NEW TAILCAST MANUFACTURING PROCESS

K. Olofsson[1*], A. George[1], G. Nilsson[1], R. Långström[1], A. Merlo[2], E. Tamburini[3]

[1]*Swerea SICOMP AB, Box 271, SE-941 26 Piteå, Sweden*
[2]*CeSI, Via Tintoretto, 10, 20093 Cologno Monzese; Italy*
[3]*FIDIA S.p.A., corso Lombardia, 11 - 10099 San Mauro Torinese, Italy*
**kurt.olofsson@swerea.se*

Keywords: composites, casting, CTE

Abstract

A new material- and manufacturing concept has been developed in the ongoing EU research project COMETA. The concept is called Tailored Reinforcement for Epoxy Casting (TailCast). TailCast uses a pre-consolidated grid structure made of continuous fibers, which is loaded as an insert into a conventional casting process. The resulting material- and product structure can hence be designed to incorporate a tailored reinforcement package of continuous fibers, short fibers and particles. This paper deals with material- and process developments towards a low Coefficient of Thermal Expansion (CTE) as well as the manufacture of a flange demonstrator for COMETA. The gained low composite CTE will furthermore reduce the sensitivity to humidity, which is important for this application.

1 Introduction

COMETA is an EU project that studies new material- and process technology for use in high precision machine tools applications. *TailCast* is a new manufacturing concept developed in this project intended to replace the typical Aluminium alloy fittings in high precision carbon/epoxy structures at a reasonable cost. A COMETA demonstrator machine part structure is in Figure 11. The spindle flange is manufactured with *TailCast*. A lowered mismatch in CTE between the flange and tube, along with a reduced sensitivity to humidity variation, will have a huge impact on the machine's precision. *TailCast* emulates the principal concept of classical steel reinforced concrete. A reinforcement grid is preformed and partly cured in a simple tool. It can consist of carbon/epoxy towpreg, shaped into a grid which follows the main geometry of the component. The grid is then placed into a production tool. Casting with a filled epoxy is then performed to obtain the finished product. The *TailCast* name means that it enables the reinforcement package to be tailored to meet the defined material specification. It uses comparatively cheap materials in a potentially cheap manufacturing process [1].

2 Material specification in COMETA

- Accurately distributed reinforcement.
- CTE < $6\cdot10^{-6}$ 1/°C.
- Low sensitivity to humidity.
- Modulus (tension) > 20000 MPa.

- Stress at first damage (tension) > 10 MPa.
- Stress at Breakage (tension) > 290 MPa.
- Machining with a resulting low surface roughness.
- Operational temperature 20-80 °C.

3 Manufacturing specification in COMETA

- Manufacture of products with complex geometry.
- Manufacture to net-shape without post machining.
- Suitable for manufacture of 100-10000 parts/year.
- Suitable for manufacturing with a low pressure (a few bar) method.
- Low cost.

4 CTE measurements on epoxy with CNT

The CTE for a polymer composite material with epoxy matrix is mainly dependent on the volume change of the matrix when the temperature is altered. The composite CTE can hence be reduced by introducing comparatively soft fillers in the matrix and stiff continuous fibers. This will reduce the composite CTE, reduce the humidity sensitivity and increase the stiffness, as applied with *TailCast*. Another possibility to affect the composite CTE is to directly reduce the epoxy CTE by introducing Carbon Nano Tubes (CNT). SICOMP has measured the CTE on a number of in-house anhydride curing pure epoxy materials manufactured with CNT. Green has published data from similar measurements [2], see Figure 1. The trends in both studies are similar with a large effect for small amounts of CNT followed by a small decrease after that. It is interesting to see that the CNT has affected a global material property like CTE (the samples were quite large). Micro mechanical calculations were performed using these data. The results indicated that the use of CNT could not meet the composite CTE specification of < $6 \cdot 10^{-6}$ 1/°C, when applied to a conventional material- and process setup. The *TailCast* process was hence selected instead. Useful improvements in material- and process technology for CNT is however expected in the coming years, which can enable it to be used for this type of application.

