. The availability of the matrix material and the extensive manufacturing capabilities globally for PP composites, make this an obvious choice for a broad range of OEMs and applications.

When the merits of this approach are accepted, the question remaining is how to combine these two dissimilar materials. This paper shows the benefits of the use of adhesives, which greatly reduce stress

concentrations and spread the load, compared to mechanical fastening, allowing a more efficient use of materials. The choice of adhesive is discussed in combination with the plastic and metal used. When plastics with low energy surfaces are used, such as polypropylene, several process steps are required to achieve an effective bond. A new adhesive is introduced, which was developed for such applications where metal is bonded to a PP composite to form a structural component, without pre-treatment. The performance is compared to alternative methods of joining.

Finally some examples of application development are presented and the potential for future innovation is discussed.

### **THE CASE FOR METAL-PLASTIC HYBRIDS**

One of the main advantages of plastic is the ability to mould complex shapes and integrate various functions into a single part. This eliminates parts and process steps. In an ideal world the engineer would like a material with the density and mouldability of plastic and the stiffness and strength of steel. An attempt to get closer to this ideal lead to the development of plastic composites, in various forms, to help boost the mechanical properties by adding glass, carbon fibre or other reinforcements, while maintaining the fabrication advantages. In most cases the designer has to compromise based on costs, packaging space, performance and weight to achieve an acceptable solution.

In recent years the trend has swung towards the use of metal-plastic hybrid systems. The aim here is to use the metal for the majority of the mechanical performance and combine this with the functional integration and complex shapes

which the plastic enables. This is now becoming the norm, for instance, for front-end carriers, where the metal-plastic combination form an upper cross-member to contribute to the stiffness of the car and withstand loading such as latch pull [1], [2]. Examples are to be seen on Ford, VW, Audi, Renault, Nissan and other vehicles.

The choice of plastic, metal and the means to combine the two have a great influence on the cost, performance and weight of the system. It is important to maximise the contribution of each component to find an optimum balance of mechanical performance at minimum weight and in a given packaging space, while maintaining a cost-effective solution.

### **WHICH PLASTIC?**

The initial tendency in the choice of plastic for use in structural applications is to consider a high performance composite. However, when contemplating a metal-plastic hybrid, the aim is to have the metal take much of the mechanical loading and to use a cost-effective plastic, which give a good balance of properties. While one could consider an unfilled plastic, there is a benefit to increasing the performance of the plastic component by adding a filler. The use of carbon fibre filled plastics is usually eliminated due to cost issues. Various applications on the market currently use a glass fibre filled Polyamide (PA) to obtain a good set of mechanical stiffness, strength and temperature resistance. However, in recent years the trend has been mainly toward the use of a Polypropylene (PP)-based composite [3]. This offers lower cost for a glass-filled composite, with a good balance of properties, broad market availability and a range of fabrication processes, such as injection moulding, compression moulding, in-line compounding and supply in pellet form.

### **BONDING FOR PERFORMANCE**

The choice of the most efficient method of combining the metal and plastic is very important to the performance of the hybrid system. Various methods are currently used in the market, including rivets and similar technologies, heat staking and

overmoulding, as a means to join the two dissimilar materials.

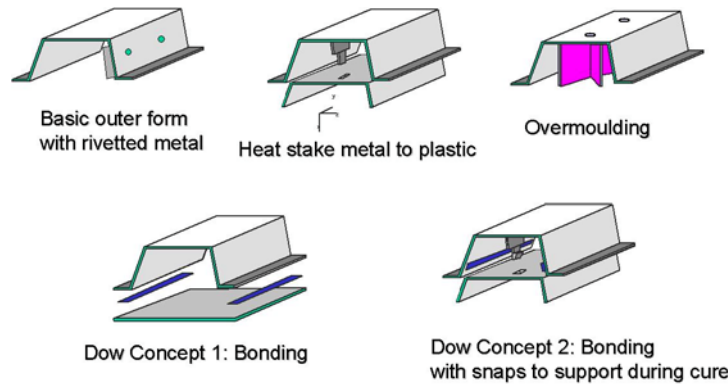
In terms of the efficiency of the joint, heat staking and rivets allow connection of the two components at discrete points only. This limits the stiffness achievable, unless the connection points are spaced very close to each other. In addition, the use of discrete points to join the parts leads to stress concentrations which limit the load bearing capacity of the structure.

