Acta Materialia Transylvanica 1/1. (2018) 19–25.
https://doi.org/10.2478/amt-2018-0006,
Hungarian: https://doi.org/10.2478/amt-2018-0005,
https://eda.eme.ro/handle/10598/30365

A New Method for Determining the Pullability of Composite Reinforcing Ceramic Fibres

János DOBRÁNSZKY,[1] Enikő BITAY[2]

[1] *MTA–BME Research Group for Composite Science, Budapest, Hungary, dobranszky.janos@eik.bme.hu*

[2] *Sapientia Hungarian University of Transylvania, Faculty of Technical and Human Sciences, Târgu-Mureş, Romania, ebitay@ms.sapientia.ro*

Abstract

A unique method for producing aluminium matrix composite wires is the Blücher's process, i.e. continuous gas-pressure infiltration. An essential condition of the process is that the fibre roving of the reinforcing fibres can be pulled across the orifices of the gas-pressure system with the least damage. The article describes a new test procedure that is capable of characterizing this essential functional property of the ceramic reinforcing fibres in a manner comparable and quantitative.

Keywords: *metal matrix composite, reinforcing fibre, continuous gas-pressure infiltration*

---

1. Introduction

Since the early 2000s, a composite core has been used as a reinforcement in high-tension electrical conductors instead of a steel core. The advantages of the composite core are the lower coefficient of thermal expansion and the higher specific strength. The composite core reinforced electric conductors of overhead transmission lines have gained ground among cables that have very low sag even at high current (HCHS core). The leading type is the so-called aluminum conductor composite core (ACCC) cable. In this cable the reinforcing core is made of carbon fiber re-enforced polymer matrix composite. In another important type of low sag electric conductors (ACCR; aluminum conductor composite reinforced), steel core wires are replaced by aluminum matrix ceramic fiber reinforced composite wires. The permissible maximum temperature of this exceeds that of the ACCC cables. In fact, only two solutions were successful in producing aluminum matrix composite wires: the first one is the Blücher process [1] which is based on continuous gas-pressure infiltration [2]. only this second is used on an industrial scale. As a key operation of the Blücher process, the fiber roving must be pulled across the gas-pressure system [3] containing the melt. In a fiber roving, more tows (thus untwisted fiber bundles) are combined.

The pullability of the reinforcing fibers as a functional property has not been studied so far. This is because using continuous gas-pressure infiltration is only possible for the Blücher process to produce composite wires, and research activities using this method have acknowledged that some types of reinforcing fibers cannot be used. For almost 15 years, a successful series of experiments on the production of carbon fiber reinforced composite wires[4], could not be reproduced, and the purely aluminum-oxide ceramic fibers (e.g. Nextel 610) have also been considered to be unsuitable for continuous gas-pressure infiltration.

The pullability as a requirement for fibers gained importance when we started researching the applicability of the Dialed carbon fiber and CeraFib 99 ceramic fiber as a composite reinforcing material. This article describes the method developed for determining the pullability of reinforcing fibers..

2. The reinforcing fibers of the composite wire

Only those materials in which the reinforcing material and the metallic matrix are separated during the entire manufacturing process [5, 6]. are called metal matrix composites. This is consistent with Ashby's definition: composites – that are, composite materials – are formed by composing two materials that are solids themselves and when the cohesive matrix is metallic then it is a metallic matrix composite [7].

When manufacturing aluminum matrix composite wires with continuous infiltration, the fiber roving has to be infiltrated in its full cross-section with the molten metal [8]. Research activities for the provision of conditions for spontaneous infiltration[9] were unsuccessful in terms of practical applicability, and although thousands of meters of composite wires were produced on the laboratory equipment, the Blücher process did not reach industrial application; this was only managed with a much slower, ultrasonic process [2].

The aluminum matrix composite wires are manufactured by means of the Blücher process, by pulling across a special three-element orifice system. The diameter of the orifices matches the fiber roving and the diameter of the composite wire to be produced. The fiber roving arrives at the inlet orifice under the pressurized chamber containing the melt, and their impregnation with the molten metal begins here.

During the pulling across, the fiber roving is compressed at the entrance of the inlet orifice, the filaments contacting the orifice wall are strongly rubbed against the orifice wall, and there may be various mechanical effects between the fibers inside the fiber roving which cause the fibers to be fractured (**Figure 1**).

