Anders Gaarud, Christian Scheuerlein, David Mate Parragh, Sébastien Clement, Jacob Bertsch, Cedric Urscheler, Roland Piccin, Federico Ravotti, Giuseppe Pezzullo, Ralf Lach

Fracture toughness, radiation hardness and processibility of polymers for superconducting magnets

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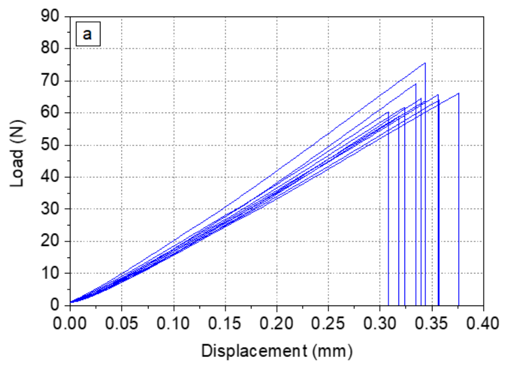
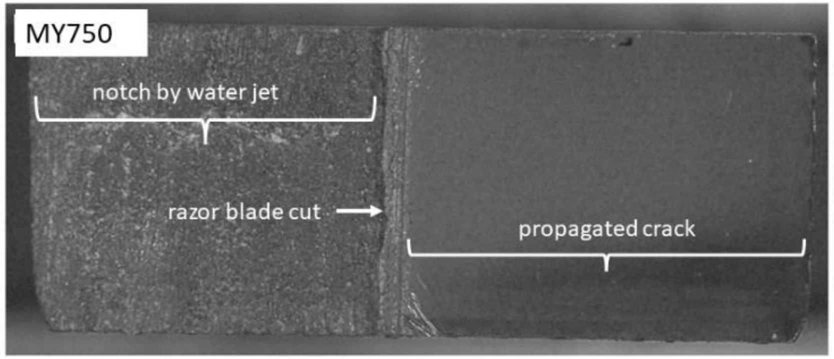
Summary of main results and outlook