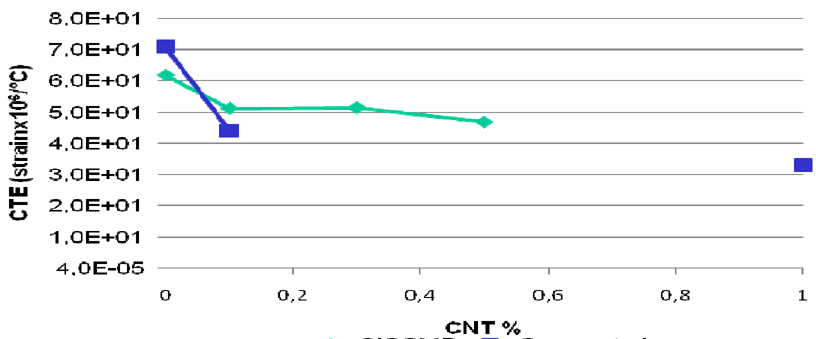

Figure 1. Measured CTE on pure epoxy samples as a function of CNT content.

5 Materials

The used casting epoxy has a low viscosity (130 mPas) at casting, and a suitable potlife and cure time. The casting epoxy and towpreg are suited for final cure at 120 °C. Postcure at higher temperature can be used to increase the material adhesion. These materials have been used:

- Grid: TCR UF3369 towpreg with carbon-, glass- and Kevlar as reinforcements.
- Casting epoxy: Hexion 04908/Huntsman Aradur 42 epoxy amine hardener system.
- Short fiber: Short carbon fiber with 0.06 mm length.
- Particle: Silica filler with 63 and 80 μm size.
- Particle: S60HS glass micro spheres from 3M.
- Particle: Thermoplastic HA1931, HDPE, PP and TB3580 from DuPont.
- Particle: Natural rubber from Trelleborg.

6 Micro mechanical calculations

Micro-mechanical calculations are essential for the study of untried material concepts. This has here been applied on casting epoxy systems reinforced with silica particles, glass micro sphere particles, rubber particles, short glass fibers, short carbon fibers and continuous fibers in different combinations. The effective properties for the reinforced matrix is calculated and used with in-house micro-mechanical laminate software (as the matrix properties) together with the effective properties for the towpreg (as the fiber properties) along with the effective fiber fraction (for the towpreg). This use of laminate theory is an approximation since it assumes evenly distributed fibers in the material, instead of the *TailCast* towpreg grid. The calculation results still seem to be reasonably accurate. Used material data is in Table 1.

	Epoxy	***Silica***	***S38HS Glass Sphere***	***S60HS Glass Sphere***	***Short Glass Fiber***	***Short Carbon Fiber***	***TRH50 Carbon Fiber***
ρ[kg/m^3]	1180	2540	380	600	2540	1790	1816
E [MPa]	3000	20000	[1]2581	[1]4465	70000	230000	250000
β [1/°C]	$69\cdot10^{-6}$	$5.4\cdot10^{-6}$	$5.4\cdot10^{-6}$	$5.4\cdot10^{-6}$	$5.4\cdot10^{-6}$	$-0.1\cdot10^{-6}$	$-0.55\cdot10^{-6}$
μ [-]	0.35	0.22	0.22	0.22	0.22	0.22	0.30

[1]Calculated effective modulus for a hollow sphere particle.

Table 1. Constituent micro-mechanical properties used in the calculations.

7 Material sample manufacture

Filament winding in a special flat tool is used to manufacture 2D grids from towpreg, see Figure 2. The grid is consolidated with vacuum pressure for 3 h at 80 °C. Vacuum infusion is then used to manufacture flat *TailCast* samples. The sample in Figure 3 has Kevlar towpreg and thermoplastic particles in the epoxy. The manufactured materials for material testing are in Table 2.

