Fail-safe composite-cast metal structure and method.

A method for manufacturing a structural component (100) includes forming a groove (104) in an outer surface of a fibre-reinforced body (102). Molten metal is introduced to an exposed surface of the groove (104) and to a predetermined portion of the outer surface of the body (102). The cast metal (106) is cooled in a controlled manner to thermally alter sufficient resin (103) in the body (102) so as to create a secure interconnection of the cast metal (106) on the body (102). The cast metal (106) adjacent the groove (104) is sized so that it will fail prior to separation of the cast metal (106) from the body (102) under excessive tensile loads. A portion (108A) of the cast metal (106) remains on the body (102) so that elongation of the component significantly exceeds ultimate elongation of the fibre-reinforced body (102) and the cast metal (106).
The present invention relates generally to a method of die-cast moulding a metal directly onto a fibre-reinforced plastics body to form a structure as specified in the preamble of claim 1, for example as disclosed in EP-A-0 501 537. In particular, a structure formed pursuant to the method of the present invention includes a pre-selected failure site to control separation of the cast metal from the plastics body when the structure is subjected to excessive tensile loads.

Links, generally formed as elongated metallic members having eyelets on each end, are well-known in the automotive industry. In particular, links are used to connect various components in a suspension system. In use, a link can be subject to compressive, tensile and shear loads.

It is desirable to substitute lighter materials for traditional metals such as aluminium in order to form links. Fibre-reinforced plastics, typically referred to as FRP hereinafter, may find increasing usage in the automotive industry, despite its higher cost, because of its high strength-to-weight ratios. However, one problem with substituting FRP for metal in any automotive component is the fact that it is difficult or impossible to form FRP into shapes that are convoluted or discontinuous. Thus, FRP may serve well for use in making a drive shaft, which is an elongated tube of constant cross-section, but not for use in making a transmission case, with its labyrinthine internal passages.

Another limitation is that many automotive components must be attached directly to another metal component at some point, which may require that the FRP component be provided with a localised metal fastening member. For example, an FRP drive shaft must have a metal connector at each end for attachment to the remainder of the drive line. It is difficult to successfully and securely mate FRP directly to metal, especially when the attachment point will be subject to heavy loading and stress. Many patents are directed just to the problem of joining metal end pieces to FRP drive shafts, most of which disclose procedures which involve the use of various adhesives, rivets, splines or combinations thereof.

The designer of an FRP link would face both problems noted above. The main body of a link is basically a rod or beam with a fairly constant cross-section and a smooth exterior surface, presenting no particular protrusions or discontinuities. This is a basic shape that would lend itself well to FRP manufacture. A matrix of full-length, reinforcing glass fibres soaked with a conventional thermosetting resin is formed in a mould with the desired beam shape, and then heat-cured. However, each end of the beam must be connected to other structures, e.g., between a suspension support and a wheel assembly support. Die-casting a metal eyelet directly to the end of an FRP beam would be preferable, in terms of time, cost and strength, to attaching a separate connector by adhesive or mechanical means. However, the thermosetting resin that binds the glass fibres together decomposes badly at the melting temperatures of suitable metals, such as aluminium alloy. Tests that subjected FRP to molten metal for times comparable to the cycle times involved in standard die-casting operations found such severe thermal decomposition of the resin as to conclude that the process would not be feasible.

A particular aspect of a joint between an FRP body and a metal must be addressed when the component is subject to tensile loads. Under excessive tensile loads, the metal may completely pull away from the FRP member. If the component is a link, e.g., an FRP rod connected to a metal eyelet, complete separation of the eyelet from the rod under excessive tensile loads is unsatisfactory.

A method of increasing the ultimate elongation of a cast structural component according to the present invention is characterised by the features specified in the characterising portion of claim 1.

The present invention comprises an improved method for making a structure in which metal is die-cast directly onto a fibre-reinforced plastics body. Thermal alteration of the binding resin results in a bonding interface between the FRP body and metal. Furthermore, the structure is formed so that, if excessive tensile loads are incurred, a pre-selected failure will occur in the metal prior to the complete separation of the metal from the FRP body. This pre-selected failure provides a safety factor in load-carrying applications such as links since the bonding interface between a portion of the metal continues to resist separation from the FRP body.

