THE MANAGEMENT METHODOLOGY USED FOR THE INTRODUCTION OF NEW "ECO –FRIENDLY" MATERIALS WITHIN MEDIUM VOLTAGE SWITCHGEAR SYSTEMS.

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ABSTRACT

This paper discusses the interaction between the design methodology, the fabrication and the qualification necessary for the introduction of an alternative "environmentally friendly" thermoplastic tie rod into switchgear equipment.

The mathematical procedures used for the selection of thermoplastics, in order to satisfy the technical and environmental requirements of the tie rod, will be outlined. Various models using computer aided design for favourable thermoplastics will be illustrated and their influence on the processing of injection moulded prototypes subjected to specific mechanical and electrical tests will be demonstrated.

INTRODUCTION

AREVA T&D /DRC wish to replace certain materials within their products, which could be regarded as environmentally unfavourable and which could pose an economic threat to their future prosperity. At first sight the replacement of these materials may appear to be relatively easy based solely upon environmental considerations. However what this paper wishes to demonstrate is how the selection procedure is a more complicated interaction between properties, design, processing and end performance and that an in-depth understanding and appreciation of the overall material science and technology is necessary in order to achieve any degree of success.

DEMONSTRATOR

The interaction of these various tasks is best illustrated by the replacement of an existing tie rod (Fig 1), cast from a silica filled epoxy and configured in the shape of a cone having metal inserts moulded at each end. It is located within a range of pole-mounted SDR (Switch Disconnector Railway) switches, but having a specific rating here of 25 kV for the railway network. The tie rod's function is to fulfil two purposes:

- as an electrical insulation barrier between the vacuum interrupter bottle and ground
- as a means to transmit the mechanical movements of the actuator to the mobile contact of the vacuum interrupter.

The intention is to replace this thermoset with an alternative material that could potentially be recycled and be less impact to the environment during its full working life cycle.

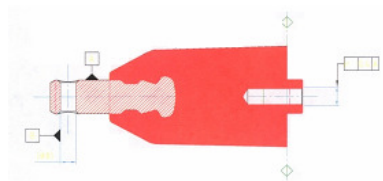

Figure 1: Tie rod of a pole mounted switch

MATERIAL SELECTION

A simplified flow diagram (Fig 2) illustrates the various tasks performed in trying to choose a successful candidate. It is not proposed to discuss the costs here but obviously they do have a bearing on the final selected candidate.

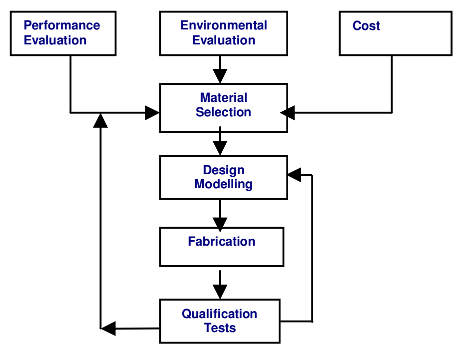

Figure 2: Flow diagram showing the selection and development methodology

Environmental Evaluation

The evaluation of materials based upon their environmental impact covers many complex issues. In order to comply with the standards, legislation and simplify many of these tasks the environmental performance of materials was analysed using a computer software tool [1]. This tool is based on the product Life Cycle Assessment, which permits a quantitative environmental evaluation by using eleven different pollution burdens dealing with products and processes. Different mathematical methods were used to categorize the various materials in an order of selection priority [2]. Needless to say it is not the intention to address these issues here but just to give some insight of the background knowledge required.

Functional Performance Evaluation

Design specifications are normally available for any component used within a switch disconnector as they define the minimum performance that must be maintained. Clearly the overriding importance is that any alternative material selected for the tie rod must still be capable of satisfying all these functional requirements without the possibility of failure in service. Each of these functional requirements was given a degree of importance denoted by a weighting of 1 to 5, the highest value the most critical for service operation. The relationship between the intrinsic properties, functional requirement and its importance are shown in Table 1. In order to determine whether any replacement material would be technically better or worse than the existing epoxy, a principle of ranking was devised based upon a fuzzy performance summation mathematical model [3].

Survey and Potential Candidates

When different materials were studied for their technical and environmental performances [4], the outcome gave a preferential order of merit. Since many of these candidates were thermoplastics, which had the greatest potential for recycling, it was decided to examine a suitable design for injection moulding these types of materials.