C. Scheuerlein,
23.05.2024, Polymer Laboratory meeting

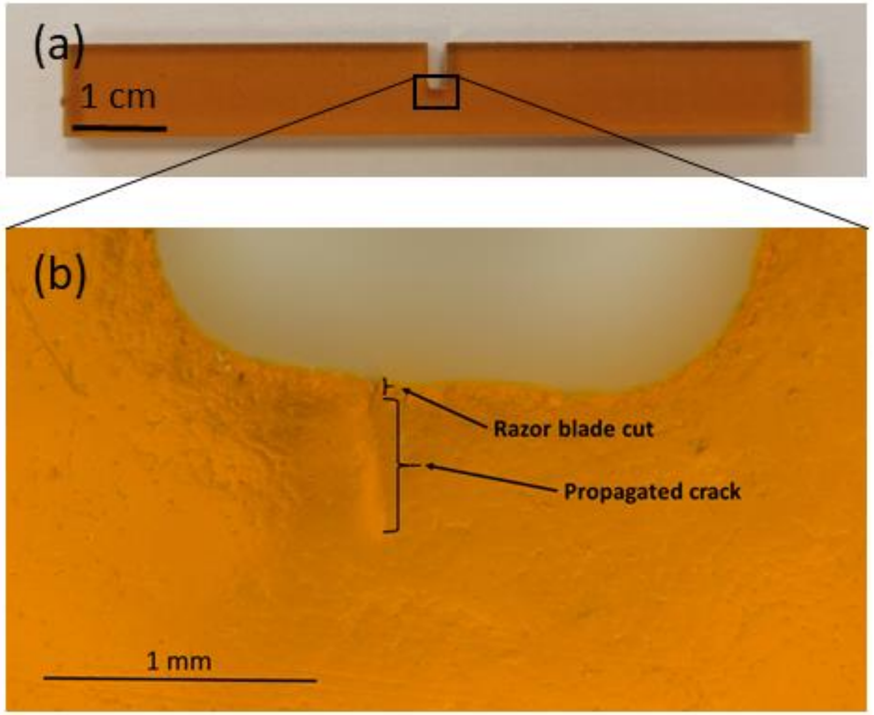
Fracture toughness measurements

- Inspired by work of ETHZ and PSI, see for instance the paper A. Brem et al, "*Elasticity, plasticity and fracture toughness at ambient and cryogenic temperatures of epoxy systems used for the impregnation of high-field superconducting magnets*"
- Fracture toughness measurements according to ISO 13586. Plastics – *Determination of fracture toughness (G_{IC} and K_{IC}) – Linear elastic fracture mechanics (LEFM) approach*, mostly done at Polymerlab, with help from R. Lach, Polymer Service GmbH Merseburg.





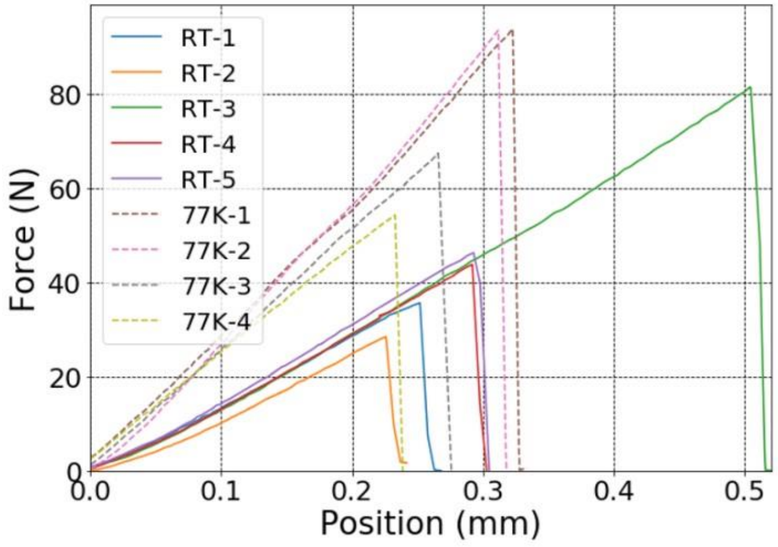
Linear-elastic behaviour and unstable crack propagation of MY750.

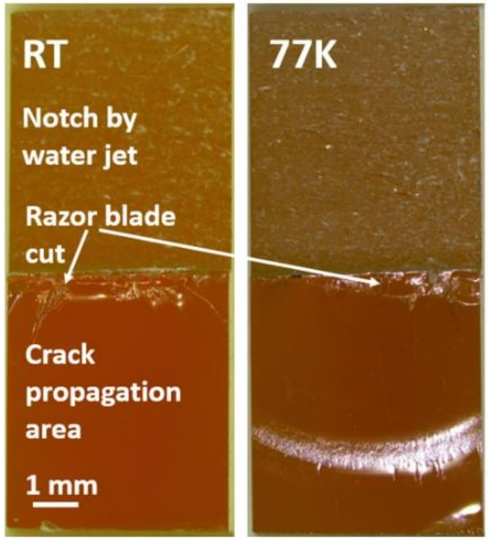


Single edge notched bending (SENB) specimen for mode I fracture toughness tests in 3-point bending with notch, razor blade cut, and propagated crack.

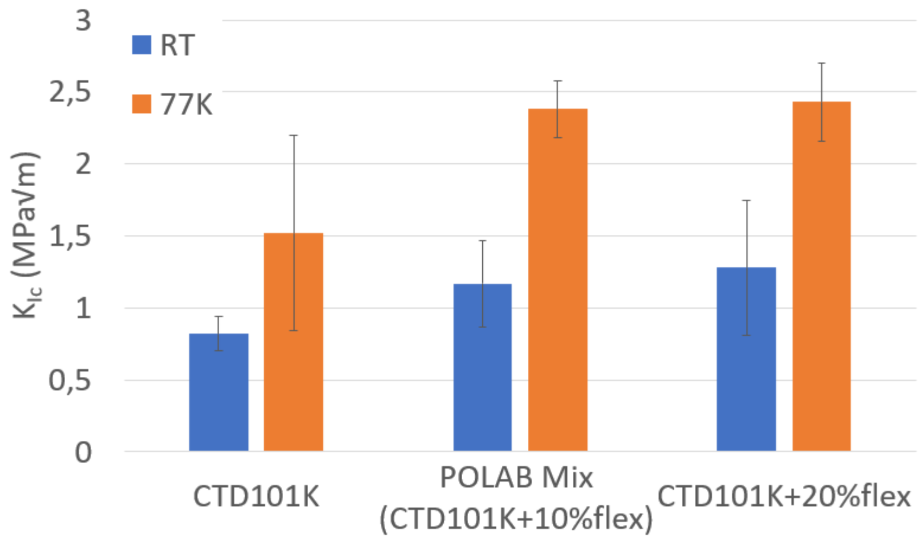
Improving fracture toughness of the CTD101K epoxy resin system used for HL-LHC magnet impregnation