The present invention includes a method for manufacturing a structural component including the step of forming a groove in an outer surface of a fibre-reinforced body. Molten metal is introduced to an exposed surface of the groove and to a predetermined portion of the outer surface of the body. The metal is cooled in a controlled manner so as to thermally alter sufficient resin to create a secure interconnection of the metal with the body. The metal adjacent the groove is sized so that it will fail prior to separation of the metal from the body under excessive tensile loads. A portion of the metal remains on the body so that elongation of the component significantly exceeds ultimate elongation of the fibre-reinforced body and the cast metal.

The invention and how it may be performed are hereinafter particularly disclosed with reference to the accompanying drawings, in which:
Figure 1 is a perspective view of a moulding apparatus illustrating a pair of larger master dies designed to contain a pair of smaller unit dies, which are removed for ease of illustration;

Figure 2 is a perspective view of a shot-chamber that feeds a charge of molten metal into the moulding apparatus of Figure 1;

Figure 3 is plan view of one of the unit dies designed for the master dies of Figure 1, illustrating a cavity machined therein;

Figure 4 is a sectional view of two unit dies spaced apart, illustrating the plane in which they part;

Figure 5 is a perspective view of an FRP body;

Figure 6 is a sectional view of the FRP body of Figure 5, taken along the line 6-6 of Figure 5;

Figure 7 is a sectional view of the two unit dies of Figure 4 closed together with the FRP body of Figure 5 supported between them and extending into the mated cavities thereof;

Figure 8 is a cross-sectional view taken through the unit dies of Figure 7 after injection of metal around the end of the FRP body of Figure 5 and schematically showing the heat flow therefrom;

Figure 9 is a plan view of the completed part, showing a flow of melted resin that has squeezed out of the FRP-metal interface;

Figure 10 is a cross-sectional view taken along the line 10-10 of Figure 9, showing schematically the interlock of the cast metal with the fibres exposed at the surface of the FRP body;

Figure 11 is an actual photo-micrograph taken with a scanning electron microscope at approximately 250X magnification, showing an enlarged circled portion of the interface of Figure 10;

Figure 12 is a perspective view of a link having a FRP rod and a pair of opposite eyelets, each eyelet having a neck receiving the rod;

Figure 13 is a sectional view taken along the line 10-10 of Figure 9, showing schematically the heat flow therefrom;

Figure 14 is a view similar to Figure 13, illustrating the fracture of the neck due to extreme tensile loading and the retention of the rod in the remaining neck portion;

Figure 15 is a perspective view of a vehicular suspension system illustrating the link of Figure 12 connecting a knuckle and spindle assembly to a suspension cradle; and

Figure 16 is a graph schematically illustrating the elongation of the link of Figures 12-15, marked to indicate the fracture of the neck at Xa and the separation of the rod from an outer portion of the neck at Xs.

A moulding apparatus for use with the present invention is illustrated as a cold-chamber, die-cast-
drilled in the body 36 to match the locator pins 32 of unit die 28.

The temperature-sensitivity and responsiveness of the fibres 38 and resin 40 as compared to metal 24 is important. Metal 24 is a standard 380 aluminium alloy, which is commonly used in die-casting, and which has a melting-point of 660 °C (1220 °F). Whilst the glass fibres 38 can withstand such a high temperature, this temperature is substantially beyond the temperature that the resin 40 could be expected to withstand without suffering very significant decomposition, even to the point of total structural failure of the part. In fact, tests showed that a sample like body 36, when dipped into molten aluminium for a time comparable to a normal moulding cycle time, did suffer debilitating thermal decomposition. Thus, it was expected that an untreated, unprotected part like body 36 would never survive having molten aluminium die-cast to it. Nevertheless, a method for doing so was developed and is described next.