Functional Requirements of Tie Rod in Circuit Breaker	Relative Importance by Weighting	Intrinsic Property	Silica Filled Epoxy	Units
MECHANICAL				
Tension dynamic shock 20kN	W_1 5	Tensile strength, Tensile Modulus, Flexural strength	70-80 10500 110-125	MPa MPa MPa
Compressive dynamic shock 2.6 kN	W_2 5	Compressive strength, Tensile Modulus	140-150 10500	MPa MPa
Torque 32 N.m.	W_3 5	Flexural strength	110-125	MPa
Creep at 90 °C, 1000 h at 2300 N in compression (Deformation <3mm)	W_4 5	Creep behaviour 0.2%10,000h @23°C @50°C @85°C	 12 10 5	 MPa MPa MPa
Fatigue 30,000 operations	W_5 5	Notched impact strength	7-10	MJ/mm^2
ELECTRICAL				
Voltage withstand 95 kV (50Hz) for 1 minute	W_6 5	Loss tangent, Dielectric strength, Permittivity	2% 18-20 4	kV/mm
Lightning impulse 250 kV- full & chopped waves	W_7 5	Loss tangent, Dielectric strength, Permittivity	2% 18-20 (depend of the thickness) 4	kV/mm
Partial discharge activity <5 pC at 45 kV	W_8 5	Porosity	Ideally void free	
GEOMETRY				
Insulation height 90mm Diameter 53.6 mm	W_9 **3**	CTI	>600	
	W_{10} 3	Arc resistance	182-186	s
THERMAL				
Temperature cycling 60 cycles of 24h: -40°C (10.6h) to 115°C (10.6h) with a 2°C/min slope.	W_{11} 5	Continuous service temperature	100°C	°C
	W_{12} 3	Glass transition temperature	110-125	°C
	W_{13} 3	Thermal conductivity	0.8-0.9	W/mK
	W_{14} 3	Linear Expansion	$35\text{-}37 \times 10^{-6}$	1/K
PHYSICAL & CHEMICAL				
	W_{15} 3	Density	1.75-1.8	kg/dm^3
	W_{16} 3	Moisture absorption 10 days /23°C in air 1 h in boiling water	 0.1-0.2 0.1-0.2	 % %

Table 1: Showing the relationship between the functional requirements and intrinsic properties

SPECIFICATION

Critical aspects of the specification must be assured. Some of these relate to the visual appearance of the tie rod i.e. the distance between the inserts is maintained (119 mm), there are no cracks, defects and bubbles present. Another is the partial discharge (pd) test carried out on the assembled pressurised SF6 switchgear system. Its fitness for service has to be pd free (< 5 pC.) at 45 kV_{rms} without flashover, tracking and puncturing of the material. This test is carried out before and after each of the other electrical and mechanical tests given below.

Test	Test Conditions	Test Sequence	Acceptance criteria
1. Partial discharge (p.d.)	Performed at room temperature on 3 parts in complete switchgear insulated by SF6. Part cleaned before test	Apply voltage upto 45 kV_{rms} at a rate of 8 kV/s.	No partial discharge at 45 kV_{rms} (<5 pC) No flashover. No tracking. No material puncturing.
2. Power frequency		Test voltage increased to 95kV_{rms} for 1 minute. Repeat p.d. test.	Based on IEC 60060-1. As above
3. Lightning impulse		Test carried out at 250 kV_{peak} of both polarities using a waveform of 1.2/50. Repeat p.d. test.	Based on IEC 60060-1. As above

Table 2: Electrical test requirements (IEC 60056)

Test	Test Conditions	Test Sequence	Common Acceptance criteria	Specific acceptance criteria
4. Tensile	3 parts at 20 kN at three temperatures (20°C, -40°C & 90°C)	Measure distance between inserts. Apply progressive tensile load of 20 kN for 60 s at 20°C. Re-measure distance between inserts. Perform at -40°C and 90°C.	After test: No breaking. No cracking No insert detachment No partial discharge at 45 kV_{rms} (<5 pC)	Elongation between inserts after test <0.3 mm.
5. Torsion	3 parts at 32 N.m.	Measure angle between inserts at 20°C. Apply progressive torsion couple of 32 N.m for 60 s at 20°C. Re-measure angle between inserts at 20°C.		Angular displacement between inserts of <1°.
6. Compression creep	3 parts at 2.6 kN for 1000 hours at 90°C.	Measure the distance between the inserts at 20°C. Maintain 2.6 kN compressive load for 1000 hours at 90°C. Re-measure the distance between the inserts at 20°C.		Compressive displacement between inserts of < 0.1 mm

Table 3: Mechanical test requirements (IEC 60056)

DESIGN

Exploratory -rheology

The injection moulding of any component covers a number of complex parameters: the drying of the thermoplastic to remove residual moisture, the feed and gate positions within the tool, the holding pressure/time during injection and the melt and tool temperatures during moulding.