- Proposal from Sébastien Clement: Improve fracture toughness of the three component CTD101K system by adding flexibiliser Araldite DY040.





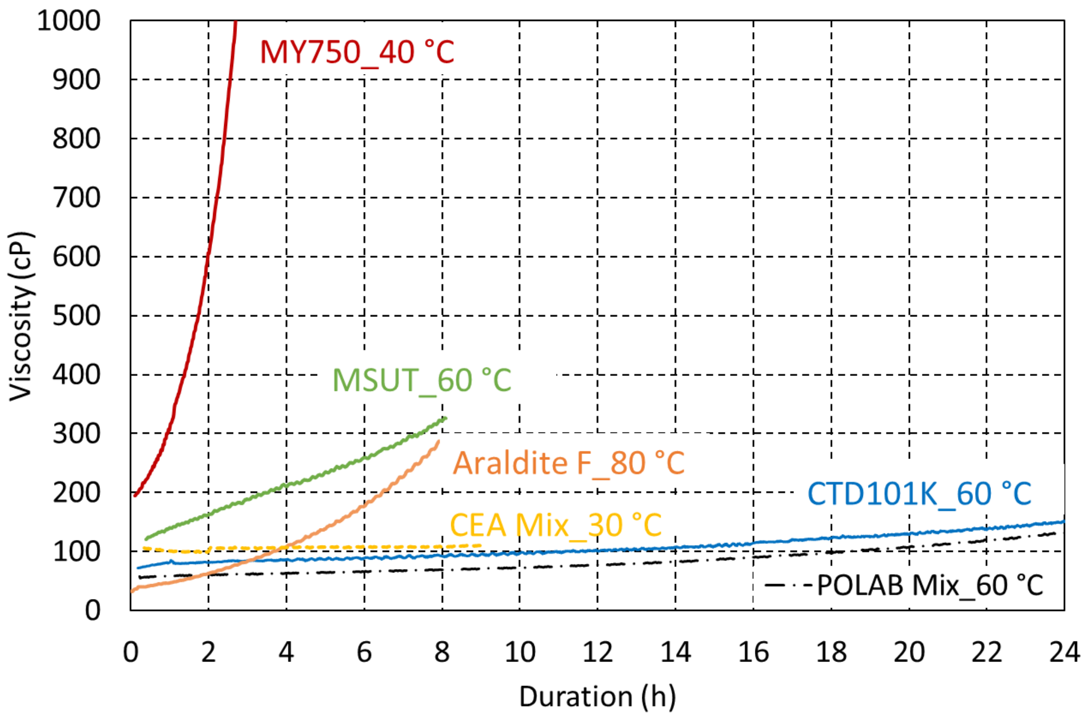
Load–displacement curves of CTD101K + 20 wt.% DY040 (left) and typical fracture surfaces (right) at RT and 77 K.