The basic steps of the present die-cast moulding method are illustrated in Figures 7 and 2. Firstly, body 36 is supported within the cavity 30 by unit die 28 by inserting locator pins 32 through holes 42. Then the unit dies 26 and 28 are closed together. Whilst most of the length of body 36 is closely contacted and pinched-off by the inner surfaces of the cavities 30 in the unit dies 26 and 28, an end of the body 36 extends freely into the enlarged ends of the mated cavities 30. An unobstructed chamber is thereby created that completely surrounds the end of body 36. The interior surfaces of the enlarged ends of the mated cavities 30 are close to the exterior surface of the end of body 36, so the surrounding chamber they create is symmetrical, with a basic thickness of 3.175mm (one eighth of an inch), as measured perpendicular to the surface of body 36. Next a charge of molten metal 24 is forcibly pushed in to the chamber from shot chamber 20 by plunger 22, and fills the chamber around the end of body 36 completely in less than a tenth of a second. Non-illustrated vents and wells in the unit dies 26 and 28 are provided to accommodate the displaced air as the molten metal 24 enters the chamber around the end of body 36 under pressure.

As can be seen in Figure 8, an inner jacket-like envelope is established at the interface of metal 24 with the external surfaces of body 36, and a surrounding outer jacket-like envelope is established at the interface between metal 24 and the inner surfaces of the cavities 30. A relatively rapid outer heat flow from molten metal 24 to the unit dies 26 and 28 is immediately established at the outer envelope, which is visually represented by the longer arrows in Figure 8. The radially-outward heat flow from molten metal 24 results from the large heat-sink mass of the unit dies 26 and 28 and the master dies 12, an effect that is aided by the circulation of cooling water through water lines 14 and water passage 34. Water is pumped through at a flow rate of approximately 75.71 dm³ (20 gallons a minute). Heat flow from the molten metal 24 is also kept rapid and even by the relative thinness of the filled volume around the end of body 36, and by the symmetry of the volume described above.

The unit dies 26 and 28 are kept closed for about ten seconds, during which time the metal 24 cools to about 260 °C (500 °F) and solidifies. The steady-state operation temperature of the unit dies 26 and 28 has been measured to be about 177 °C (350 °F).

The end product is illustrated in Figure 9. After ten seconds, the unit dies 26 and 28 are opened and the completed part, consisting of body 36 and now-solidified metal end member 44, is ejected and water-cooled to room temperature. After removal of the completed part from the unit dies 26 and 28, a black substance is sometimes observed to ooze out and solidify in a small, shiny pool indicated at 46 at the joint between the surface of body 36 and metal end member 44, which is further explained below. Clearly, the body 36 has not decomposed or burned to the point where it has been eaten through or has fallen off, but its response to heavy loading is more important as to proof of production feasibility. In fact, the completed part is not used as an actual component, but as a tensile test specimen to indicate that feasibility. It is held by the holes 42 in a test machine and a measured pulling force applied to metal member 44. Tensile loads of approximately 6227.51 N (1400 pounds) have been achieved. A component like a wiper arm would have a body shaped much like body 36 and a metal end connection member similar to member 44, which could be later drilled, machined, splined or otherwise shaped. This is impressive evidence of production worth. Two phenomena are thought to contribute to the success of the process and the strength of the metal-to-body bond. One is clearly the rapid and even cooling of the molten metal 24, which protects the body 36 from excessive damage. Even more important, however, is what happens at the inner envelope, described next.

The action at the interface between molten metal 24 and the exterior surface of the end of body 36 is illustrated in Figures 8-11. The heat flow out of molten metal 24 is not so rapid that no heat flows radially inward therefrom to the surface of body 36. Instead, a radial inward heat flow to the surface of body 36 is established, represented by the shorter arrows in Figure 8. Just as with the outward heat flow, the rate is kept relatively even by the symmetry of the surrounding volume. Whilst
the temperature at the metal-FRP surface interface has not been directly measured, it has been observed from laboratory tests that resin like resin 40 begins to decompose at between 371 °C and 427 °C (700 °F and 800 °F). It appears that the temperature at the surface of body 36 must approach that temperature, because it is clear from two observed phenomena that some of the resin 40 at the upper surface layer of body 36 does decompose, a phenomenon represented by the phantom line in Figure 10. One observation is the solidified outflow 46. This is clearly melted or otherwise liquefied resin 40, at least in part, since it is not metal and the glass fibres 38 will not melt even at the melting temperature of the metal 24. More telling is what is observed by cutting, polishing and observing the interface under magnification, as seen in Figures 10 and 11. The resin 40 has clearly degraded over a layer varying from about 30 to 70 micrometres in thickness, exposing some of the fibres 38. The metal 24 has clearly flowed amongst and around the exposed fibres 38, creating a secure interlock and interconnection therewith.

