Meccanica dei Materiali e delle Strutture
Vol. 2 (2011), no.1, pp. 17--27
ISSN: 2035-679X
Dipartimento di Ingegneria Civile, Ambientale ed Aerospaziale - DICA

EFFECT OF SURFACE FINISH ON THE MECHANICAL BEHAVIOR OF DACRON© 360 WOVEN

Salvatore Benfratello, Antonino Cirello* and Luigi Palizzolo

Dipartimento di Ingegneria Civile, Ambientale e Aerospaziale e Geotecnica (DICA)
Università degli Studi di Palermo
Viale delle Scienze, 90128 Palermo, Italy
e-mail: salvatore.benfratello@unipa.it – luigi.palizzolo@unipa.it

*Mi. Me. srl
Via delle Industrie,8 90040 Isola delle Femmine, Palermo, Italy
e-mail: design@doylesails.eu

(Ricevuto 7 Febbraio 2009, Accettato 10 Marzo 2009)

Key words: Dacron, Mechanical behavior, Woven, Surface finish.

Parole chiave: Dacron, Comportamento costitutivo, Tessuti, Finitura superficiale.

Abstract. *In the present paper some experimental analyses effected on Dacron© 360 woven with and without surface treatment, aimed to characterize the effect of this treatment on the constitutive behavior, are presented. This woven, widely adopted in sail manufacturing, is obtained by weaving polyethylene terephthalate (PET) yarn and it shows some peculiar features due to the manufacturing process. The experimental tests, in terms of tensile tests, clearly show the orthotropy features of the material and the effect of the treatment which results in a stiffer behavior especially along the warp and bias direction and in an increment of ultimate strength in all directions.*

Sommario. *Nel presente lavoro vengono presentate alcune indagini sperimentali mirate alla caratterizzazione dell'effetto del trattamento superficiale sul comportamento costitutivo di un tessuto in Dacron© 360. Tale tessuto, largamente utilizzato nella realizzazione di vele, è ottenuto dalla tessitura di fili di polietilene tereftalato (PET) e presenta alcune peculiarità dovute al processo manifatturiero. Le prove di trazione realizzate evidenziano le caratteristiche di ortotropia del materiale e l'effetto del trattamento superficiale che si manifesta principalmente in un comportamento più rigido nella direzione dell'ordito ed in quella inclinata e in un aumento della resistenza ultima in tutte le direzioni.*

1 INTRODUCTION

Since the early age of the mankind the necessity to develop an efficient transport machine have involved a large human resources. One of the first example of the effort to achieve this fundamental goal is the painted disc found in Kuwait dating to the late 5th millennium BC and representing a ship under sail[1].

Nowadays, even if the development of thermal engines have relegated the sail only to recreational use, the impellent necessity to limit the emission of greenhouse gases has pushed the interest toward sail technologies. From the other hand, sail is a fundamental field for developing technological solutions from many engineering research fields (material, aerodynamics, hydrodynamics and so forth).

In the early age of sailing the adopted material for sail construction has been only a natural fibre like cotton or flax, being the latter the traditional fibre of sails until it was supplanted by cotton during the 19th century. At first cotton was used as a matter of necessity in the United States as it was indigenous fibre and its spreading was improved due to the difficulties in flax supplying during wars as well as to the increased demand for sailcloth for military use. From mechanical point of view flax is stronger while cotton is lighter, and both these natural fibres have poor resistance to rot, UV light and water absorption. From sail engineering point of view, the typical sails of ancient boat were made with very low aspect ratio and used only by running and broad reaching condition; therefore there was no pregnant necessity to have form stability. With the aerodynamics improvements and understandings in the early ages of 20th century, the sail planform became tall and flatter than before so that natural fibres became obsolete. At the same ages the development of the synthetic fibres like polyester ones push the sail design to modern sail configurations. Sailmakers have nowadays a very wide range of materials to made the sail. The key features that distinguish a “fast” from a “slow” sail are its shape related to the particular boat and rig and its ability to consistently maintain that shape. These two features rely mostly on the design of the sail (the way the panels are placed together) and the sail cloth used. Regarding the sail design, in the early time, sail construction followed the development of the cloth so that for a long time sail design followed the vertical scheme (figure 1a) in order to ensure long life due to double cloth thickness along panel junction. At the end of the 19th century the Great Nathanael Heresohoff suggested to change towards cross cut scheme following which the cloth should be oriented with fill along maximum stress direction (figure 1b) but this suggestion has not been adopted until 1920.

