AN INFLUENCE OF SEGMENTED MANDREL ON STRENGTH PROPERTIES OF WOUND MOTOR CASE ICCM-16 PROCEEDINGS

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Abstract

In order to increase the efficiency of the filament winding manufacturing process of motor case, based on using the washable mandrels, a segmented mandrel was designed and produced. This mandrel is assembled of longitudinal aluminum segments, connected together on both ends of an internal steel shaft.

After winding and curing of the first case on the segmented mandrel it was found that the fibers of the upper wound layers on the cylinder part of the case were wrinkled. This paper analyses the possible reasons of the phenomena by numerical simulation of mechanical interaction between mandrel and wet wound fibers. Special tests were performed to prove the conclusions of simulation.

Using the conclusions of simulation, some improvements were realized in mandrel design. As a result, the radial displacement of the segments decreased and fiber's wrinkles disappeared.

1 Structure of Segmented Mandrel

Washable mandrels are usually used in the filament winding manufacturing process of motor cases. An essential disadvantage of washable mandrels is their one cycle life: for each one new case a new one mandrel should be produced.

To increase the efficiency of the filament winding process of motor case, a segmented mandrel was designed and produced. This mandrel is assembled of longitudinal aluminum segments, connected together on both ends of an internal steel shaft, see fig.1. Each segment has few supports on the shaft along its length. The fewer the segment supports, the easier the removal procedure of shaft after winding. An assembly of segmented mandrel is demonstrated on fig.2.

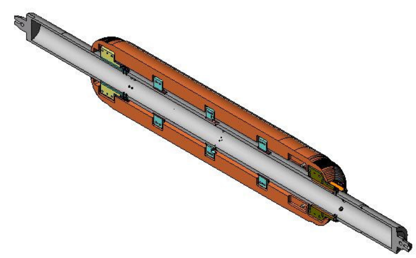

Fig. 1. Internal structure of segmented mandrel

Fig. 2. Assembly of segmented mandrel

2 Phenomenon of Wrinkled Fibers

After winding and curing of the first case on the segmented mandrel it was found that the fibers of the upper wound layers on the cylinder part of the case were wrinkled, see fig.3.

Wrinkles were located in two areas on the cylinder, along the trajectories of the helical wound layers. Each wrinkle was parallel to the longitudinal axis of the case.

Fig.3. Wrinkles on the external surface of the first wound case

During the pressure test of this case some wrinkled fibers broke locally under relatively low internal pressure, without general failure of the case. The burst pressure of the case, achieved in this test, was essentially lower than the nominal value of the burst pressure for the same cases, manufactured on washable mandrels.

3 Special Heating Tests

In order to investigate a wrinkling phenomenon and to identify the type of wound layers that wrinkled, two special tests were designed and

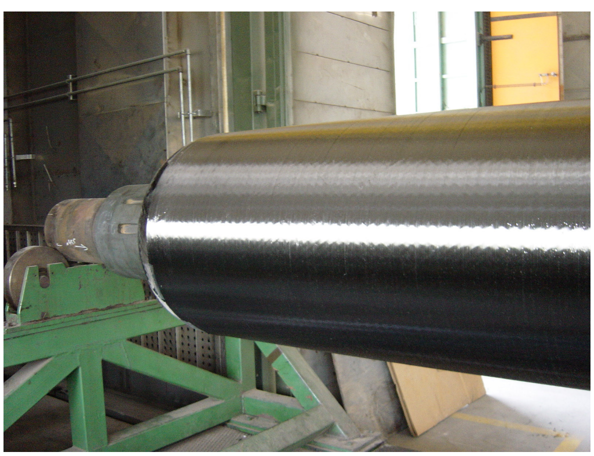

Fig.4. Mandrel wound without hardener enters the oven

performed. The segmented mandrel was wound by fibers, impregnated with resin only, without hardener. The wound mandrel was put into the oven (see fig.4) and heated according to the normal cure procedure.

During various stages of cure the mandrel was pulled out from the oven and checked. The phenomenon of wrinkled fibers was reproduced on the advanced stage of the curing, fig.5.

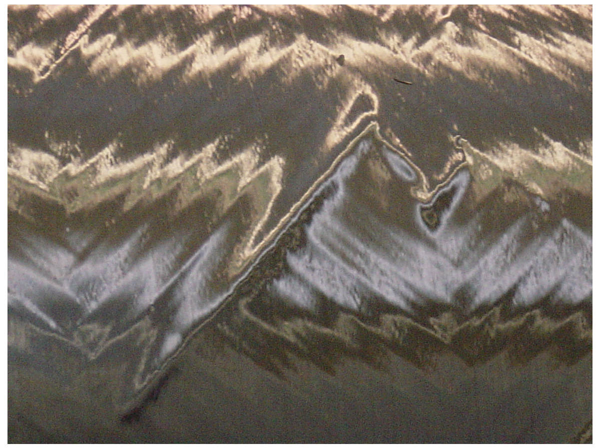

Fig.5. Wrinkles on the external surface of the heated case. Heating test 1

Wrinkles were found in upper hoop wound layers, and were oriented in the direction of helical wound fibers.