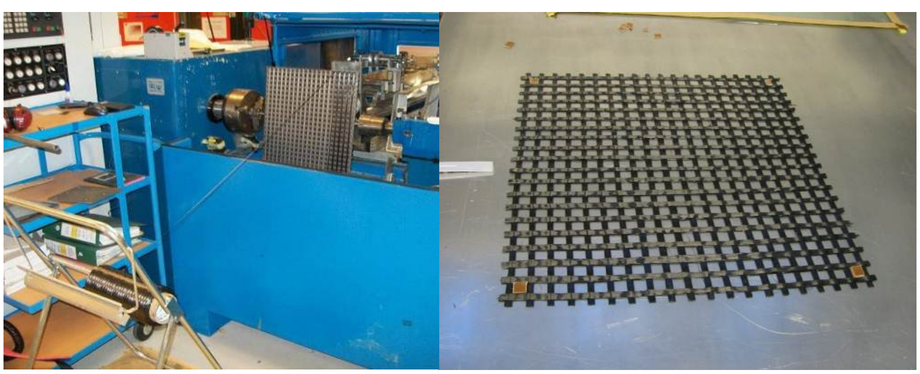

Figure 2. Winding of preform in tool. Towpreg grid ready for infusion.

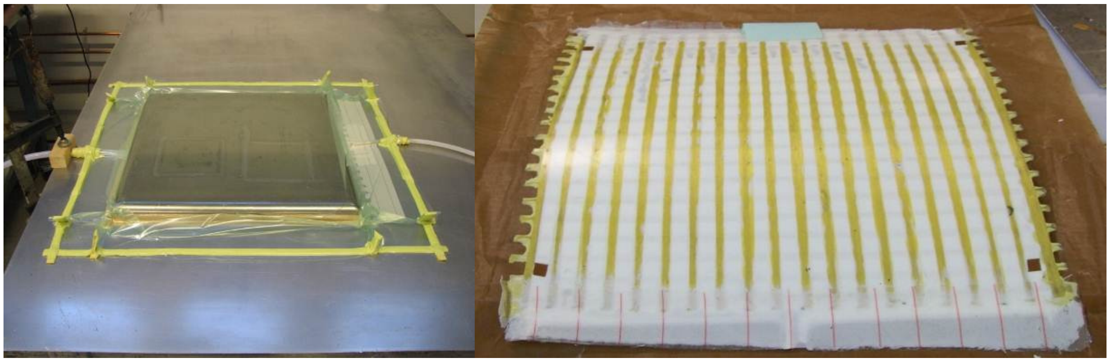

Figure 3. Assembly ready for vacuum infusion. Manufactured plate.

Material Nr [-]	*[1]Towpreg [-]*	*[2]Particle [-]*	*[2]Short fiber [-]*
1	19 % Carbon	50 % Silica	-
2	21 % Carbon	55 % Silica	-
3	24 % Carbon	50 % Glass Microspheres + 5 % Rubber	-
4	22 % Carbon	50 % Glass Microspheres	1 % Carbon
5	22 % Carbon	50 % Glass Microspheres	-
6	26 % Carbon	50 % Glass Microspheres	-
7	26 % Carbon	50 % Glass Microspheres	3 % Carbon
8	16 % Glass	50 % Silica	-
9	15 % Glass	50 % Glass Microspheres	-

[1]Volume % towpreg (fiber + epoxy) in the material.
[2]Volume % filler (particle, short fiber) in the matrix.
Table 2. Manufactured materials for material testing.

8 Comparison of measurements to theoretical

8.1 CTE

Measured- and theoretical values for the composite and filled matrix CTE are in Figure 4. The agreement is fair except for material Nr 3. The likely reason was traced down to a too high pre-cure temperature of 110 °C for the towpreg. This can give a poor adhesion between the towpreg and matrix. The pre-cure of the towpreg was lowered for the following materials. Materials Nr 4-7 show a low CTE.