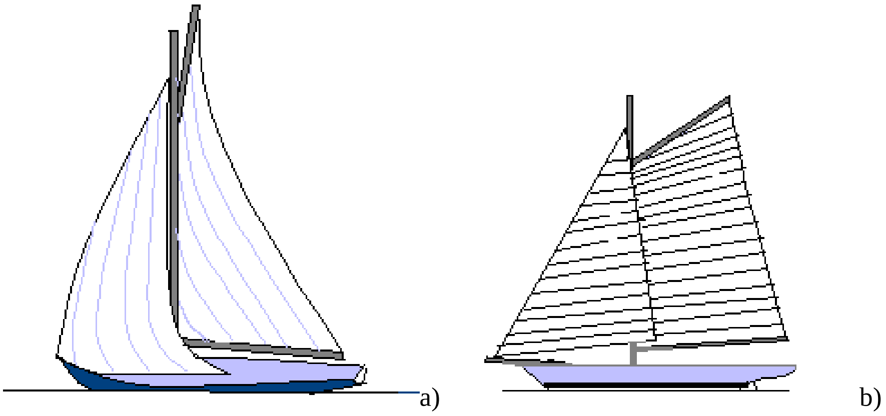


Figure 1: a) Vertical seam construction scheme; b) Cross cut construction scheme.

The developments of scientific knowledge in aerodynamics and material behaviour suggested an optimization approach to sail construction. In figure 2 a typical sketch of the principal stress direction for sail in upwind condition is reported. In order to improve the sail performance sailmakers try to use the anisotropic cloth characteristics orienting panels along the maximum stress direction. This approach led to different sail cut, the most adopted of which (radial, biradial and full radial) are sketched in figure 3. For this kind of sails the strengthen direction should be warp. At the same time it is fundamental to remark that sail is a "live" 3D shape, subjected to several wind and sea conditions so the principal stress directions are variable and it is very important that even fill and bias direction have the necessary strength to keep the designed shape.

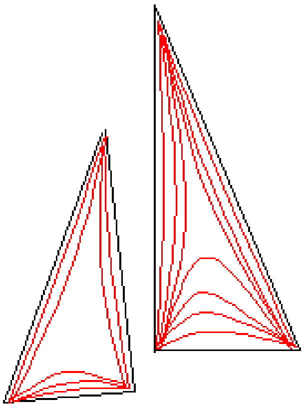


Figure 2: Principal stress direction in upwind condition.

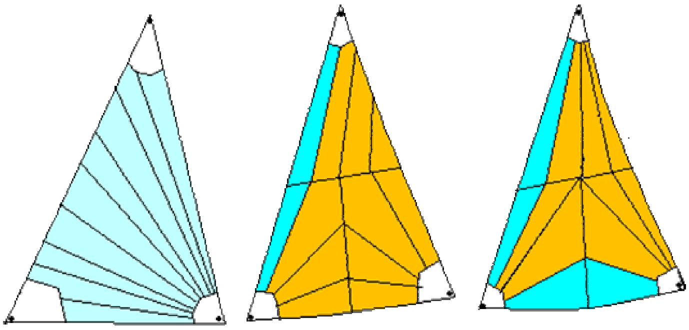


Figure 3: From left to right: Radial, Biradial, full radial construction scheme.