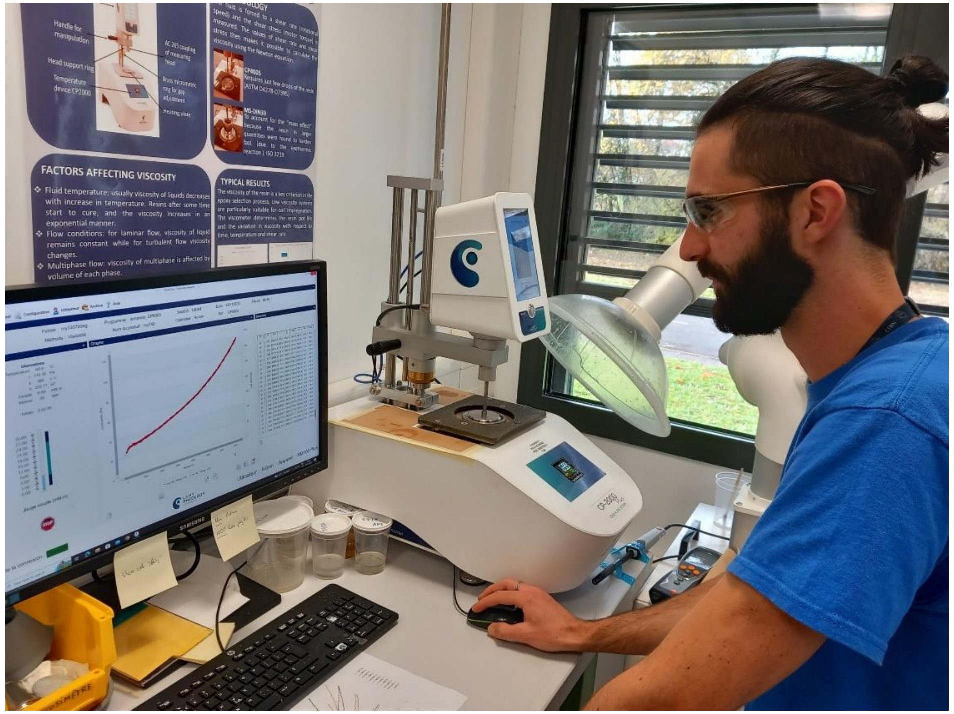
Comparison of K_{IC} at RT and 77 K of CTD101K, POLAB Mix and CTD101K+20 wt.% DY040.

Effect of DY040 addition on processability

- Viscosity and pot life of the CTD101K system are maintained when adding 10 wt.% of the DY040 flexibiliser.