While it is clear that it does occur in fact, the exact mechanism of the thermal degradation of resin 40 is not exactly understood. It apparently gasifies, and in some cases at least, condenses and liquefies again, witness pool 46. Clearly, the decomposition process is limited in effect and depth, as it does not structurally threaten the part. An important factor in the control and limitation of the level of thermal decomposition is the rapid and even cooling of the metal 24 so that not too much resin 40 is lost. Another controlling and limiting factor may well be the exposed layers of fibres 38 themselves acting as insulation against the heat, and the fibre content of body 36 is relatively high. Other control factors may be the exclusion of air by the close fill of the molten metal 24, or the pressure that it is under. It is very significant that the thermal decomposition process is limited and controlled, by whatever mechanism, as opposed to being prevented altogether. A logical approach, knowing that the molten metal 24 was far hotter than necessary to induce rapid thermal decomposi-

tion of the resin 40, would be to try to prevent it from occurring at all, or at least substantially, by more rapid cooling, or by deliberate heat insulation and protection of the outer surface of body 36 over that portion to be contacted by molten metal 24. In fact, this was tried with various thermal barrier materials, such as stainless steel flakes and silica, which were also test-cast with a metal having a lower melting temperature. Whilst thermal loss of resin was substantially prevented, the metal-to-FRP surface joint was not nearly so strong.

Variations of the process should be possible within the basic outlines disclosed. Most broadly conceived, the idea is to introduce molten metal directly to the surface of the FRP part, and then cooling and time-limiting its contact sufficiently to expose a top layer of reinforcing fibres around which molten metal may flow and interlock with. As disclosed, the molten metal is introduced in surrounding relation to an external surface of an FRP part, but it could conceivably be poured directly into a concavity in the part, with no mould, and cooled by some other means. More could be done to adjust the characteristics of the FRP fibres and resin to the molten metal and vice-versa so as to achieve the desired result, such as by increasing the fibre content at the surface, or experimenting with different metals, temperatures, or even surface coatings that provide some, but not a complete, thermal barrier. For example, it is thought that the shrinkage of the cooling aluminium around the end of body 36 aids in creating the bond. Other metals might shrink even tighter. Each designer will undoubtedly experiment with different cooling rates, metal thicknesses and cycle times so as to achieve the optimum level of the resin degradation and metal interlock that has been discovered here.

Whilst the symmetry of the chamber surrounding the end of body 36 aids in even-cooling, asymmetric shapes could be moulded, as well. Judicious placement of cooling lines could be used to control the cooling rate. Therefore, it will be understood that it is not intended to limit the invention to just the embodiment disclosed.

Whilst body 36 was designed as a tensile test specimen, an automotive link formed according to the die-cast moulding method described above is indicated generally at 100 in Figure 12. The link 100 can be designed for compressive and tensile loading, and can be adapted for a variety of applications, including between a knuckle and spindle assembly 122 and a cradle 124 in a vehicular suspension system 120 as illustrated in Figure 15. Such a suspension link 100 is a load-bearing member subjected to alternating tensile and compressive forces during operation of a vehicle. Various elastomeric bushings (not illustrated) and fasteners (not illustrated) can be used to secure each end of the link 100 to a desired support.

The completed part, i.e., the link 100, includes an elongated rod 102. The rod 102 is a FRP body made with full-length glass reinforcing fibres 101 in a thermo-setting resin 103. The rod 102 is preferably formed by a pultrusion process. In this process, continuous fibres 101 are pulled into a resin wet-out bath where the fibres 101 are saturated with liquid resin 103. Then the fibres 101 are drawn from the bath through a squeeze-out die, which controls the fibre/resin ratio, and into a heated final forming die where the thermo-setting resin 103 hardens and cures. The solid composite material
thus formed is pulled out of the final forming die by in-line pulling units which grip the composite material and work in tandem to pull the material through the entire process continuously. A flying cut-off unit cuts the composite material into predetermined lengths.