Overmoulding of the plastic on a metal insert in the tool forms discrete mechanical connections where the plastic flows through the holes in the metal and allows further interaction of the materials where the plastic is formed around the metal. However, the main limitation with this approach is related to the injection-moulding process. It is not physically possible to form a closed section in a normal tool, resulting in a structure that is open on one side. To maximise the mechanical stiffness, it is very beneficial to have a closed section to obtain a high moment of inertia.

The approach proposed taken in the work presented in this paper is to bond the metal to the plastic using an adhesive, as suggested in figure 1. The adhesive enables a continuous joint between the metal and the plastic and allows a closed section to maximise the moment of inertia and hence the stiffness. A continuous joint distributes the load uniformly and reduces difficulties with stress concentrations. This increases the load bearing capacity of the structure. This gives the engineer the options to

- increase the total mechanical performance of the structure, or
- reduce the weight of the structure for the same performance as other approaches, or
- reduce the packaging space required to achieve the mechanical performance targets, or
- balance the various benefits according to the requirements.

A comparison of some of the main joining techniques was conducted on a structure which is representative of a beam section found in many applications which are required to carry load. These are presented in some detail below.



**Figure 1: Various methods of joining metal to plastic to form a hybrid structure**

### WHICH ADHESIVE?

When considering a bonded hybrid approach, the selection of the adhesive depends on the materials and process to be used and the end performance required. In general, the metal chosen is an e-coated steel, as used in many applications in the car. As discussed above PP-based composites are becoming the plastics of choice for these applications for various reasons. One of the difficulties with PP, however, is its low surface energy, which makes it difficult to bond using normal adhesives. Pre-treatment, in the form of flaming or plasma, and use of a primer are normally required to prepare the surface. This will then enable bonding, for example with a polyurethane (PU) adhesive. The pre-treatment and primer, however, do present extra process steps, costs and a question on the consistency of the quality.

In a recent development at Dow Automotive, a new adhesive system is being perfected. The adhesive, low energy surface adhesive (LESA), bonds to low energy surfaces, such as that of PP parts, without pre-treatment or primers. The initial version of this acrylic based

adhesive has been tested in prototype front-end carriers and has delivered the improvements in performance expected, based on design and structure described above. In the meantime the LESA system is being further improved to obtain the balance of properties required for many structural applications in the car, where the system will experience a range of temperatures and loading conditions.

Two LESA versions were used for this study, Dow's BETAMATE™ LESA 74020 and BETAMATE LESA 74030. The PU adhesive used was BETAMATE 2810. A summary of the important properties is shown in table I. The LESA adhesive display a range of properties, one with high modulus, low elongation and relatively high strength. The other LESA was developed to increase the elongation and balance the stiffness and strength. The PU adhesive used has a much lower modulus and strength, but greatly increased elongation. To a large extent, the properties can be tuned to needs of the application. To limit the numbers of tests, the adhesives described in table I were considered to be sufficient to give a range of behaviours.

**Table I: Main mechanical properties of the adhesives used in the study**

Adhesive	Elastic Modulus (MPa)	Tensile Strength (MPa)	Elongation at Break (%)
BETAMATE LESA 74020	2200	17.2	1.0
BETAMATE LESA 74030	1000	13.8	60
BETAMATE 2810 PU	7	8	200



**Figure 2: Basic plastic beam used in testing**

## TESTING

To compare the various technologies to form a metal-plastic composite structure, a beam geometry was chosen which has been used in the past for similar experiments and various other technologies [4]. The basic plastic beam geometry is shown in figure 2. The plastic parts were moulded in Dow's DLGF 9310.00Z, a 30% long-glass fibre reinforced PP (LGF-PP30) with a nominal fibre length of 11 mm before processing. These parts were designed primarily for torsional loading with cross-ribs. To form a closed hybrid section a metal plate was joined to the plastic beam along the two flanges, using various methods (see figure 3):

- Rivets
- Bonding using Dow's PU adhesive BETAMATE 2810
- Bonding using Dow's BETAMATE LESA 74020
- Bonding using Dow's BETAMATE LESA 74030.

