# Use of Fiber Reinforced Plastics in cartridge valves manifold

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### Abstract

The concept of the work presented starts from the fact that since years, the fluid power industry is basing its performance on metallic materials and components, reaching a high level of performance. Nevertheless, some constraints hinder further development in terms of high weight of stainless steel components, or limit in the use of environmentally friendly operating fluids for the oxidation of metals. The use of lighter material (Fiber Reinforced Plastics – FRP) in fluid power applications could perform a substantial development of the energy efficiency tanks to weight reduction and to optimization of fluid-dynamic of hydraulic circuit components, and consequently, a reduction in environment emission caused by off-road machine. In the paper presented here the authors handle the numerical simulation of a fluid power manifold for a cartridge valve. Starting from the numeric analysis of the actual (metallic) part, the authors have performed a numerical re-design, using fiber reinforced plastics as base material, with the aim of having the same metallic manifold's strain. The results are encouraging and show the limits and the advantages connected to the FRP use in fluid power components.

KEYWORDS: fiber reinforced plastics, manifold, numerical simulation.

### 1. Introduction

"In most cases, real breakthroughs in the energy sector can only come from progress in basic materials science that underpins energy technologies", this sentence, which is at the base of the presented work, is taken from one of the FP 7 call focused on the application of new materials in the industry world. For years the fluid power industry has based its performance on metallic materials and components, reaching a high level of performance, but clashing with some constraints hinder further development in terms of:

- High weight of stainless steel components that is in contrast with energy saving policy;
- Limit in the use of environmentally friendly operating fluids for the oxidation of metals;
- Bulky components when manufactured in cast iron or steel, leading to energy losses in passive parts of work cycle (70% of the operation);
- Difficulties and cost constraints in procurement of raw materials with strong dependence on seasonal and geo-political questions;
- High cost and difficulties in recycling materials due to the presence of mutually incompatible parts.

The FRP (Fiber Reinforced Plastics) are used since years in the chemical industries, thanks to their resistance to a lot of aggressive substances, in low pressure (10-20 bar) application. The use of this kind of material is virtually inexistent in the fluid power world. There is a shortage of scientific studies on this topic, but recently something begin to be presented in the fluid power conferences /1/, /3/ and scientific journals /2/, and the application of FRP in low-middle pressure fluid power applications (30-80 bar) seems could be done /4/, /5/.

A typical cast-iron directional valve block with many modules for a mid-size hydraulic excavator can weigh as much as 300-400 kg, with all the disadvantages and problems in mounting, assembling, maintaining and dismounting. The same component in FRP, with similar performances, could weigh less than 100 kg (even less when appropriately optimized). This saving in dead weigh will allow a substantial reduction in energy consumption of a mobile machine, a more rational mass distribution in the machine and greater flexibility in the design feature, no longer limited by the stringent requirements of the cast-iron production process. The paper aims to contribute to exploit the potential of non-metallic materials in order to make their use in fluid power industry possible and aims also to contribute to developing a new generation of components (pumps, motors, valves, actuators) made of reinforced plastics, a material that is nowadays used only for seals and, partially, hoses.

# 2. The Fiber Reinforced Plastics

The FRP, also known as Technopolymers are a special part of the polymer family. A polymer consists of repeating units of monomers (individual molecules) that combine to form a long chain. The polymers may consist of a single type of molecule (known as a homopolymer) or may be combinations of more than one molecule (known as a copolymer).

A major class of polymers known as thermoplastics may be re-melted, as opposed to thermosets, which form irreversible crosslinks between polymer chains. Within the thermoplastics category, there are amorphous and crystalline polymers. Amorphous polymers have random orientation of their polymer chains, whereas crystalline polymers form highly ordered crystal structures within an amorphous matrix (**Figure 1**). The term semi-crystalline polymer is used for polymers containing both crystalline and amorphous regions.



Figure 1: Schematic scheme of amorphous (left) and semi-crystalline (right) polymer

Polymers are often used in combination with other ingredients to make a useful product. The combination of polymer and additives is often referred to as a plastic, the combination of reinforcement and polymer is referred as composite, if the fibers are organized into the space, or FRP if the fibers are randomly distributed. Typical ingredients used to produce FRP are fiberglass, mineral, heat stabilizers, flame retardants and other processing aids. Fiberglass reinforcement provides strength and stiffness particularly as the temperature is increased beyond the polymer glass transition temperature (Tg), where the amorphous region becomes mobile.