Experience has shown that even the filaments of easy-to-handle oxide ceramic fiber roving become fragmented within (**Figure 2**). The roving

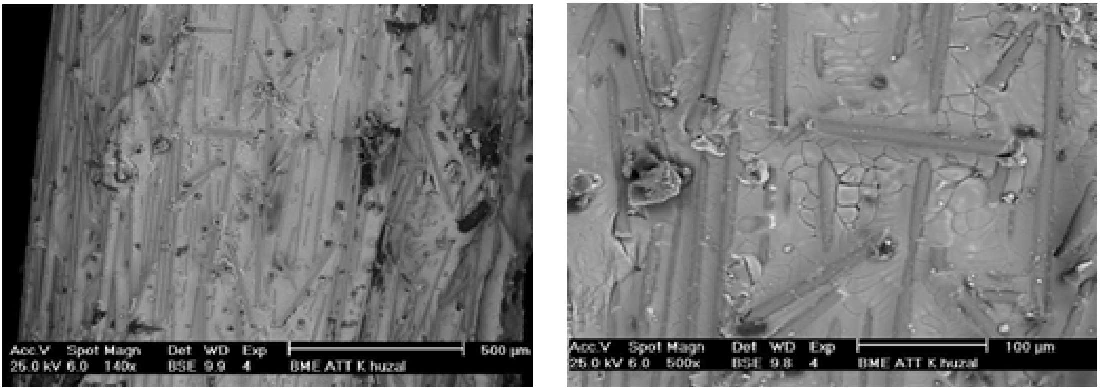

Figure 1. *Total width of the surface of the aluminum matrix composite wire (above) and a detailed view (below); it can be seen clearly how the fibers on the surface are fractured*

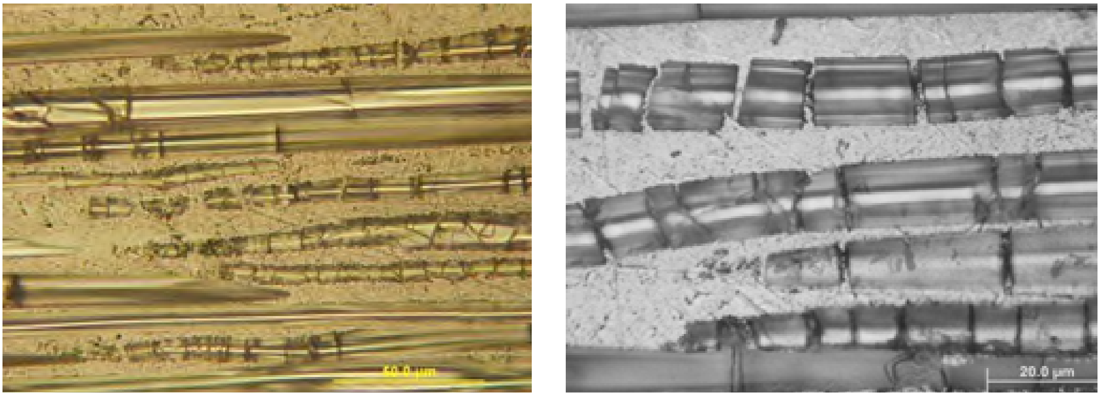

Figure 2. *Wire fractures inside the composite wire; polished longitudinal section of the composite wire on an optical micrograph*

Figure 3. *Fluffing of the carbon fiber tow at the en-trance of the inlet orifice made of graphite*

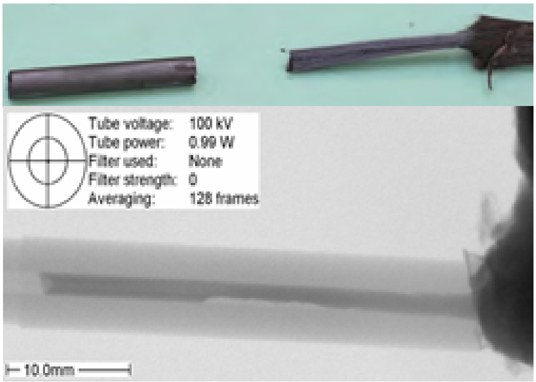

Figure 4. *The optical and X-ray microscope image of the carbon fiber tow torn in the orifice*