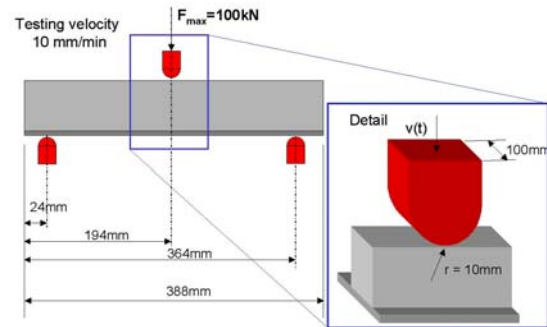


**Figure 3: Test hybrid beam with metal attached using adhesive and rivets**

The plastic beam and the metal-plastic hybrid beam were tested in static bending and torsion conditions, to compare the stiffness of the structures and for comparison with other technologies in the literature. In addition, the parts were tested

using a high-speed impact conditions in bending to determine the behaviour under dynamic loading, similar to crash. This test was designed to put the joint between the metal and plastic under severe loading and test the limits of the technologies.

In all cases a series of tests was conducted and the average data was used for comparisons.



**Figure 4: Static bending test setup**

## STATIC BENDING TEST

The static bending test was set up as shown in figures 4 and 5. Two variations of the test were conducted, one loading from the "top" (plastic) side and the other from the "bottom" (metal) side.

The parts were tested to failure and the force deflection curves were recorded. When loading from the top the LGF-PP30 underwent local deformation due to the localised stresses caused by the low diameter of the loading head. Thus, particular deflection of the hybrid beam deformation relates to localisation effects. Loading from the bottom resulted, finally, in failure in tension of the LGF-PP30 at the opposing face. No failure of the adhesive or rivet regions was observed. Parts after failure are shown in figure 6.



**Figure 5: Static bending test equipment**

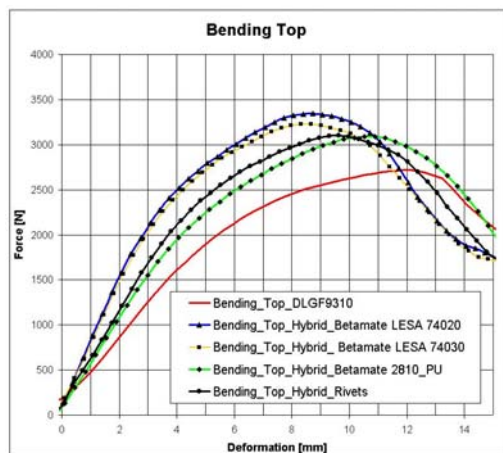


**Figure 6: Parts after static bending test**

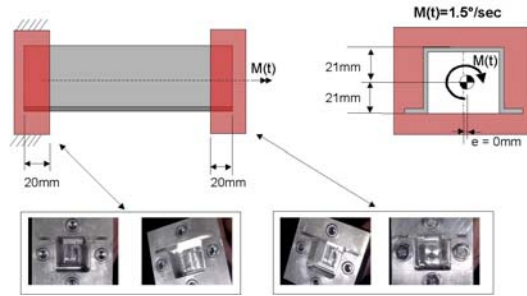
The results of the various bending tests, for loading on top, are shown in figure 7. The hybrid beam was not optimised for bending, so the bending stiffness is not as high as it could be with modified design. However, in this case, it is interesting to compare the various effects of the joining technology used. The basic plastic beam curve serves as the baseline to demonstrate the improvements in stiffness brought by attaching the metal.

The hybrids with the LESA show the highest stiffness and load bearing capacity. The PU adhesive and the riveted hybrid beams show approximately the same performance. The PU adhesive used has a low modulus, as described above. The bond-line thickness was 2mm, compared to a bond-line of approximately 1mm for the LESA hybrids. The change in stiffness of the hybrid in bending with change of elastic modulus of the adhesive, at a given bond-line thickness, is not large.