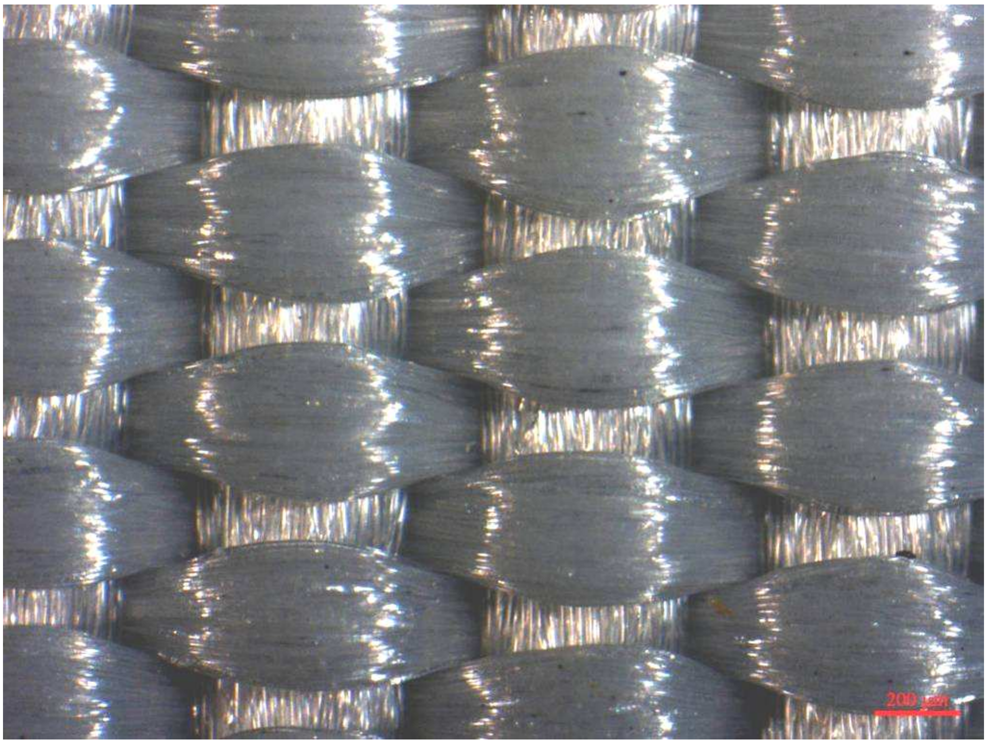
Regarding the sail cloth used, missing out natural fibres already described above, the most adopted synthetic fibres are: Nylon, Polyester (PET), PEN fiber (Pentex), Kevlar, Technora, Twaron, Spectra, Dyneema, Certran, Zylon (PBO), Vectran, Carbon Fiber. Due to its characteristics and low price PET (whose commercial name is Dacron$^{©}$) is the most used material in sailcloth construction. The Dacron$^{©}$ sailcloth is a woven fabric with different mechanical performances in fill and warp direction and like all other woven cloth shows a relevant weakness in bias direction. In order to overcome this drawback and to improve general performances of the cloth (e.g. surface roughness, water absorption), manufacturing industries defined several cloth treatments (also called finishes), the selection of which strongly depends on the requirements of the sail. It is important to emphasize that Dacron$^{©}$ woven fabric is usually used in cross cut construction, and that at the same time the sail has not a flat surface with only one load direction; as a consequence the sailcloth is loaded by different directions and it is important that cloth possesses also good warp and bias mechanical behaviour in terms of both strength and stiffness. In order to achieve these behaviours a lot of Dacron$^{©}$ fabrics have been developed with threads of different characteristics in weft and warp directions combining this with different cloth treatment.

Aim of the paper is to analyze the effects of the cloth treatment on the mechanical behaviour of a commercial woven fabric. In order to achieve this goal, in the following sections the cloth with and without treatment are first examined by a geometric point of view; once the cloth has been characterized tensile tests have been performed following international standard in order to identify the mechanical characteristics. Finally, an examination of the tested specimens at the end of the tests are also reported and the results discussed and commented. The cloths (with and without treatment) from which the specimens tested in the research have been prepared, have been produced by world leading industries Dimension-Polyant GmbH.