The fluid power applications require polymeric materials able to work at high temperatures with a low sensibility of their mechanical properties to the temperature variation. From the wide range of products available on the market, two are chosen for the aim of this work: the Amodel A-1145 HS made by Solvay S.A. and the Ultrason E 2010 G6 made by Basf Corporation. Both the considered technopolymers can be moulded in an injection molding machine, reducing the production costs tanks to the possibility to almost eliminate the machining phases necessary, on the contrary, for the metallic manifolds.

### 2.1. Amodel A-1145 HS

Amodel resins are classified in the general chemical family known as polyamides. Polyamides can be produced from a wide variety of acids and amines, and a number of polyamides are commercially important. The mechanical properties, in function of the temperature variation, of these material are reported in the **Figure 2** and **Figure 3**.



Figure 2: Tensile strength variation as a temperature function



Figure 3: Tensile modulus variation as a temperature function

As showed in previous figures the semi-crystalline grades of Amodel PPA resins have good mechanical properties and good thermal performance, so they can be used to simulate the cartridge valve manifold. The polymer A 1145-HS is reinforced with 45% of glass fibers by weight and has a specific weight of 1,59 g/cm<sup>3</sup>.

### 2.2. Ultrason E 2010 G6

Ultrason is the trade name of a BASF family products including polyethersulfone (Type E), polysulfone (Type S), and polyphenylsulfone (Type P) plastics. It comprises products for injection moulding and extrusion, as well as powder products for solution processing. This material has a high strength (**figure 5**), good stiffness (**figure 4**) and toughness, thanks to its amorphous structure; these properties are kept over a wide temperature range as reported in the following figures. The Ultrason E 2010 G6 is reinforced with 30 % of glass fibers by weight and has a specific weight of 1,60 g/cm<sup>3</sup>



Figure 4: Tensile modulus variation as a temperature function



Figure 5: Tensile strength variation as a temperature function

#### 2.3. Creep analysis

The major difference between plastics and the more traditional materials is the timedependent viscoelastic behaviour of polymers. Plastic parts under load relax with time if they are maintained at a controlled deformation (stress relaxation), or they continue to deform if they are held under a constant load (creep). Creep is the continued extension or deformation of a plastic part under continuous load. It results from the viscoelastic flow of the polymer with time. Creep is probably the most widely studied long-term property. In general, glass and mineral/glass reinforced grades creep less than the unreinforced grades. The time required to observe measurable creep will also be shorter for the unreinforced grades. Creep data are usually expressed as "apparent creep modulus" as a function of the logarithm of time under constant load (assumed to be constant stress). Remembering that modulus is the ratio of stress over strain, therefore, apparent creep modulus is the constant stress divided by the actual measured strain. Apparent, or creep, modulus will decrease at elevated temperatures with a corresponding increase in creep deformation. Therefore, to evaluate creep properties, strain is measured as a function of time while a specimen is subjected to a constant load at specified environmental conditions. The procedure followed to determine the creep behaviour is described in ISO 899-1/2:2003 (Plastics --Determination of creep behaviour).

To consider the creep behaviour in our study the apparent creep modulus, instead of elastic modulus, has been used. The **table 1** shows the different creep modulus

measured applying 34,5 MPa for 1000 hours at three different temperatures (23°C; 125°C; 175°C). These values have been introduced in the software "ANSYS 13" to simulate the real manifold deformations after a constant use at high temperature.

Table 1			
	23°C	125°C	175°C
A 1145-HS	13 GPa	4,2 GPa	2,8 GPa
E 2010G6	8,2 GPa	N.A.	5,8 GPa

Table 1: Apparent creep modulus

# 3. FEM analysis

# 3.1. Metallic manifold simulation

As first step a reference (metal made) manifold for cartridge valve has been simulated, to evaluate the main deformation due to the hydraulic pressure. The manifold dimensions have been taken from a producer data sheet: it is 76,2 mm long, 57,2 mm wide and 25,4 mm high. The manifold, showed in the **figure 6**, has four different holes to connect the hydraulic lines: the cartridge valve is inserted in a <sup>3</sup>/<sub>4</sub> inch hole which go through the entire body; on the left side there are two different output holes of <sup>1</sup>/<sub>4</sub> inch and 3/8 inch respectively; on the right side there is another 3/8 inch output hole (not visible in the image).



Figure 6: The reference manifold

The reference manifold could be made in steel or in aluminium, in the first case it weighs about 700 g, in the second case it weighs about 250 g. It has been simulated considering both the materials and a hydraulic pressure of 250 bar. The materials characteristics and the maximum radial deformations are reported in the **table 2**.