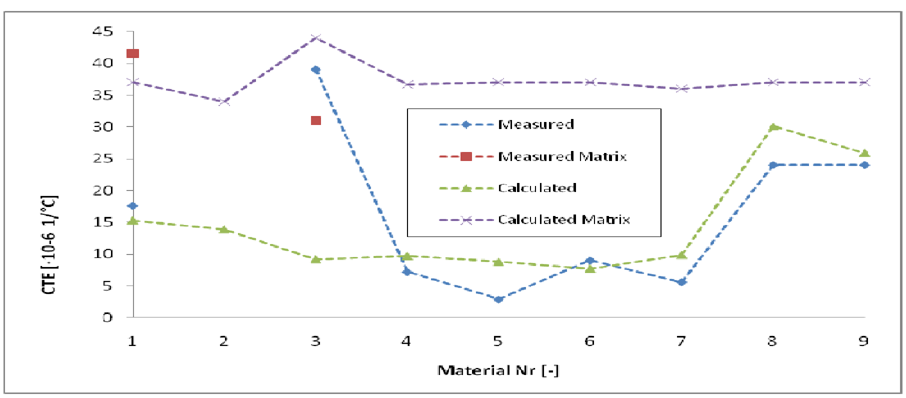

Figure 4. Measured- and calculated values for the CTE.

8.2 Modulus

Measured- and theoretical values for the modulus E are in Figure 5. The agreement is fair except for material Nr 3, 4 and 7. The likely reason is poor manufacturing quality for material Nr 3. Material Nr 4 and 7 contain short carbon fibers, which deviates from the theory.

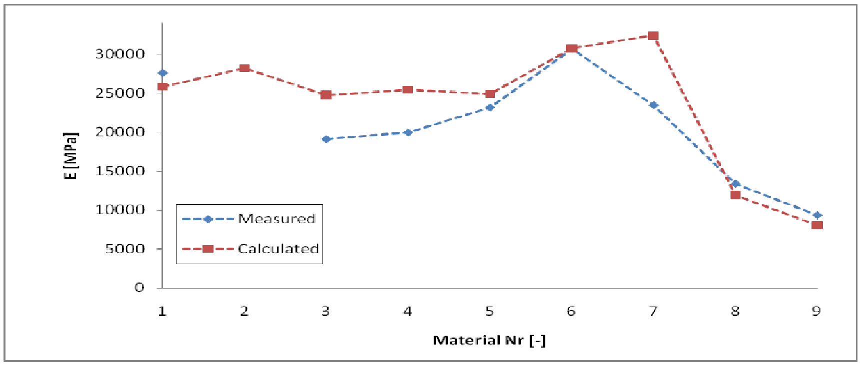

Figure 5. Measured- and calculated values for the modulus E.

8.3 Micro-crack initiation stress

Measured- and theoretical values for the micro-crack initiation stress σ_i are in Figure 6. The agreement is fair except for material Nr 3, 4 and 7. The reason is poor manufacturing quality for material Nr 3. Material Nr 4 and 7 contain short carbon fibers, which deviates from theory.

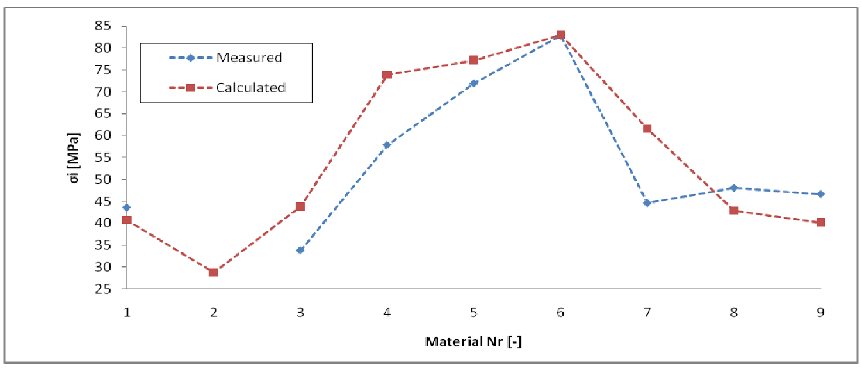

Figure 6. Measured- and calculated values for the micro-crack initiation stress σ_i.