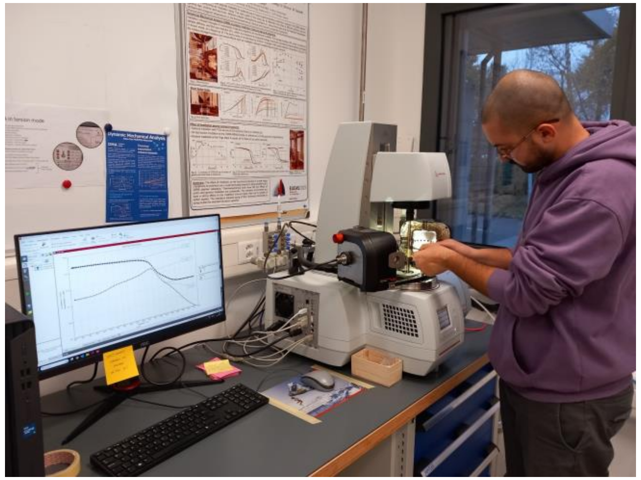


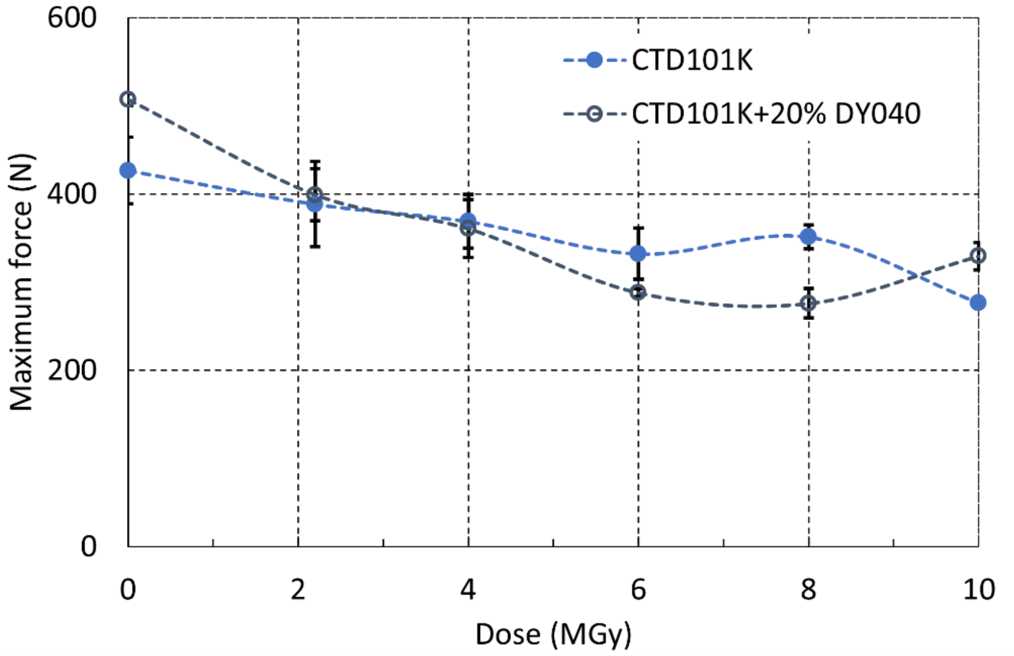
Comparison of the viscosity evolution of uncured epoxy resin mix at the processing temperature.



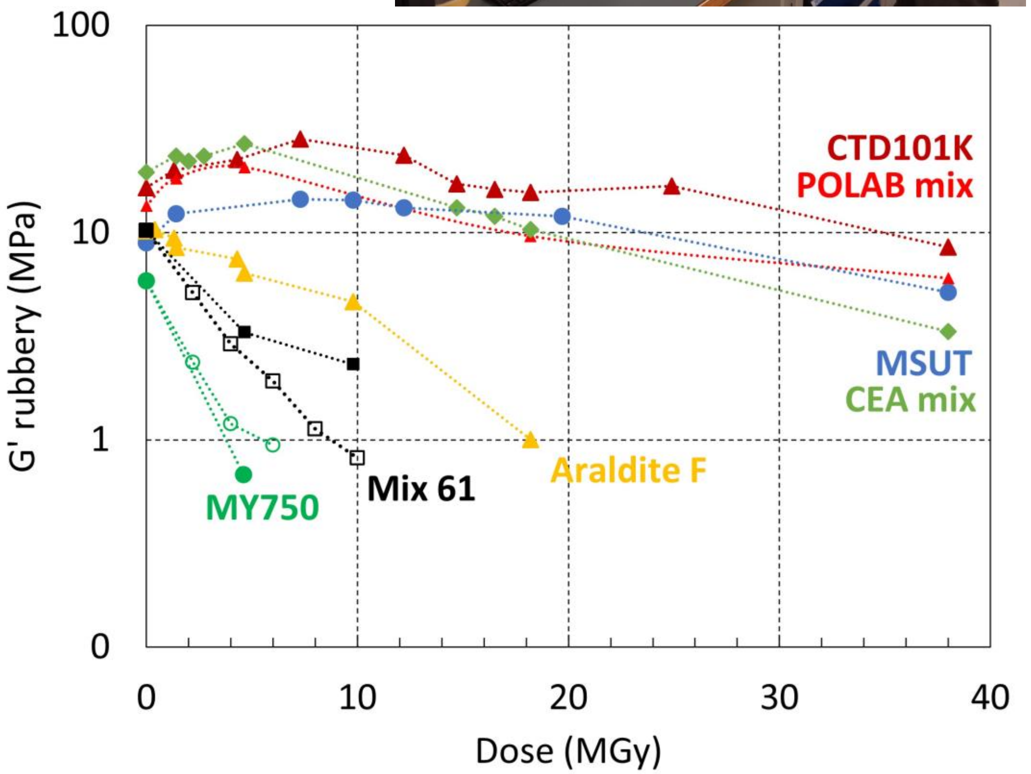
Effect of DY040 addition on radiation hardness

- Radiation hardness of the CTD101K system is maintained when adding 10 wt.% of DY040.