A study was carried out using a "Moldflow" model to determine these parameters using a glass filled Polybutylene Terephthalate /Polyethylene Terephthalate (PBTP/PETP 30%GF). The tool design incorporated two injection gates at each end of the cavity adjacent to the metal inserts and determined the injection pressure, mould and melt temperatures (Fig 3). The circular rib nearer one end was to maintain the electrical creepage distance. The outcome was the potential of cold welds at a mid point during injection. Also when the initial melt solidified around the inserts at the injection gates, then the holding pressure on the melt within the central region of the tie rod would not be maintained causing shrinkage with the formation of voids.

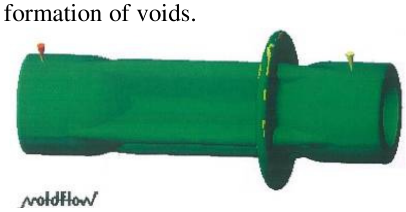

Figure 3: Showing the exploratory design

A second design was considered with a single gate injection point at one end and with reservoirs at the other end to accommodate this shrinkage during solidification. The analysis showed that it eliminated the occurrence of cold welds but not the porosity within the structure.

Prototype-mechanical

Here the injection point and gate were positioned at the central region of the tie rod. . The stress distribution and displacement for a PAA-50%GF moulded tie rod were analysed using a linear FEM (Optistruct V7.0) programme based upon a quarter model symmetry and assumed an isotropic, material with adhesion around the metal inserts. The study showed that the compressive and tensile modes were the same while the torque was thirty times smaller in magnitude (Fig 4).

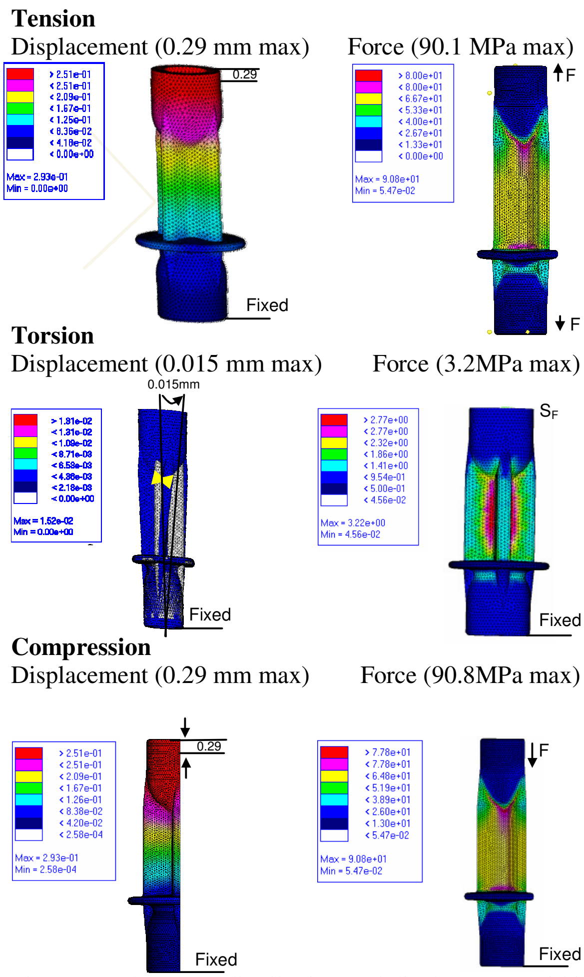

Figure 4: The stress distribution and displacement within the tie rod for a) tension, b) torsion and c) compression.

Since the tie rod experiences a greater tensile stress in service (20 kN) rather than in compression (2.6 kN) then the dominant design stress is in tension. This attains a maximum value just below the insert and at the base of the circular rib.

INJECTION MOULDING

Moulding trials were performed on a FANUC Roboshot S-2000i 100 injection machine. The tool was thermostatically controlled by pressurized water within the separate halves of the tool. Additional temperature and pressure measurements were recorded using thermocouples inserted into each half of the tool and a transducer beneath one of the ejector pins.

QUALIFICATION

Mechanical and Electrical Testing

Selected glass filled thermoplastics, Polyphenylene Sulphide (PPS-40%GF), Polybutylene Terephthalate (PBTP-30%GF), Polycarbonate (PC-30%GF) and Polyarylamide (PAA-50%GF) exhibiting favourable environmental and functional performances were injection moulded to produce tie rods.
Each tie rod was then subjected to specific electrical (pd test) and mechanical (20 kN for 2 mins at temperatures of -40°C, 20°C and 90°C) tests as part of the qualification procedure. The outcome was that both the PC-30%GF and PBTP-30%GF failed the pd test with Discharge Inception Voltages (DIV) at between 30-50 kV. When these tie rods were cut opposite the sprue within the thicker central region, voids were observed (Fig 5).