becomes fluffy, clogs the entrance of the orifice (**Figure 3**), and at the end pulls the orifice off or breaks it. **Figure 3** shows the formation of fluffs at the 1.6 mm diameter graphite orifice when pulling across the Dialed K63712 carbon fiber tow (the tow is an untwisted fiber bundle of numerous filaments), after burning off the sizing. The drawnin fiber pieces are caught by the central orifice, the entrance of which is immersed in the melt and gradually clogs the entrance (**Figure 4**), causing the roving to break.

Typically, the carbon fibers are characterized by fluffing, and when pulling the oxide ceramic fibers (**Figure 5**), the separation of the filaments from the roving is typical with breaking of the whole roving in the inlet or central orifice (**Figure 6**).

3. Experiments and tests

It is clear from the foregoing that the critical point of the production of composite wires by continuous gas-pressure infiltration is the conditions of pulling the fiber roving across, which

Figure 5. *CeraFib 99 fiber roving fed into the inlet orifice, prepared for pulling across*

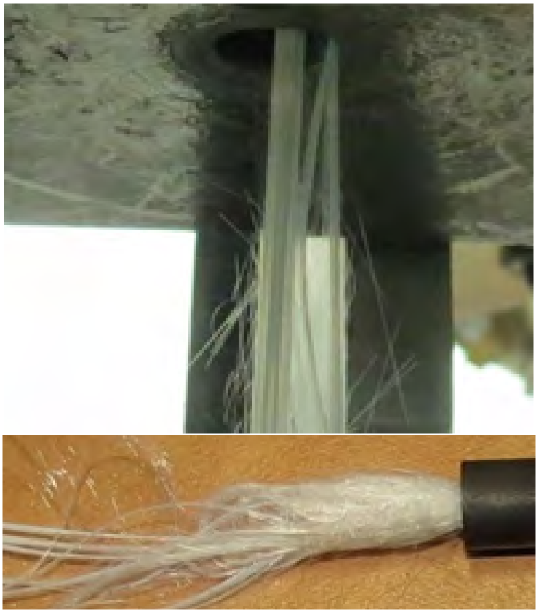

Figure 6. *The CeraFib 99 fiber roving in the process of tearing before the inlet orifice and then torn apart*

all together can be called pullability. Since an inadequate pullability in each case ends in the breaking of the fiber tow – or the whole fiber roving when more tows are used–, it may seem obvious that pullability could be characterized by some strength characteristic of ceramic fibers. However, neither the strength, nor the specific modulus [10–11] provided by the manufacturers suffice, because they say nothing about the breaking behavior of ceramic fibers due to shearing or bending load. For filaments, surface roughness (**Figure 7**) is a sensitive feature, but not for the fiber roving, because as it is pulled across, the pulling system simultaneously moves bunches of thousands of filaments in a fiber roving.

The Al99.5+CeraFib composite wire production process consisted of pulling across a fiber roving comprising approximately 4000 filaments, consisting of 5 fiber tows (**Figure 8**).

In our earlier research it was found that the single-component (e.g. Al2O3) oxide ceramic or carbon fiber bundles are very fragile. The pullability of single-component fibers can be so bad that during the 20 years of the active use of the Blücher