Second heating test was performed for same mandrel, wound differently with fibers impregnated by resin without hardener: all upper hoop layers

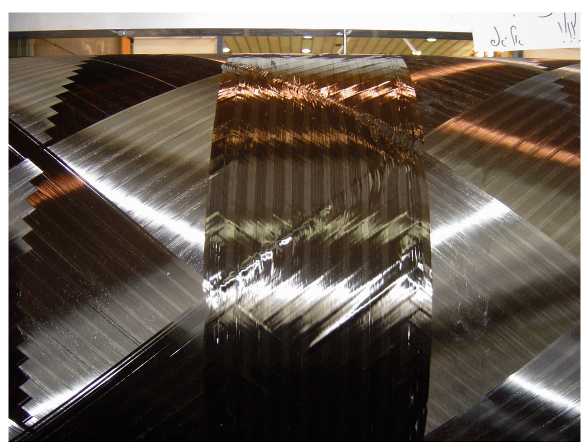

Fig.6. Wrinkles on the external hoop wound surface of the heated case in the heating test 2

were wound only locally, on a restricted area of the cylinder. On the remaining part of the cylinder the upper wound layer was last helical layer.

As it was done in heating test 1, the wound mandrel was put into the oven and heated according to the normal cure procedure. The phenomenon of wrinkled fibers was reproduced once more on the advanced stage of the curing, on the hoop wound external surface of the case only, see fig.6.

After cooling the heated mandrel all wrinkles disappeared, wound fibers lined up, as they were before heating.

4 Mechanical Model of Mandrel/Fibers Interaction

Due to the heating tests it was understood, that it is enough to explain the phenomenon as the interaction of heated mandrel with fibers, impregnated by virtual non-curable resin system. In the first case the wrinkling phenomenon occurred but modified by using a curable resin system during the winding.

To investigate the reason of the wrinkles appearance, the stress-strain state of the wound non –cured layers of fibers in interaction with the stress-strain state of the mandrel segments in heating process were analyzed.

Symbols:

E_f	-	Elastic modulus of impregnated fibers
s_f	-	Fiber cross section area
Z	-	Longitudinal coordinate of mandrel
W_f	-	Width of wound fibers tow
ε_f	-	Strain of helical wound fibers
R	-	External cylinder radius of mandrel
r	-	External radius of shaft
L	-	Length of cylinder on room temperature
*	-	Indicates the parameter's value on the heating stage
ΔT	-	Maximum mandrel temperature in the oven above the room temperature
R_f	-	Radius of curvature of cylinder in fiber direction
φ	-	Winding angle on cylinder
T	-	Fiber tension
W	-	Radial displacement of segment under fibers pressure
h	-	Vertical diagonal of elementary rhombus
d	-	Horizontal diagonal of elementary rhombus
α_1	-	Coefficient of thermal expansion of segment raw material
α_2	-	Coefficient of thermal expansion of shaft raw material

The maximal longitudinal expansion of the mandrel's segment should be calculated according to the formula:

$$L^* = L(1 + \alpha_1 * \Delta T) \qquad (1)$$

The maximal radial expansion of the mandrel's cylinder should be calculated according to the formula:

$$R^* = r(1 + \alpha_2 \Delta T) + (R - r)(1 + \alpha_1 \Delta T) \qquad (2)$$

Tension along the fiber is:

$$T = E_f * \varepsilon_f * s_f \qquad (3)$$

where fiber strain depends on thermal and mechanical deformations of the segments in the oven.

As the result of segments deformation (composed of the longitudinal and radial thermal expansions and radial elastic displacements), the winding angles are changed, and the length of the fiber's trajectory is changed also. This change determines the fiber's strain.

To estimate the change of the winding angles- the elementary rhombus of the helical wound structure before heating, see fig. 7,9 should be compared to the same rhombus after heating, fig. 8,10.