A circumferential groove 104 is provided at a predetermined depth and width near each end portion of the rod 102. Preferably, the rod 102 has a smooth, continuous outer circumference and the groove 104 is a uniform channel cut in the circumference. However, other rod cross-sections and groove configurations are within the scope of the present invention.

A casting is formed as an eyelet 106 in unit dies similar to unit dies 26 and 28, wherein the unit dies have suitably formed cavities. Each eyelet 106 includes a neck 108 to accept a predetermined length of the rod 102. Each groove 104 is cut in the rod 102 so that the neck 108 extends past the groove 104 for a predetermined distance. Webs 110 can be provided on the outer surfaces of the eyelet 106 and neck 108 to strengthen the casting.

Molten metal 24, such as a standard 380 aluminium alloy, is introduced into unit dies supporting the rod 102 according to the die-cast moulding method disclosed above. As the molten metal 24 solidifies, an annular projection 114 is formed in the inner periphery of the neck 108 which extends radially inwardly to completely fill the groove 104. The resin 103 at the outer circumference of the rod 102 and the exposed surface of the groove 104 undergoes thermal alteration and exposes glass fibres 101. As described above, even cooling of the molten metal 24 protects the rod 102 from excessive damage. The joint formed between the projection 114 and the grove 104 and between the rod 102 and the neck 108 is referred to hereinafter as the "interlocking region".

Figure 13 schematically illustrates tensile loading in the link 100 during use thereof. The tensile load in the eyelet 106 is indicated by arrows 116 and the tensile load in the rod is indicated by arrows 118. This tensile loading produces mechanical stresses in five locations within the link 100. Bending stresses present in eyelet 106 are illustrated at 120. Tensile stresses in the neck 108 are illustrated at 122. Tensile stresses in the rod 102 are illustrated at 128. Shear stresses 126 are present in the portion of the rod 102 from the annular projection 114 to the end of the rod 102. Shear stresses 124 are present in the annular projection 114.

Stress in any material causes the material to elongate. If the elongation exceeds the ultimate elongation of the material, the material will begin to crack and fail. Both materials used to fabricate the link 100 have a low ultimate elongation and are brittle materials. The aluminium at eyelet 106, neck 108, and annular projection 114 has an ultimate elongation of 3%. The FRP in the composite rod 102 has an ultimate elongation of 2.5%. A brittle material tends to fail very rapidly after a crack forms.

It would be expected that if the stress at any one of the five locations within the link 100 caused the respective ultimate elongation in the material to be exceeded at that location, the respective material would crack and rapid failure would result. However, failure at a selected site of the five locations does not exhibit a rapid, brittle failure. The present design is intended to create failure at this selected location during extreme tensile loading of the link 100.

The location in the link 100 which does not exhibit a rapid, brittle failure during extreme tensile loading is the portion of the neck 108 located adjacent the annular groove 104. At this location tensile stress 122' and shearing stress 124' are present in the aluminium. In addition the sharp corner of the annular groove 104 creates a stress-concentration factor which amplifies stresses 122' and 124'. Thus, the portion of the neck 108 adjacent the annular projection 114 is made weaker than the eyelet 106, the rod 102 in a tensile mode, and the rod in a shear mode.

Under high tensile loading, a crack 130 develops in an inner surface of the neck 108 adjacent projection 114 and propagates to the outer surface of the neck 108, eventually causing an inner portion 108A of the neck 108 to break away from an outer portion 108B of the neck 108 as illustrated in Figure 14. However, the fracture of the neck 108 does not result in immediate separation of the rod 102 from portion 108B. As schematically illustrated in Figure 16, tensile loading of the link 100 increases to F_A, at which point the neck 108 fractures into portions 108A and 108B after an elongation of X_A. Subsequently, a varying force is required to pull the rod 102 from the outer neck portion 108B for a total elongation of X_B. As the rod 102 pulls away from the outer portion 108B of the neck 108, a chamber 132 is formed.