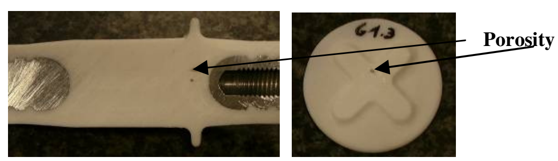

Figure 5: Photographs showing the voids present within the axial and radial sectioned tie rod.

The PPS-40%GF was pd free, passed the tensile load at room temperature but failed at the extreme temperatures. The PAA-50%GF passed the mechanical testing at all three different temperatures and still remained discharge free.
It was recognized that porosity within the material could be attributed to a number of different reasons: a higher shrinkage during solidification, especially for the semi-crystalline polymers, a short holding pressure on the melt during the phase change or the injection gate in the wrong location.
Further injection moulding trials (Trial 2) were undertaken using PETP-55%GF, PBTP-40%GF/mineral, PBTP-50%GF and PAA-50%GF containing higher glass contents to reduce the shrinkage. The holding pressure on the melt was prolonged and the draft angle and diameter of the sprue was increased. Voids were still present within the PBTP-40%GF/ mineral and it was

rejected. During mechanical testing the PEPT 55%GF exhibited a brittle fracture below the acceptable level at 20°C, either caused by a lower polymer content or the isotropic orientation of the glass fibre in this region of maximum stress (Fig 6). The orientation of the glass fibre around the inserts is anisotropic (Zones 1 & 111), whereas in the central region of maximum tensile load, it is isotropic (Zone 11), which is not good for the overall design. Both the PBTP 50%GF, and the PAA -50%GF passed the pd and tensile tests.

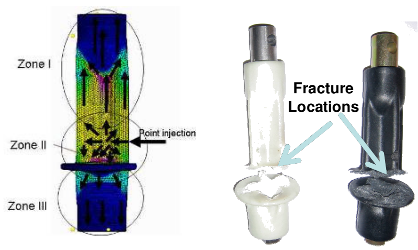

Figure 6: Showing the fibre orientation within the tie rod

Compression Creep

During service the tie rod must remain dimensionally stable when subjected to a prolonged compressive load at elevated temperatures. This is important in the selection of suitable materials, which must pass the qualification for creep behaviour (Table 3- section 6). When this test was performed on PAA-50%GF, it passed the pd test of < 5pC and the axial dimensional change of <0.1 mm.

Co-Axial Alignment

It is important for the metal inserts at each end of the tie rod to be axially aligned with the actuator and the vacuum interrupter. Besides the difficulty in assembling the parts, any eccentricity creates excessive wear and causes premature failure of the equipment. The axial misalignment of the metal inserts is shown in Table 4 for a number of different thermoplastics.

Material	Average co-axial misalignment (mm)
Silica filled epoxy	0.225
PAA 50%GF	1.350
PPS 40 % GF	1.517
PBTP 50% GF	1.676

Table 4: The misalignment of steel inserts moulded in thermoplastics compared to the existing epoxy

This misalignment of the thermoplastic materials is 6 to 8 times greater in magnitude than the original epoxy composite and is attributed to warpage during moulding.

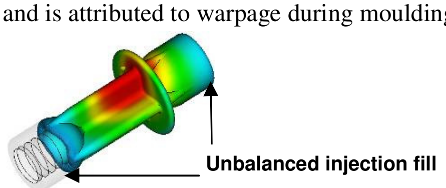

Figure 7: Showing the fill after an injection time of 0.8 seconds.

The injection fill of the cavity after 0.8 seconds is shown (Fig 7) requiring an additional 0.2 seconds to completely fill the cavity.
This extended period creates an imbalance in the rate of solidification around the injection point and causes a greater distortion on one side of the tie rod (Fig 8).

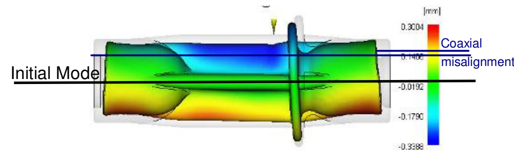

Figure 8: Showing the coaxial distortion after moulding

As a result the PAA -50%GF failed the torsional angular displacement of < 1° and had to be rejected.

CONCLUSIONS

Even though materials can be selected based upon their intrinsic properties to achieve their functional and environmental requirements for a component, it is still essential to have a clear understanding of how the design and processing parameters can influence the quality of the final product in order to satisfy its qualification specification. Experience gained from this work has allowed us to define a new tie rod design, which will be discussed in the future.

ACKNOWLEGMENTS

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