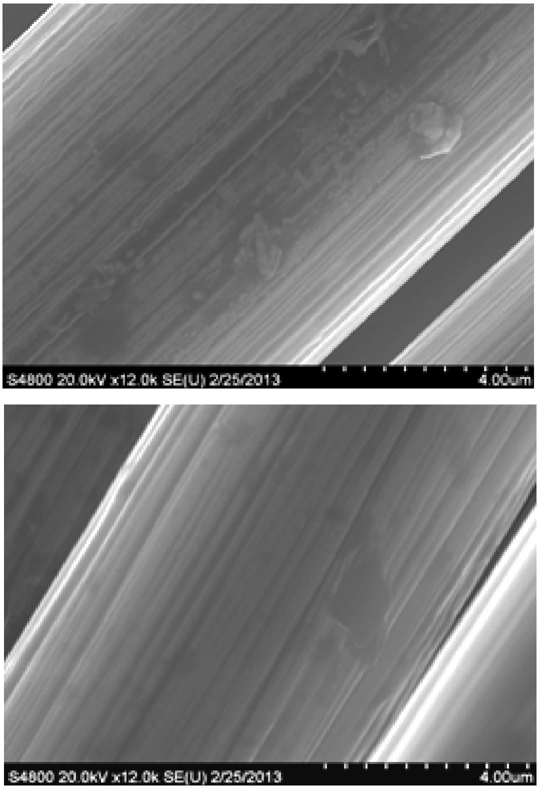

Figure 7. *Surface of filaments; a) Dialed K6372 carbon fiber, b) Zoltek carbon fiberl*

Figure 8. *Pulling across the fiber roving of five tows in the Blücher process*

process (until the end of 2014), no real amount of composite wire was produced from pure oxide ceramic fibers (e.g. Nextel 610), and only one experimental series involving carbon fibers was really effective. In contrast, manufacturing from reinforcing fibers containing mullite and amorphous silica (e.g. Nextel 440) worked with adequate stability to meet the industrial requirements.

For a long time, all this has been explained by the wettability problems, so research efforts have also focused on improving wetting. However, when we started to manufacture Dialed carbon fiber reinforced composite wires, the results of the ‘dry’ (without molten metal, at room temperature) pulling experiments performed during the development of the inlet orifice revealed that the biggest obstacle was not the weak wetting but the fragmentation and fluffing of the fiber roving. As a result of this discovery, the entire gas-pressure system was completely transformed. In this major design, manufacturing, experimental and material testing work, our excellent post-graduate students played a key role: Péter Törzsök and Károly Tihanyi. Thanks to their extraordinary work, the problem of manufacturing carbon fiber reinforced aluminum matrix composite wires has been solved, and 15 years after the first and only successful series of experiments [4] at Northeastern University (Boston, MA, USA), we managed to repeat it in Budapest [12].

An important element of the solution was to discover the pullability characteristics of the fiber roving and to carry out the appropriate development work to ensure the required pullability (these results have not been published yet).

To characterize the pullability of fiber tows or roving, we developed a testing procedure: the so-called TPTK test. The essence of this is that a loop formed from the fiber bundle is drawn onto the edge of a tool with a polished surface, by uniformly pulling its two branches; the typical dimensions of the tool are shown in **Figure 9** and the test arrangement is shown in **Figure 10**.

Figure 11 – the TPTK diagram – shows the change of tensile force on two types of fiber tow. During drawing, the filaments and the fiber tow itself break at the forced bending angle and bending radius. We look for the greatest force; this is

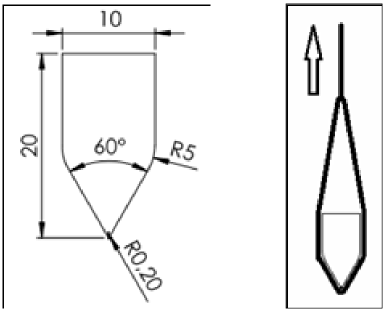

Figure 9. *The tool developed for testing pullability and the outline of the TPTK test*

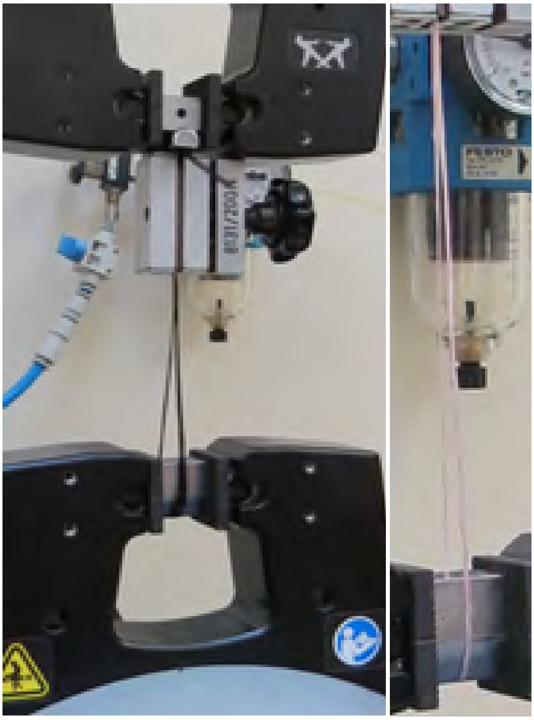

Figure 10. *Mounting the tool developed for testing pullability in the tensile testing machine, using different fiber bundles as an exam-ple*