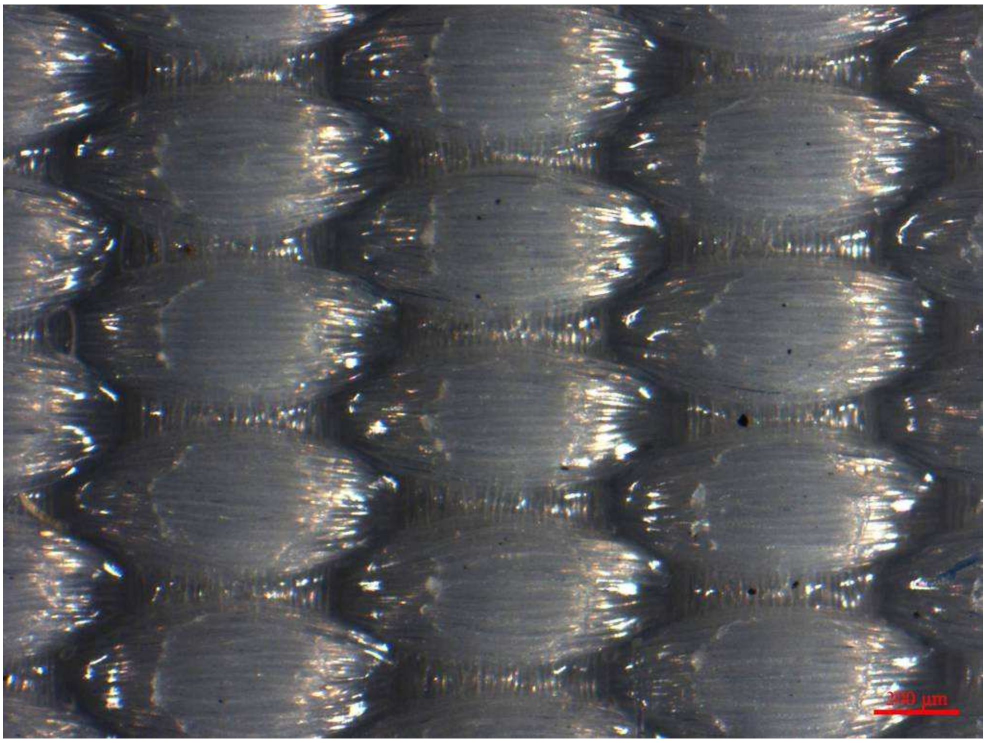
2 GENERAL ANALYSIS

The first step in this research has been the choice of the cloth to be studied. After a deep investigation it has been decided to focus the attention on Dacron$^©$ 360 for its wide use. Dimension-Polyant informed that the selected cloth is available with only one type of treatment, called impregnating treatment. This mainly consists in running the cloth through a bath of a melamine resin and in squeezing it. Depending on the amount of resin remaining in the cloth after squeezing process different stiffness levels are obtained. The cloth under examination is available only with a medium stiffness level and this treatment is called MTO. In order to characterize the amount of resin in the treated cloth two specimens prepared from treated and non-treated cloth but with the same shape and dimensions have been weighted with Sartorius ED 22025-CW electronic weighting system (sensitivity 0.01 g) revealing that the treated cloth is 10% heavier than the non-treated one being this difference ascribed to the melamine resin.

The second step has been the investigation of the material under examination focusing the attention to the geometric characteristics of the cross-section related to weaving. The images have been obtained with a Leica MS5 microscope equipped with a Kodak DC180 camera and related software. In figures 4 microscope photos of the surface of a specimen obtained from woven with no finish (figure 4a) and with MTO finish (figure 4b) are reported. A comparison of these figures immediately reveals a first effect of the treatment: in the case of no treatment, warp (horizontal) and weft (vertical) threads are well separated and they appear more defined. In the case of MTO treatment, instead, the warp threads are closer each other. The effect of the treatment is also clear when examining with the microscope the cross-section in weft (figures 5) and warp (figures 6) direction. Besides the typical pattern of weft and warp threads, figures 5 and 6 confirm that the treatment process deeply change the aspect of the cloth since the treated cloth appears with fibres “glued” with melamine resin resulting in a more compact general shape. From the other hand, non-treated cloth appears with fibres “independent” resulting in a more defined shape. Another important geometric characteristic is the thickness: in the case of non-treated cloth it is equal to 0.44 mm while for treated cloth it is equal to 0.38 mm, with a decrement of about 14%. This macroscopic characteristics is confirmed by microscope examination of the cross-section in the warp direction reported in figures 7. In these figures the main geometric characteristics of the fibres and threads are reported for both the case of non-treated and treated cloth. First of all it has to be observed that the thread cross-section shows the typical lenticular form already studied by Pierce[2] and Shanahan et al[3]. As it can be easily recognized the decrement of the two axes of this lenticular form is equal to 11% and to 21%, respectively for the major and minor axis. This remark suggests that the form of the cross section is also changed, resulting in a more squeezed shape in the case of treated cloth.



a)



b)

Figure 4: Microscope photos of the woven surface - a) 40x particular of woven with no finish. b) 40x particular of woven with MTO finish.