The results of bending from the bottom showed similar trends with regard to the ranking of the various techniques. The details are not presented here for the sake of conciseness.



**Figure 7: Force-Deflection Results for Static Bending on Top**

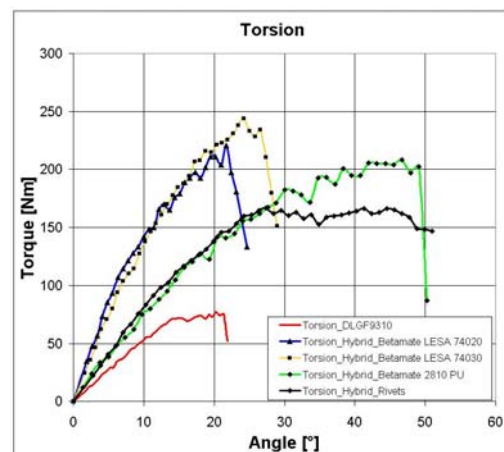


**Figure 8: Setup for torsion testing**

### STATIC TORSION TEST

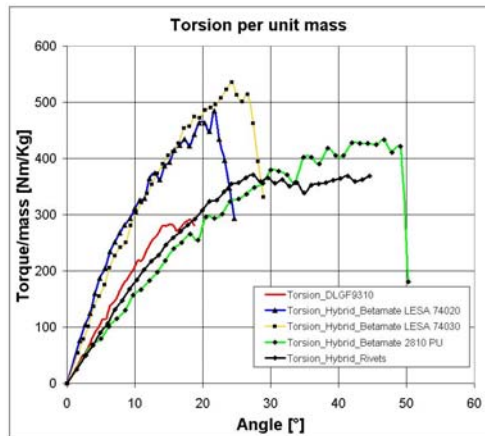
The torsional test was conducted by clamping one end of the beam and applying a torque to the other end, as shown in figure 8. The curves of torque versus angle of rotation were recorded.

In this case the total stiffness of the structure is high, due to the design of the part and the hybrid structure. The torque-angle curves are shown in figure 9. By using the BETAMATE LESA to form a hybrid metal-plastic structure, the stiffness is increased by 300% and the total load bearing capacity is increased by 200%, compared to the straight LGF-PP30 part. The hybrid with the BETAMATE LESA 74030 shows a slightly lower stiffness than BETAMATE LESA 74020 initially, but has a slightly higher load bearing capacity. The hybrids with PU adhesive and rivets have similar stiffness performance, but the load bearing capacity with the BETAMATE 2810 PU adhesive is higher.



**Figure 9: Torque-Rotation results in static torsion**





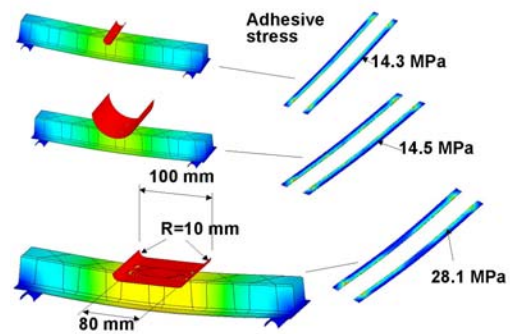
**Figure 10: Torsion results per unit mass**

When we consider the torsional stiffness per unit mass, the results look different, as shown in figure 10. It is then clear that the stiffness and load bearing capacity for the hybrids bonded with BETAMATE LESA are higher for each kilogram that is used. In a car, this means that the stiffness can be increased, or the overall weight can be reduced compared to other technologies.

#### IMPACT TESTING

The static stiffness of components is normally important in automotive applications to improve the daily performance of the car, whether it is for improved handling or other regular functions. However, the engineer must also design for events such as crash or misuse, where impact loading can cause failure. In many cases the components should contribute to the energy absorption in crash and when they fail there should be no sharp fragments which can cause injury to occupants or others. The metal component is normally used to withstand the majority of the loading, without fracture, and it is normally desirable that the plastic does not separate from the metal. For this reason, a series of impact tests was also conducted to ensure that the developments in the area of bonded-hybrid composite structure will fulfil these strenuous requirements.