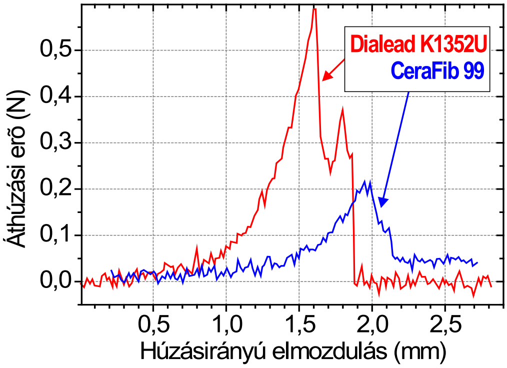

Figure 11. *TPTK diagram of two types of reinforcing fiber*

the TPTK factor that represents a numerical characteristic of pullability.

Table 1. shows the max. force, namely the TPTK factor, characteristic of the pullability for six different reinforcing fibers.

Table 1. *Test data of six reinforcing fibers*

Fiber type	Number of filaments	F_{max} (N)
Tyranno TY-S1A04PX	400	5,11
Tyranno TY-S1A04PX	400	5,05
Tyranno TY-S1A04PX	400	4,06
Dialead K1352U	2000	0,59
Dialead K1352U	2000	0,50
Dialead K1352U	2000	0,59
Dialead K63712	12 000	1,93
Dialead K63712	12 000	1,31
Dialead K63712	12 000	1,85
CeraFib99	468	0,21
CeraFib99	468	0,21
CeraFib99	468	0,17
CeraFib99	468	0,22
Nextel 440	750	2,49
Nextel 440	750	3,51
Nextel 440	750	2,49
Nextel 610	400	0,91
Nextel 610	400	0,83
Nextel 610	400	0,97

4. Evaluating the results

The TPTK diagram, of course, can be evaluated along a wide variety of alignment principles, in which the various features of the filaments – e.g. the number and cross-section of the filaments, the condition of the surface coating of the fiber tow, etc. – can be incorporated, but our experience shows that the maximum value of the pulling force measured during the TPTK test is perfectly suitable for characterizing pullability.

However, we believe that using the TPTK test could provide meaningful information not only for a tow, but also for more tows containing fiber roving, and also for individual filaments. The latter requires a measuring system such as the three-point bending test of the filaments [13] or the filament damage mechanisms due to slip and kink [14, 15].

Generally, in the manufacture of composite wires, depending on the wire diameter and the number of filaments of the tow, 5 to 20 tows must be combined in a fiber roving and fed across the inlet orifice into the gas-pressure system.

During our many years of research, we have found that the increase of the number of combined tows (e.g. Nextel 440) in terms of well pullable reinforcing fibers has no significant effect on pullability. At the same time, in the case of very fragile fibers, pullability is considerably deteriorated by the increase in the number of tows. Even when using up carbon fibers, the pullability of the fiber roving is deteriorated when the diameter of the composite wire requires the introduction and pulling across of more than one tow.

For this reason, we have evaluated the results of TPTK tests based on breakage of the fiber loops, that the force measured during the test is very appropriate indeed for the characterization of the pullability. Thus, the necessarily different tensions when combining multiple tows do not cause any disruptions.

5. Conclusions

Based on the results of the above-mentioned research work and its evaluation, we regard the following conclusions as important to emphasize.

In the production of aluminum matrix composite wires by the Blücher process, the pullability of the reinforcing fibers shall be considered to be a basic functional characteristic. The technical meaning of pullability is that the fiber roving can be pulled through the orifices of the gas-pressure system, especially in the inlet orifice, without fluffing and breaking of fibers causing fracture of the whole fiber roving.

A new test procedure was described for the characterization of pullability, which is based on a bending-pulling-shearing load of the closed loop formed from a piece of fiber tow under forced conditions, until full breakage occurs. For the quantitative characterization of pullability, the TPTK factor was introduced, which is the same as the maximum force measurable during the test.