The initial winding angle in each station on the cylinder may be calculated from the elementary rhombus:

$$tg\varphi = \frac{h}{d} \qquad (4)$$

After heating, the dimensions of the rhombus are deformed:

$$h_* = \frac{2\pi(R^* - w)}{2\pi R^*} h \qquad (5)$$

$$d_* = d(1 + \alpha_1 * \Delta T) \qquad (6)$$

and winding angles are changed correspondingly:

$$tg\varphi_* = \frac{\left(1 - \frac{W}{R}\right) tg\varphi}{(1 + \alpha_1 * \Delta T)} \qquad (7)$$

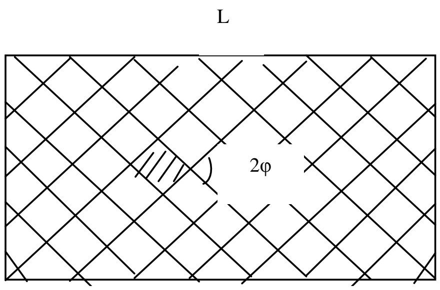

Fig. 7 The non-deformed structure of fibers on the cylinder

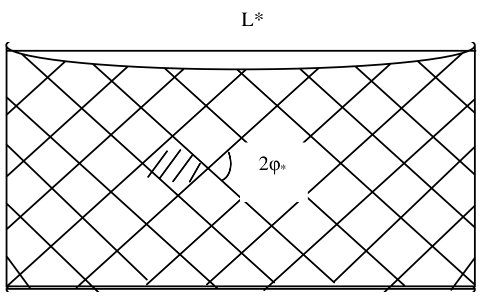

Fig. 8 The deformed structure of fibers. on the cylinder $\varphi_* < \varphi$

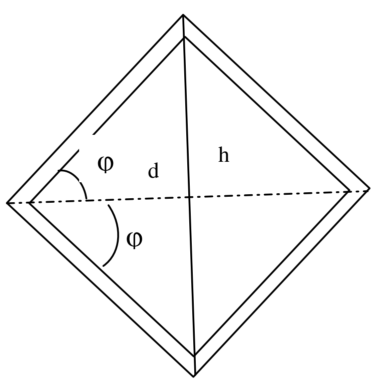

Fig. 9 Elementary rhombus of helically wound fibers before heating

The domes area of the mandrel is relatively small in comparison with cylinder length, and radial elastic displacements are absent in this area, according to mandrel design, so we suppose, that the path of the wound fibers on the domes does not change essentially during the heating.

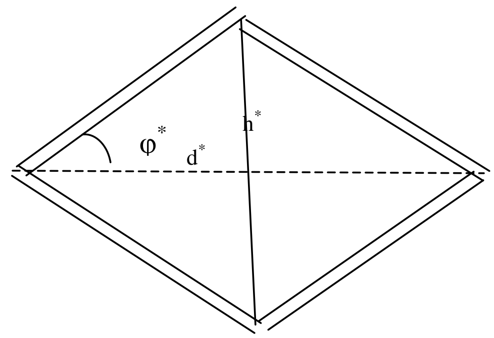

Fig. 10 Elementary rhombus of helically wound fibers after heating

Due to these assumption the elongation and strain of the helically wound fibers may be estimated as:

$$\varepsilon_f = \frac{\int_0^{L_*} \sqrt{1 + tg^2 \varphi_*}\, dz - \int_0^{L} \sqrt{1 + tg^2 \varphi}\, dz}{\int_0^{L} \sqrt{1 + tg^2 \varphi}\, dz} \qquad (8)$$

The elongation of the mandrel initiates the elongation of fibers, and increases the pressure between fibers and segments of the mandrel.

Pressure of one helical wound layer (containing two half layers wound with ±φ angles) on the cylinder part of the mandrel may be calculated as:

$$q_1 = \frac{2T}{R_f * W_f} = \frac{2T \sin^2 \varphi}{R * W_f} \qquad (9)$$

$$R_f = \frac{R}{\sin^2 \varphi} \qquad (10)$$

Finite elements model was used to describe the elastic radial displacements of the segments under external pressure and maximum temperature, see fig.11.

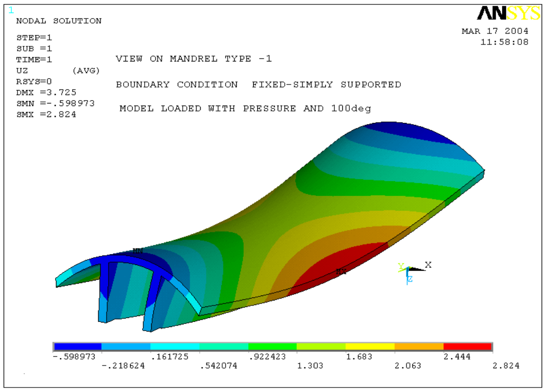

Fig.11 Vertical displacements of the segments of mandrel under external pressure and high temperature

According to equation (1-10) the radial displacement of the segment depends on the fibers pressure, which is a function of radial displacement. These closed non-linear system of equations may be solved by the following iteration procedure.

Fiber tension, found on the i-stage of iteration process, is used to estimate the fibers pressure on the mandrel, and radial displacement of the segments on the (i+1) – iteration stage. The maximum (i+1) stage pressure on the mandrel is compared with i-stage pressure. Iteration process, should be stopped, when the difference in the pressure values is within the previously determined tolerance δ, see fig. 12.