The goal of the testing was to put the joining technology to the test. To set up an efficient test, CAE simulation was used to design the impactor and the test setup. The parts were loaded in bending and the impactor shape and size was determined through simulation, as in figure 11.



**Figure 11: Computer-aided Engineering (CAE) to design impactor to apply stress at the joint**

The impactor and test setup was then developed according to the dimensions determined from the CAE analyses. The parts were impacted with a 13 Kg mass at 7.1 m/s, which corresponds to 327.7 Joules. This energy is in the order of the energy expected when one considers a pedestrian impact at the bonnet leading edge of a car, where such a structure might be used as part of the front-end carrier [5]. However, this is applicable for many other applications.

The impact event was filmed in each case and some snapshots are shown in figures 12-16 for the various beam and hybrid structures.

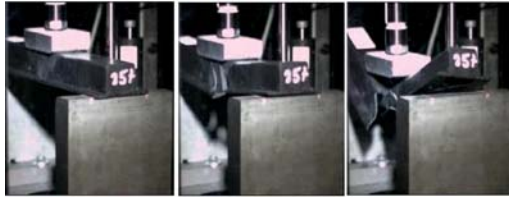
The LGF-PP30 beam, as expected broke in two with various fragments.

The riveted hybrid quickly developed crack initiated at the rivets and eventually part of the plastic separated, also with various small fragments.

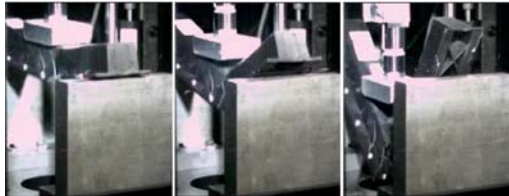
The hybrid bonded with the PU-based adhesive remained intact with some small fragments of plastic.

The hybrid bonded with BETAMATE LESA 74020 showed separation of part of the plastic and there were fragments of plastic and adhesive.

The best results were achieved with BETAMATE LESA 74030, where the parts remained intact, with some small fragments of plastic, but a very stable structure. No fragments of adhesive were observed and there was no failure around the bond-line.



**Figure 12: Impact of LGF-PP30 beam**



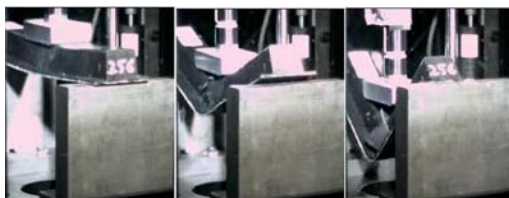
**Figure 13: Impact of hybrid with rivets**



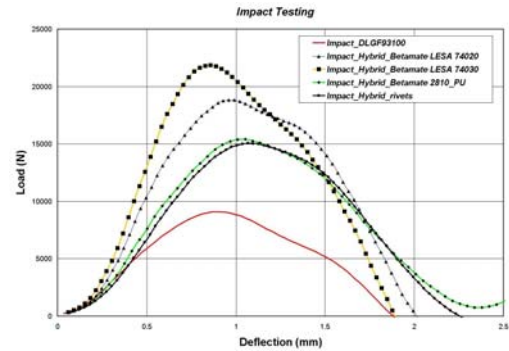
**Figure 14: Impact of hybrid bonded with BETAMATE 2810 PU adhesive**