8.4 Breakage stress

Measured- and theoretical values for the breakage stress σ_B are in Figure 7. The agreement is fair except for material Nr 4 and 7 containing short carbon fibers, which deviates from theory.

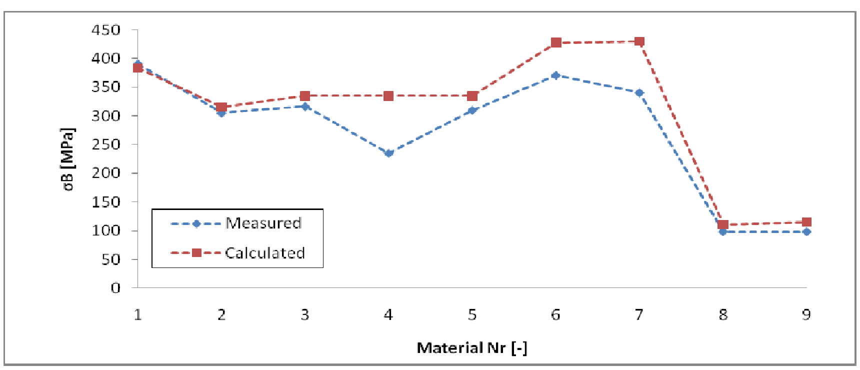

Figure 7. Measured- and calculated values for the breakage stress σ_B.

8.6 Evaluation

Materials with large differences in the calculated- and measured composite CTE, are indicated to have poor adhesion between the towpreg and matrix. Only materials Nr 4-9 are manufactured without significant defects. The other materials have overly pre-cured towpreg as well as an unbalanced towpreg grid. The observed effect of added short carbon fiber to the epoxy is that it lowers the composite modulus, lowers the ultimate strength and creates a more brittle material. This can partly be due to the larger viscosity and associated manufacturing defects. The use of glass fiber towpreg gives a less brittle material but also degrades many of the other material properties. Table 3 gives material properties for flat materials with the intended towpreg volume percent, using a combination of measured and calculated values to obtain the material properties. It can be observed that the stiffer solid silica filler increases the matrix modulus and hence increases the composite CTE for the material, compared to glass microspheres.

Material [-]	*[1]Reinforcement [-]*	*Density [kg/m³]*	*ε_i [%]*	*E [MPa]*	*σ_i [MPa]*	*σ_B [MPa]*	*CTE [$\cdot 10^{-6}$ 1/°C]*
1	Carbon/S	1797	0.27	25132	68	377	13.9
5	Carbon/GM	1041	0.31	21274	66	257	8.7
8	Glass/S	1885	0.36	12610	45	118	28
9	Glass/GM	1129	0.50	8700	44	114	23.5

[1]S = silica filler. GM = glass microspheres.

Table 3. Material data with 22.1 % towpreg volume percent.

Material Nr 5 is considered the best material. The reason is that it combines carbon towpreg with an effective matrix with fairly low CTE and low modulus. It has 22.1 volume % of TRH50 carbon fiber towpreg in a 0°/90° grid structure together with 50 volume % S60HS glass microsphere particle filled epoxy and meets most of the demands in the COMETA specification. Figure 8 show calculated values for modulus, CTE and density versus the towpreg volume fraction, to check the sensitivity to local variations in towpreg content. The material is quite stable for towpreg volume fraction 22 % ±3 %.