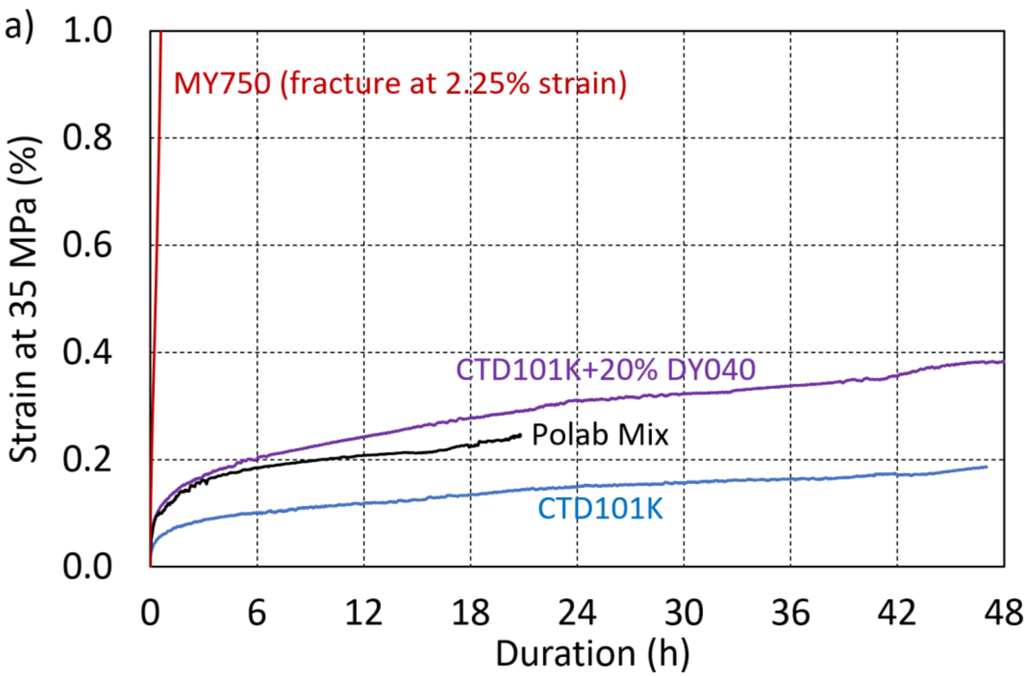
Effect of ^{60}Co gamma irradiation at RT on force at fracture during 3-point bending test in short beam configuration.