**Figure 15: Impact of hybrid bonded using BETAMATE LESA 74020 adhesive**



**Figure 16: Impact of hybrid bonded using BETAMATE LESA 74030 adhesive**



**Figure 17: Force deflection curve for impact loading (first peak)**

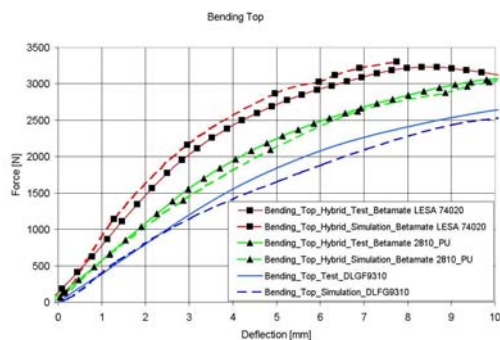
The force deflection for all tests was recorded. Due to the dynamic nature of the load, there was an oscillation in the load during the event. The loads for the first peak are shown in figure 17. Again the hybrid structures with the BETAMATE LESA adhesive exhibit the greatest stiffness and loads. The riveted hybrid and that with the PU-based adhesive are quite similar in load behaviour. In the first oscillation of the impact, the hybrid with BETAMATE LESA 74030 absorbs 2.5 times the energy of the DLGF9310 part. However, the energy absorption throughout the event is not discussed in detail here, because the goal of the test was to load the joining technology to the limits and not to design an energy absorber.

## **APPLICATION AND MATERIAL DEVELOPMENT**

The data above give the engineer insight into how hybrid structure, particularly bonded metal-plastic composite hybrids behave. The development of real applications and the improvement of materials is based on these experiences and the understanding of the materials and the application requirements. The BETAMATE LESA 74030 is suitable for most structural applications and is being further developed to take into account other needs for structural applications in the car.

The understanding of the composite plastic material and the combination with the adhesive and metal to form a hybrid structure is critical for application development. The current trend towards the elimination of prototyping in application development pushes the engineer to extend the boundaries of CAE and

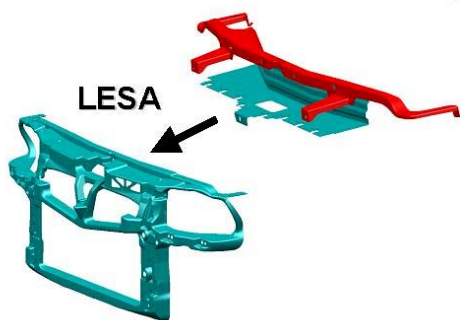
simulation, so that the design can be completed virtually, before any steel is cut to form a mould. The work presented above is also being used as a basis to further develop this capability. This is especially challenging when injection-moulded composites are combined in bonded structures. An example of the simulation of the bending of the hybrid beam, discussed above, is shown in figure 18, compared to the actual test values. The correlation is good and such simulations are currently being used in application development.



**Figure 18: Load-Deflection curves for bending. Comparison of simulation and test results.**

The understanding of the behaviour of these composites is being further developed to master the simulation of damage and failure.

An example of an application, which applies the principle of bonded hybrid metal-plastic composites, is shown in figure 19. This part, a DOW Automotive development based on the VW Golf 4 front-end, was produced to compare to a production part and demonstrated a stiffness increase of 40-100% and a weight reduction of 19% [2].



**Figure 19: Front-end system constructed as bonded hybrid metal-plastic composite.**

## FUTURE INNOVATIVE SOLUTIONS

It is expected that very soon the bonded hybrid metal-plastic composite structure will appear on the market in structural applications in the car. In the coming years it will gain widespread use in automotive applications, where a combination of structural performance and functional integration is required. Examples of such applications include front-end systems, roof modules, tailgates, door modules, seating and instrument panels.

## CONCLUSIONS

The data above shows the advantages of thinking out-of-the-box when approaching application development. The bonded structure described above enables lighter designs and improved performance. In addition the newly developed adhesive enables bonding directly on composites with low surface energy, without pre-treatment. This reduces the costs of the bonding process. In addition, the ability to bond to PP-based composites with this adhesive enables the use of more cost-effective composites.

The stiffness of the adhesive has a relatively limited effect on the static behaviour of the structures investigated. The effect is seen mainly when the elastic modulus is several orders of magnitude smaller. The static behaviour of the structure with the BETAMATE LESA 72020, with an elastic modulus of 2200 MPa, was not significantly different to that with the BETAMATE LESA 74030, with an elastic modulus of 1000 MPa. However, when we consider the case of impact loading, the elongation at break plays an important role. For this reason an adhesive with a high elongation at break is preferred.

The development of applications based on this technology will also benefit greatly from the capability to model these systems and conduct virtual prototyping. This will reduce the overall development cost and lead to more efficient design.



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