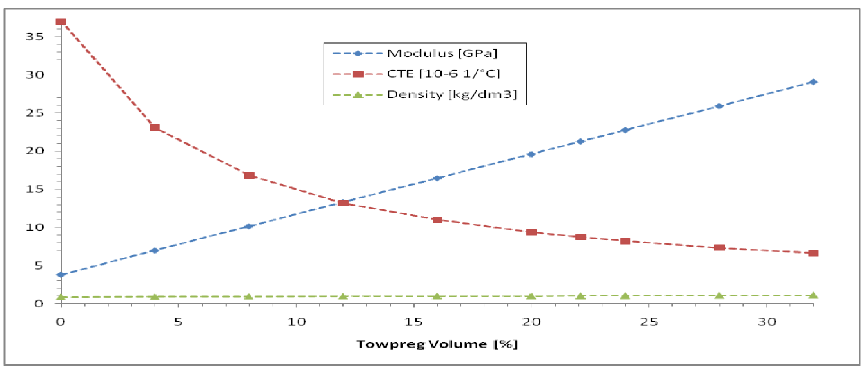

Figure 8. Calculated modulus, CTE and density versus the towpreg volume fraction.

9 Manufacture of TailCast flange

The 2D grid was consolidated with vacuum pressure for 3 h at 80 °C. The towpreg grid was then placed into the tool with 3 0°/90° grid layers in the flange neck and 11 0°/90° grid layers in the top flange. This resulted in towpreg content for the flange of 35.5 volume percent. 50 volume percent S60HS glass micro spheres were added to the casting epoxy. Isothermal pressure casting, without vacuum assistance, at 45 ºC was performed, see Figure 9. Cure in the tool was 6 h 80 °C + 4 h 120 °C + 4 h 140 °C. Demounting was performed by disassembling the tool. Final demounting of the flange from the inner steel tool was by using a tailored steel press plate and a press. The required press force was 6 kN. The manufactured flange can be seen in Figure 10. It is built into a demonstrator in COMETA, see Figure 11.

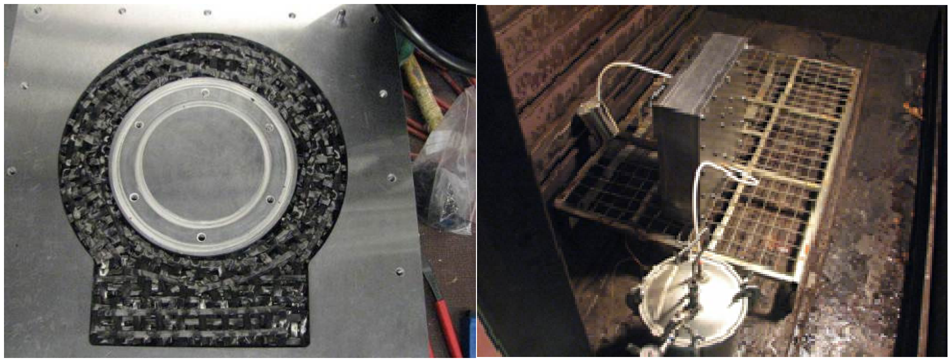

Figure 9. Top flange of towpreg loaded tool. Isothermal pressure casting at 45 °C.

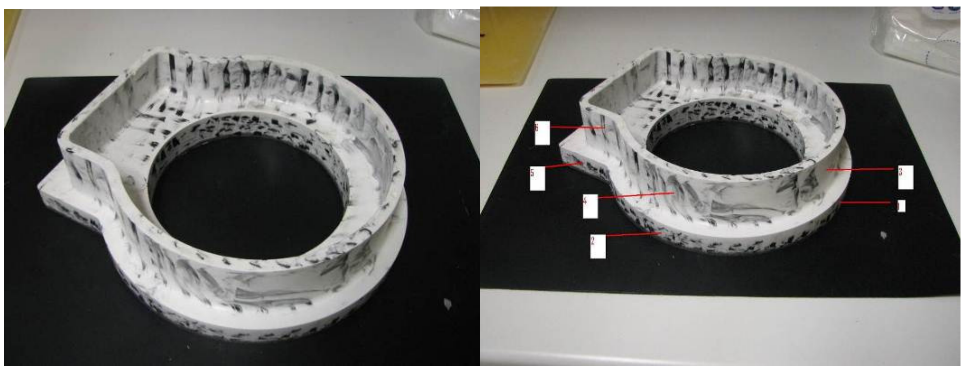

Figure 10. TailCast flange. Six positions used for CTE measurement.