Based on the pull-across experiments of the reinforcing fibers and the experiments on the production of composite wires as well as the TPTK tests, it can be concluded that the production of composite wires by the Blücher process can only be successful if the TPTK factor of the selected reinforcing fiber is greater than 1. Accordingly, pure oxide ceramic fiber and carbon fiber tows with a low number of filaments should not be used.

Acknowledgments

Among the authors, Enikő Bitay was supported in her research work by the MTA Domus Hungarica Grant Program.

References

[1] Blucher J.T., Narusawa U., Katsumata M., Nemeth A.: *Continuous manufacturing of fiber-reinforced metal matrix composite wires – technology and product characteristics*. Composites Part A: Applied Science and Manufacturing 32/12. (2001) 1759–1766. https://doi.org/10.1016/S1359-835X(01)00024-0

[2] Matsunaga T., Ogata K., Hatayama T., Shinozaki K., Yoshida M.: *Effect of acoustic cavitation on ease of infiltration of molten aluminum alloys into carbon fiber bundles using ultrasonic infiltration method.* Composites Part A: Applied Science and Manufacturing, 38/3. (2007) 771–778. https://doi.org/10.1016/j.compositesa.2006.09.003

[3] Nadler J. H., Isaacs J. A., Kowalski G. J.: *Hydrodynamic modeling of a continuous metal matrix composite fabrication process as a cylindrical array.* Materials Science & Engineering: A, 297/1–2. (2001) 132–137. https://doi.org/10.1016/S0921-5093(00)01266-1

[4] Doktor M.: *Production and characterization of continuous fiber reinforced aluminum wires.* PhD-értekezés, Technische Universität Wien, Institut für Werkstoffkunde und Materialprüfung (2000).

[5] Miracle D. B.: *Metal matrix composites – From science to technological significance*. Composite Science and Technology, 65/15–16. (2005) 2526–2540. https://doi.org/10.1016/j.compscitech.2005.05.027

[6] Evans A, Marchi CS, Mortensen A: *Metal matrix composites in industry: an introduction and a survey*. Kluwer Academic Publishers, Dordrecht, 2003.

[7] Ashby M., Sherdiff H., Cebon D.: *Materials, engineering, science, processing and design*. Butterworth-Heinemann, Oxford, 2007.

[8] Michaud V., Mortensen A.: *Infiltration processing of fibre reinforced composites: goveerning phenomena.* Composites Part A: Applied Science and Manufacturing, 32/8. (2001) 981–996. https://doi.org/10.1016/S1359-835X(01)00015-X

[9] Margueritat-Regenet C.: *Elaboration et caractérisation de fils composites C/Al. Infiltration spontanée et continue par activation chimique du mouillage.* Thèse de doctorat, Ecole nationale supérieure des mines, Paris, 2002. https://hal.archives-ouvertes.fr/tel-00005642/

[10] *High-Performance structural fibers for advanced polymer matrix composites*. National Research Council, The National Academies Press, Washington, D.C., 2005. https://doi.org/10.17226/11268

[11] Ashbee K. H .G.: *Fundamental principles of fiber reinforced composites.* Second Edition. Technomic Publishing Company, Lancaster, 1993.

[12] Tihanyi K: *Fémmátrixú hibrid anyagok gyártása.* Diplomamunka. BME Anyagtudomány és Technológia Tanszék, 2013.

[13] Steinmann W., Saelhoff A. K.: *Essential properties of fibres for composite applications.* In: Fibrous and textile materials for composite applications. Textile Science and Clothing Technology (Szerk: Rana, S., Fangueiro, R.), Springer, Singapore, 2016. 39–73. https://doi.org/10.1007/978-981-10-0234-2_2

[14] Clawson J. K.: *Structure and defects in high-performance aramid fibers*. Master Thesis, University of Illinois, Urbana, 2013. http://hdl.handle.net/2142/46888

[15] Leal A. A., Deitzel J. M., Gillespie J. W.: *Compressive strength analysis for high performance fibers with different modulus in tension and compression.* Journal of Composite Materials, 43/6. (2009) 661–674. https://doi.org/10.1177/0021998308088589