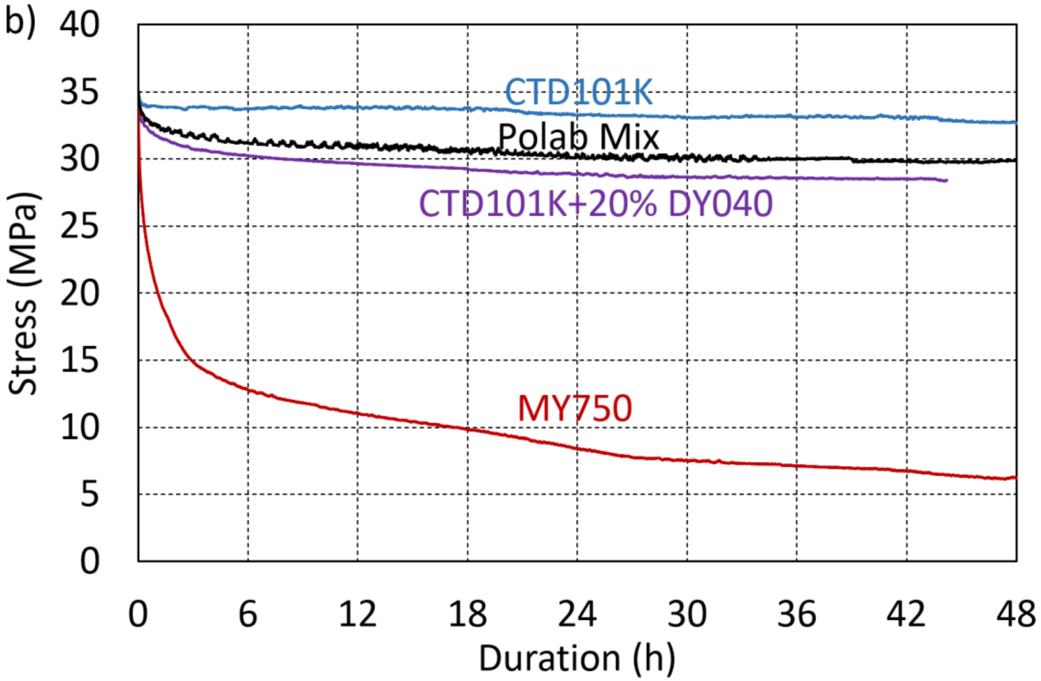


G'rubbery as a function of absorbed dose in ambient air.

Effect of DY040 addition on creep and stress relaxation

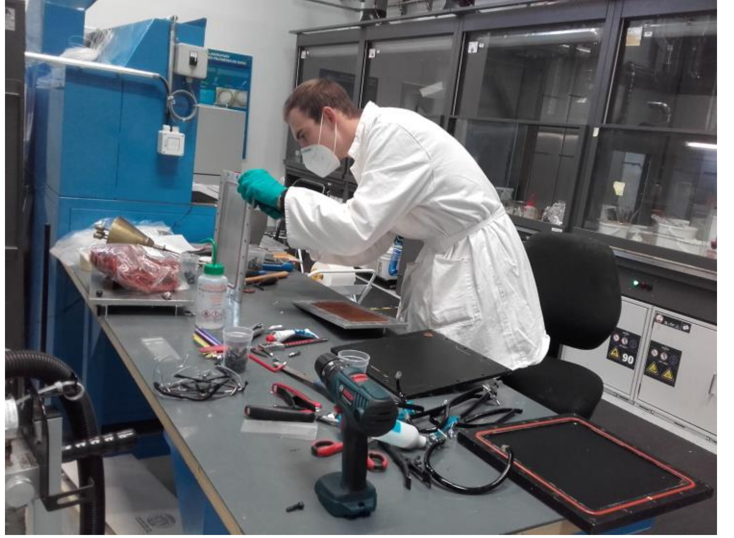
- Adding the flexibiliser slightly increases the creeping and the stress relaxation of the non-reinforced CTD101K epoxy resin.