10 CTE measurements on TailCast flange

The CTE in the tangential plane of the manufactured flange was measured at six positions. The diameter geometry was measured at 20 °C and after 5 hours heating at 100 °C. The measurement at 100 °C was performed within 2 minutes. See Figure 10 for the measurement positions. Measured data are in Table 4. The measured CTE is generally low and in line with the theoretical values. The theoretical CTE is 5-6·10^{-6} 1/°C.

Position [-]	**20 °C** [mm]	**Standard Dev.** [mm]	**100 °C** [mm]	**Standard Dev.** [mm]	**Δ*u*** [mm]	**CTE** [10^{-6} 1/°C]
1	323.10	0.044	323.35	0.050	0.25	9.67
2	286.13	0.040	286.25	0.030	0.12	5.10
3	283.05	0.004	283.15	0.010	0.10	4.27
4	252.06	0.054	252.14	0.030	0.08	4.13
5	198.16	0.004	198.35	0.030	0.19	12.20
[1]**6**	167.99	0.004	168.37	0.315	0.37	27.70

[1]Measurement error.

Table 4. Geometrical measurements at two temperatures and calculated CTE.

11 Geometry check of flange

The geometry of the manufactured flange was compared to the CAD model, using the in-house ARAMIS measurement system**.** The agreement is generally good with no large geometrical deviations. The largest deviation is in the circumferential flange radius, where a deviation of around 0.3 mm has been tracked down to a small difference between CAD and tool.

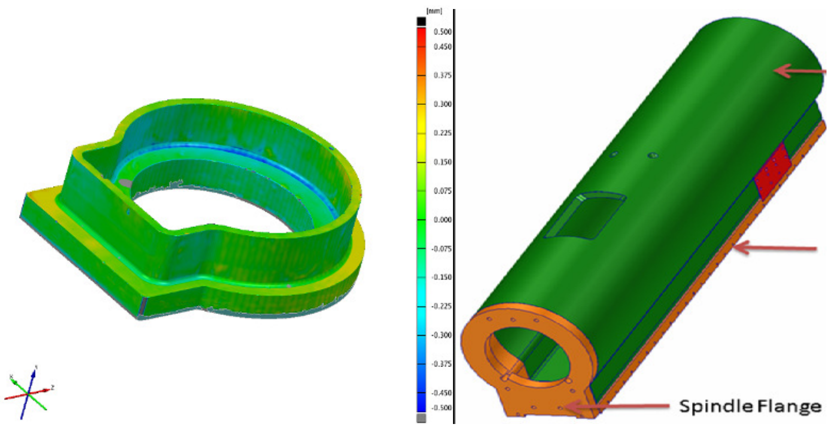

Figure 11. Measured flange geometry compared to the CAD geometry. RAM demonstrator in COMETA with flange and tube structure.

12 Conclusions

The novel *TailCast* process has been developed by material- and process concept analysis, micro-mechanical calculations, proof-of-concept manufacture of small parts, material sample manufacture, material testing and manufacture of three successful flange prototypes. Potential future improvements to simplify the grid manufacture, simplify loading of the grid into the tool and widen the process cure window have been identified. The reinforcement package in COMETA was directed towards CTE reduction but can also be tailored towards other composite material properties, using the same manufacturing process.

Acknowledgments

The work has been performed within the COMETA project (advanced polymeric compounds and metal matrix composites for excellent performances in machine tools applications, www.cometaproject.eu/), which is funded by the EU commission.

References

[1] Olofsson K., George A., Nilsson G., Långström R. *Tailored Reinforcement for Epoxy Casting-TailCast* in "Proceeding of *SICOMP Conference 2011*", Gothenburg, Sweden, (2011).

[2] Green K.J., Dean D.R., Vaidya U.K., Nyairo E. Multiscale fiber reinforced composites based on a carbon nanofiber/epoxy nanophased polymer matrix: Synthesis, mechanical, and thermomechanical behavior. *Composites: Part A*, **40**, pp. 1470-1475 (2009).