A significant amount of energy is required to completely separate the eyelet 106 from the rod 102. This is due to the penetration of the aluminium alloy into the composite material as described above. Testing has shown the amount of elongation of the link 100 is much greater than the ultimate elongation of the materials it is made from. The ultimate elongation of the aluminium alloy is 3% and the ultimate elongation of the FRP is 2.5%. As shown in Figure 16, the link 100 undergoes significant elongation prior to separation. For example, the original length of a tested link was 330mm. Separation of the rod from the outer neck portion...
The above disclosed interlocking joint provides a controllable failure mode in the event of extreme tensile loading of the link. The neck 108, groove 104, and projection 114 can be varied as desired to provide a selected load at which failure begins to occur. The length of the rod 102 behind annular projection 114 can be varied to provide a selected amount of energy to separate the portion of the casting 106 and 108B completely from the rod 102.

Although the present invention has been described with reference to a preferred embodiment thereof, workers skilled in the art will recognise that changes may be made in form and detail of that embodiment without departing from the scope of the invention as claimed hereinafter.

The disclosures in United States patent application no. 002,449, from which this application claims priority, and in the abstract accompanying this application are incorporated herein by reference.

Claims

1. A method of increasing the ultimate elongation of a cast structural component (100) which comprises the steps of: forming an elongated main body (102) comprised of a matrix of heat-resistant reinforcing fibres (101) bound together by a less heat-resistant resin (103); introducing a molten metal (24) to a predetermined portion of the outer surface of the main body (102) extending beyond an end of the main body (102) so as to establish a direct contact interface between the metal (24) and the main body (102); and cooling the metal (24) to a sufficient degree and for a sufficient time such that the molten metal (24) solidifies whilst simultaneously thermally altering sufficient resin (103) at the direct interface to expose a layer of reinforcing fibres (101) around which some molten metal (24) flows to interlock with the exposed fibres (101) and thereby create said secure interconnection therebetween.

2. A method of increasing the ultimate elongation of a cast structural component (100) according to claim 1, in which the cast structural component is a load-bearing link (100), and the method comprises the steps of: providing a rod (102) formed from said matrix of heat-resistant fibres (101) bound together by said less heat-resistant resin (103); forming said annular groove (104) in an outer surface of the rod (102) at said pre-selected distance from the end of the rod; supporting the rod (102) in a mould cavity (30) having a desired shape including a neck portion (108) surrounding the groove (104) in the rod (102) and a portion extending beyond the end of the rod (102); introducing said molten metal (24) into the mould cavity (30) so that an interface is formed with the mould cavity (30) and at the groove (104) and at a portion of the outer surface of the rod (102) adjacent the groove (104); and cooling the cavity (30) to a sufficient degree and for a sufficient time such that the molten metal (24) solidifies at the mould cavity interface whilst simultaneously thermally altering sufficient resin (103) at the groove (104) and the outer surface interface so as to expose a layer of reinforcing fibres (101) around which some molten metal (24) flows to interlock with the exposed fibres (101) and thereby create said secure interconnection therebetween.

3. A link assembly (100) comprising: a rod member (102) formed from a matrix of heat-resistant reinforcing fibres (101) bound together by a less heat-resistant resin (103) and a casting (106) formed from molten metal (24) introduced to and cooled on the rod member (102) so that an interface is formed between the metal (24) and the fibres (101) as the resin (103) is thermally altered, characterised in that the rod member (102) has an annular groove (104) formed therein at a pre-selected distance from an end of the rod member; and the casting (106) includes a neck (108) surrounding a portion of the rod member (102) adjacent the groove (104); an annular projection (114) filling the groove (104) and forming an interface with exposed fibres (101) in the groove (104), and an connection member formed at a terminating end of the neck (108) and extending beyond the end of the rod member (102).

4. A link assembly according to claim 3, in which the connection member is formed as an eyelet.

5. A link assembly according to claim 3, in which the rod member (102) is an elongated member of substantially uniform cross-section.