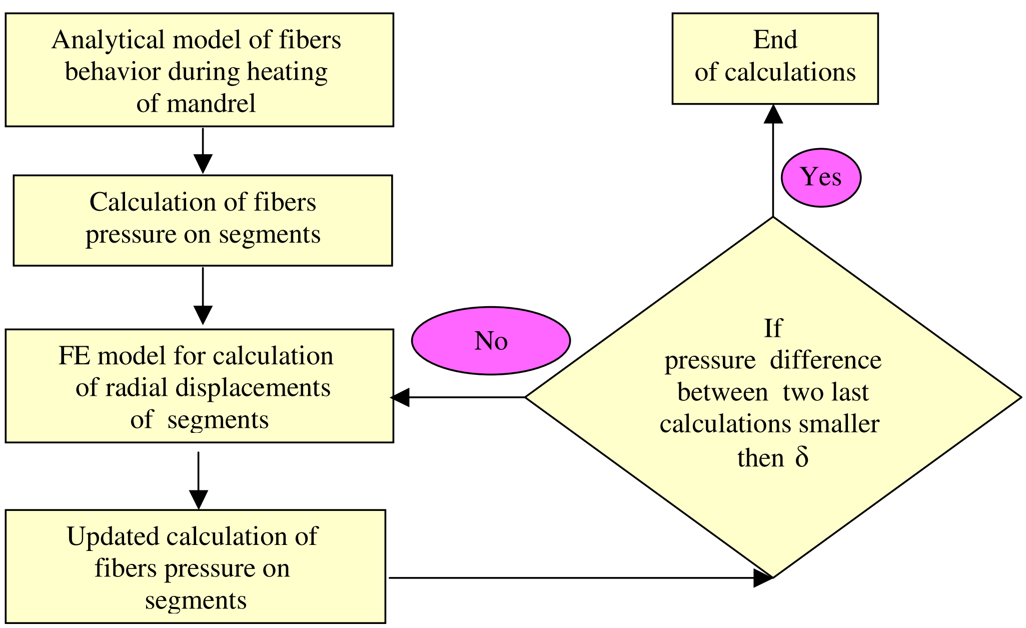

Fig.12 An iteration process of calculations

Results of calculations for designed segmented mandrel:

		mm		MPa	
$\Leftarrow$	ε_f^1=0.000527	W_{max}=3.27	$\Leftarrow$	q_0=1.4	ε_f^0=0.0025
$\Leftarrow$	ε_f^1=0.00086	W_{max}=2.72	$\Leftarrow$	q_0=1.1648	
$\Leftarrow$	ε_f^1=0.0018	W_{max}=1.125	$\Leftarrow$	q_0=.4816	
$\Leftarrow$	ε_f^1=0.0010	W_{max}=2.35	$\Leftarrow$	q_0=1.008	
$\Leftarrow$	ε_f^1=0.0017	W_{max}=1.308	$\Leftarrow$	q_0=.56	
$\Leftarrow$	ε_f^1=0.00138	W_{max}=1.804	$\Leftarrow$	q_0=.772	
$\Leftarrow$	ε_f^1=0.00141	W_{max}=1.844	$\Leftarrow$	q_0=.7896	
$\Leftarrow$	ε_f^1=0.00139	W_{max}=1.82	$\Leftarrow$	q_0=.778	
$\Leftarrow$	ε_f^1=0.00140	W_{max}=1.83	$\Leftarrow$	q_0=.784	

The value of maximum radial displacement of the mandrel, found in iteration process, indicates that the fibers of the upper hoop wound layers should be fully loose. So, the wrinkles of the loose hoop wound fibers were formed in the oven and cured on external surface of the first wound case.

Using the conclusions of stress-strain analysis, some improvements were realized in mandrel design. As a result, the radial displacement of the segments decreased, see fig. 13, and fibers wrinkles disappeared.

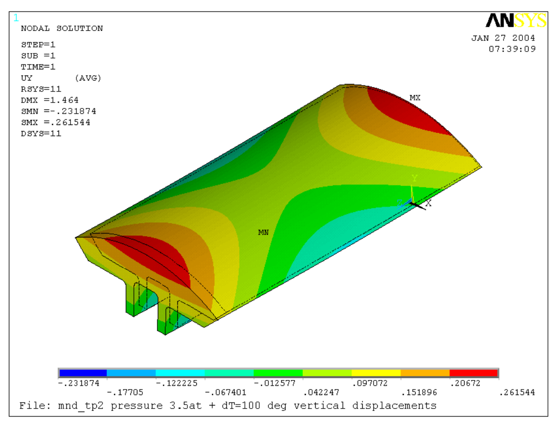

Fig.13 Vertical displacements of the segments of improved mandrel under external pressure and high temperature