Table 2			
	Elastic modulus	Hydraulic	Maximum radial
		Pressure	deformation (250 bar)
Steel	200 GPa	250 bar	0,006 mm
Aluminium	70 GPa	250 bar	0,018 mm

Table 2: Mechanical characteristics and maximum deformations of metallic manifold

# 3.2. FRP manifold

One of the main error, which could be done when a plastic made thing have to be designed, is to consider the same shape used with metallic materials. On the contrary starting from a blank paper is the best solution in most of case. This approach is as correct as the production methodology differs from that used for the metallic components. In this work we have considered the manifold as an "hole collector" so we started the design work from the following image.



Figure 7: New consideration of cartridge manifold as a "holes collector"

Than following the common design rules to design plastics components /6/, /7/, /8/, /9/ specific ribs have been developed on the new manifold.



Figure 8: Cartridge valve with helicoidal ribs

To give a uniform reinforcement distribution on the manifold surface the authors have chosen to develop a helicoidal rib (**figure 8**). The form has been developed trying to reduce the radial deformation of plastic manifold to that of metallic part. The ribs are 8 mm height and 1 mm wide; the helicoid has a pitch of 4 mm along the holes axis. The plastic ribbed manifold weighs about 57 g considering both the polymeric materials.

# 4. Results

The use of technopolymers to make a cartridge manifold appears feasible. The calculated radial deformation, at 250 bar, show the A 1145-HS ability to have a lower deformation, at ambient temperature, compared to aluminium. Despite the use of ribs to reinforce the structure, none of the selected materials is able to reach the steel performance. The polymeric materials show (**table 3**) a radial deformation amount with the temperature, as expected. The greater radial deformation, with an hydraulic pressure of 250 bar, is 0,16 mm using A 1145-HS and 0,11 mm using E 2010 G6, approximately one order of magnitude greater compared to aluminium and two order of magnitude greater compared to steel. Nevertheless is authors' opinion that this deformation range is reasonably inside of the seals deformation tolerance. The metallic manifold radial deformations don't change with the temperature increase because metals don't show creep behaviour at these temperatures.

Table 3				
	A 1145-HS	E 2010 G6	Steel	Aluminium
23 °C	0,013	0,09	0,006	0,018
80 °C	0,09	0,1	//	//
120 °C	0,16	0,11	//	//

Table 3: Radial deformation at different temperatures (250 bar)

The results obtained considering a lower hydraulic pressure (**table 4**) show the ability of technopolymers, also at higher temperatures, to have radial deformation comparable to that measured in the aluminium manifold at 250 bar.

Table 4				
	A 1145-HS	E 2010 G6	Steel	Aluminium
23 °C	0,011	0,021	0,001	0,004
80 °C	0,019	0,024	//	//
120 °C	0,038	0,026	//	//

**Table 4:** Radial deformation at different temperatures (60 bar)



Figure 9: Stress distribution at 60 bar

Considering the material strength point of view the ribbed manifold shows, at 60 bar, a maximum stress lower than 50 MPa (figure 9). This value remain almost constant

considering different materials and temperatures. Naturally this value is due to a stress concentration factor, because the internal manifold geometry has not be changed from the original one. Modifying the manifold internal geometry it could be possible to still reduce this value. However the recorded stress is lower than break stress of considered materials at 120°C (120 MPa for A 1145-HS; 90 – 100 MPa for E 2010 G6).

#### 5. Conclusions

In the previous pages a "cat was set among the pigeons". Starting from the finite element analysis of the actual (metallic) part, the authors have performed a numerical re-design, using fiber reinforced plastics as base material. The main aim is to have a manifold strain, considering a low-middle working pressure and a temperature range between 23°C and 120°C, comparable to that of metallic manifold. The creep behaviour of technopolymers has been taken into consideration in the FEM simulation using the creep modulus instead of the elastic modulus. The results are encouraging. They show the limits and the advantages connected to the FRP use in fluid power components. The radial deformation of polymeric manifold amounts with the temperature, as expected. Considering an hydraulic pressure of 250 bar and a temperature of 120°C, the maximum radial deformation is 0,16 mm using A 1145-HS and 0,11 mm using E 2010 G6, approximately one order of magnitude greater compared to aluminium and two order of magnitude greater compared to steel. Considering a hydraulic pressure of 60 bar the calculated radial deformation in the polymeric manifold is of the same order of magnitude of that calculated for the aluminium manifold at 250 bar. This is true both at ambient and high temperatures. Finally the recorded stress is lower than break stress (at 120°C) of considered materials.

The results show the ability and then the possibility to use these kind of materials to make lighter and cheaper cartridge manifold usable in the mid-low pressure applications.

The work presented here is only a first step to design a useful plastic manifold for cartridge valve, but more work is necessary to reach the final destination. Experimental test will be necessary, injection moulding simulation should be done to consider the difficulties to have the proposed ribbed manifold shape. All these aspects will be studied in future works.

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