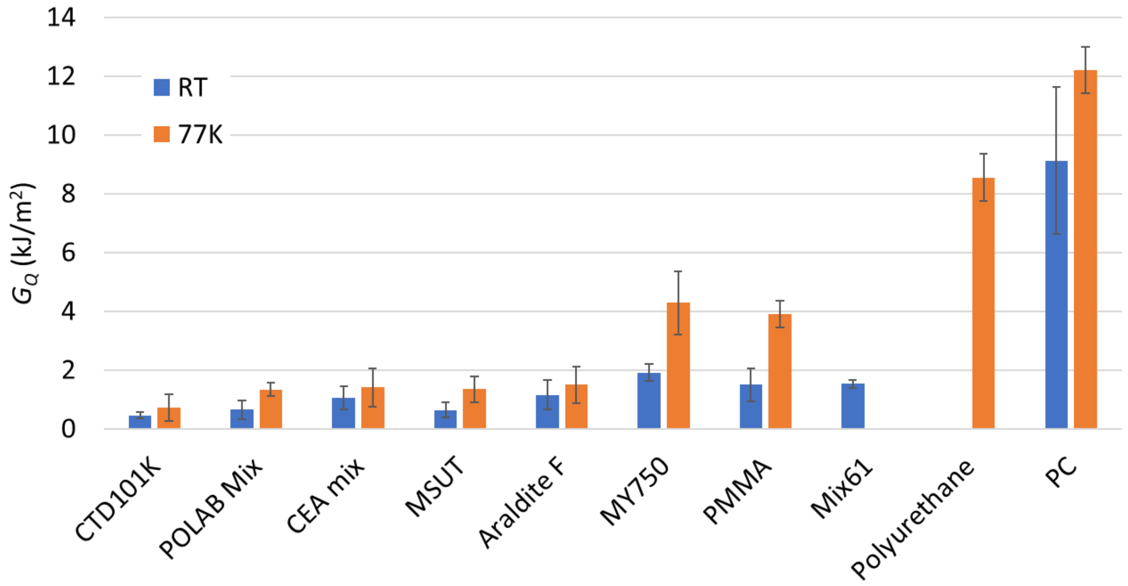


Comparison of CTD101K, POLAB Mix, CTD101K+20wt.% DY040 and MY750 (a) tensile strain as a function of duration at constant stress of 35 MPa (creep) and (b) tensile stress as a function of duration at constant strain applied at initially 35 MPa (stress relaxation).

Fracture toughness of polymers comparison



- Epoxy resins have comparatively low fracture toughness.
- Fracture toughness of radiation hard epoxy systems seems to be particularly low.
- Are high fracture toughness and radiation hardness conflicting requirements?



Comparison of critical energy release rate (G_Q) of epoxy resin systems CTD101K, POLAB Mix, CEA mix, MSUT, Araldite F, MY750, and Mix 61 with Polyurethane, PMMA and PC at RT and at 77 K.

Conclusion

- POLAB Mix has improved fracture toughness, maintaining the excellent processability and radiation hardness of the CTD101K system. POLAB Mix is qualified for impregnation of superconducting magnet coils.

Outlook

- Fracture toughness measurements at 4.2 K are in preparation in collaboration with EN-MME, PSI and ETHZ. Driving question: Is the 77 K fracture toughness comparable to the 4.2 K fracture toughness ?
- Irradiations of pure and fibre reinforced epoxy resin systems to doses >60 MGy at ambient temperature are ongoing. Driving question: What is the ambient temperature dose limit of pure and fibre reinforced epoxy resins?
- Irradiations at cryogenic temperature are in preparation. Driving question: What is the dose limit of superconducting magnet insulation systems under irradiation at superconducting magnet operating conditions?

Thank you for your attention

polymers

Article

Fracture Toughness, Radiation Hardness, and Processibility of Polymers for Superconducting Magnets

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Abstract: High fracture toughness at cryogenic temperature and radiation hardness can be conflicting requirements for the resins for the impregnation of superconducting magnet coils. The fracture toughness of different epoxy-resin systems at room temperature (RT) and at 77 K was measured, and their toughness was compared with that determined for a polyurethane, polycarbonate (PC) and poly(methyl methacrylate) (PMMA). Among the epoxy resins tested in this study, the MY750 system has the highest 77 K fracture toughness of K_{IC} = 4.6 MPa$\sqrt{m}$, which is comparable to the K_{IC} of PMMA, which also exhibits linear elastic behaviour and unstable crack propagation. The polyurethane system tested has a much higher 77 K toughness than the epoxy resins, approaching the toughness of PC, which is known as one of the toughest polymer materials. CTD101K is the least performing in terms of fracture toughness. Despite this, it is used for the impregnation of large Nb_3Sn coils for its good processing capabilities and relatively high radiation resistance. In this study, the fracture toughness of CTD101K was improved by adding the polyglycol flexibiliser Araldite DY040 as a fourth component. The different epoxy-resin systems were exposed to proton and gamma doses up to 38 MGy, and it was found that adding the DY040 flexibiliser to the CTD101K system did not significantly change the irradiation-induced ageing behaviour. The viscosity evolution of the uncured resin mix is not significantly changed when adding the DY040 flexibiliser, and at the processing temperature of 60 °C, the viscosity remains below 200 cP for more than 24 h. Therefore, the new resin referred to as POLAB Mix is now used for the impregnation of superconducting magnet coils.

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Citation: Gaarud, A.; Scheuerlein, C.; Parragh, D.M.; Clement, S.; Bertsch, J.; Urscheler, C.; Piccin, R.; Ravotti, F.; Pezzullo, G.; Lach, R. Fracture