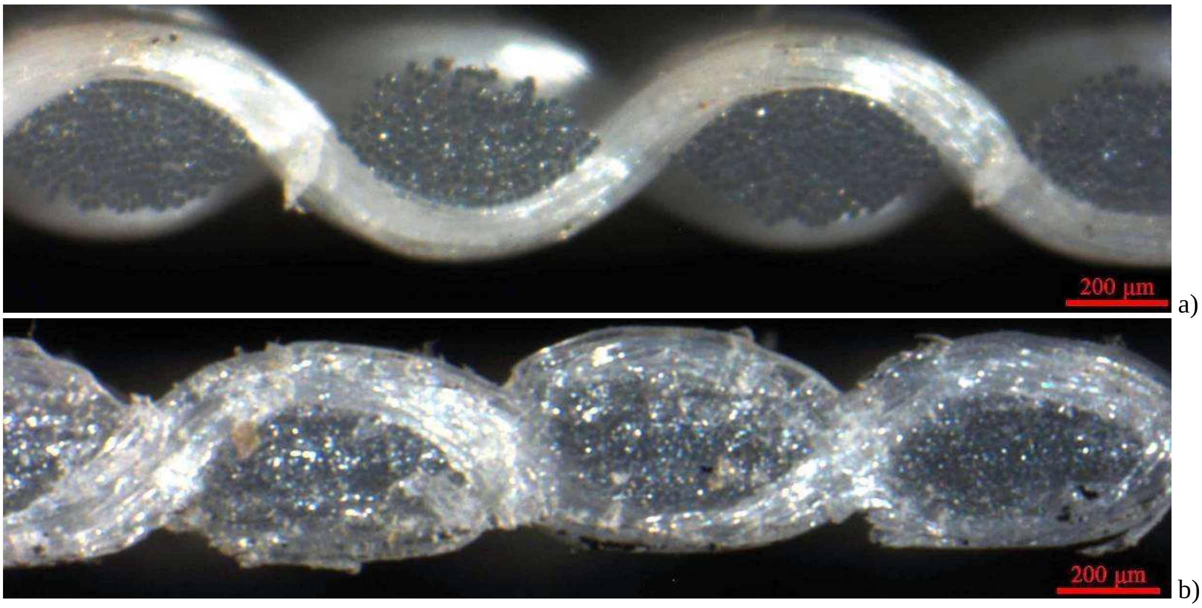


Figure 5: Microscope photos of the woven weft cross-section - a) 40x particular of woven with no finish. b) 40x particular of woven with MTO finish.

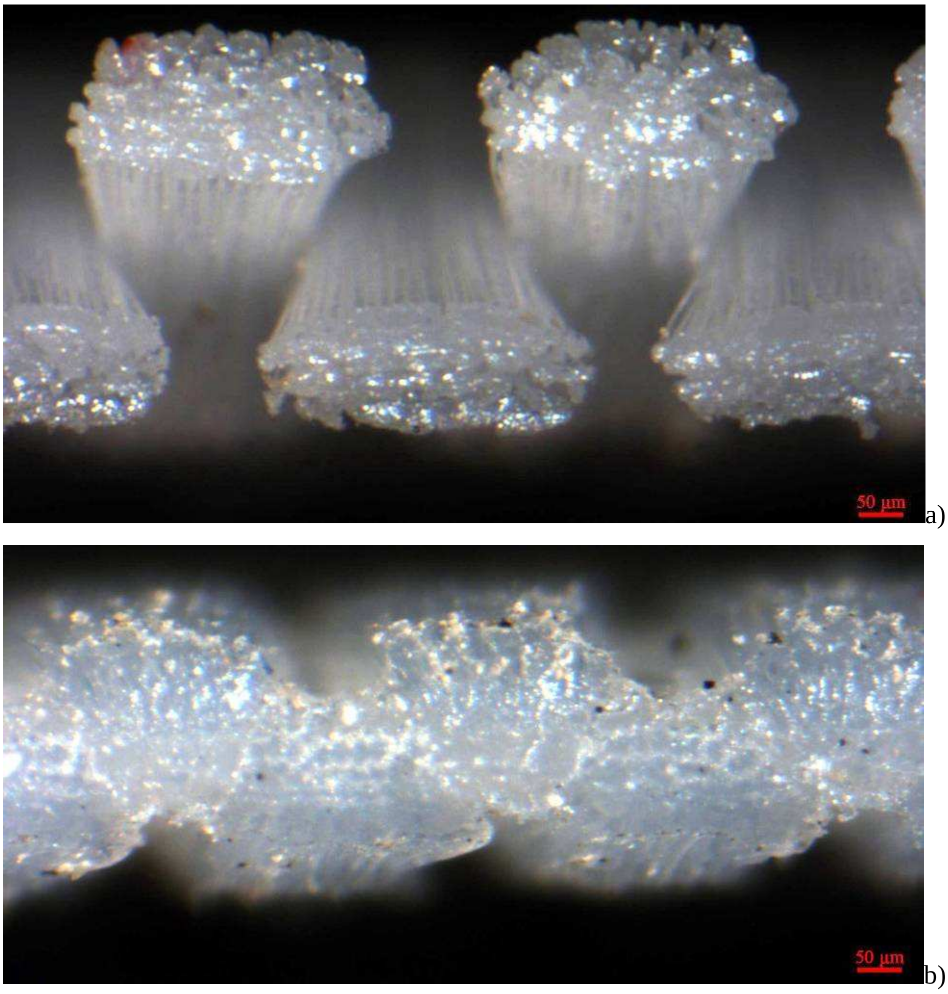


Figure 6: Microscope photos of the woven warp cross-section - a) 40x particular of woven with no finish. b) 40x particular of woven with MTO finish.

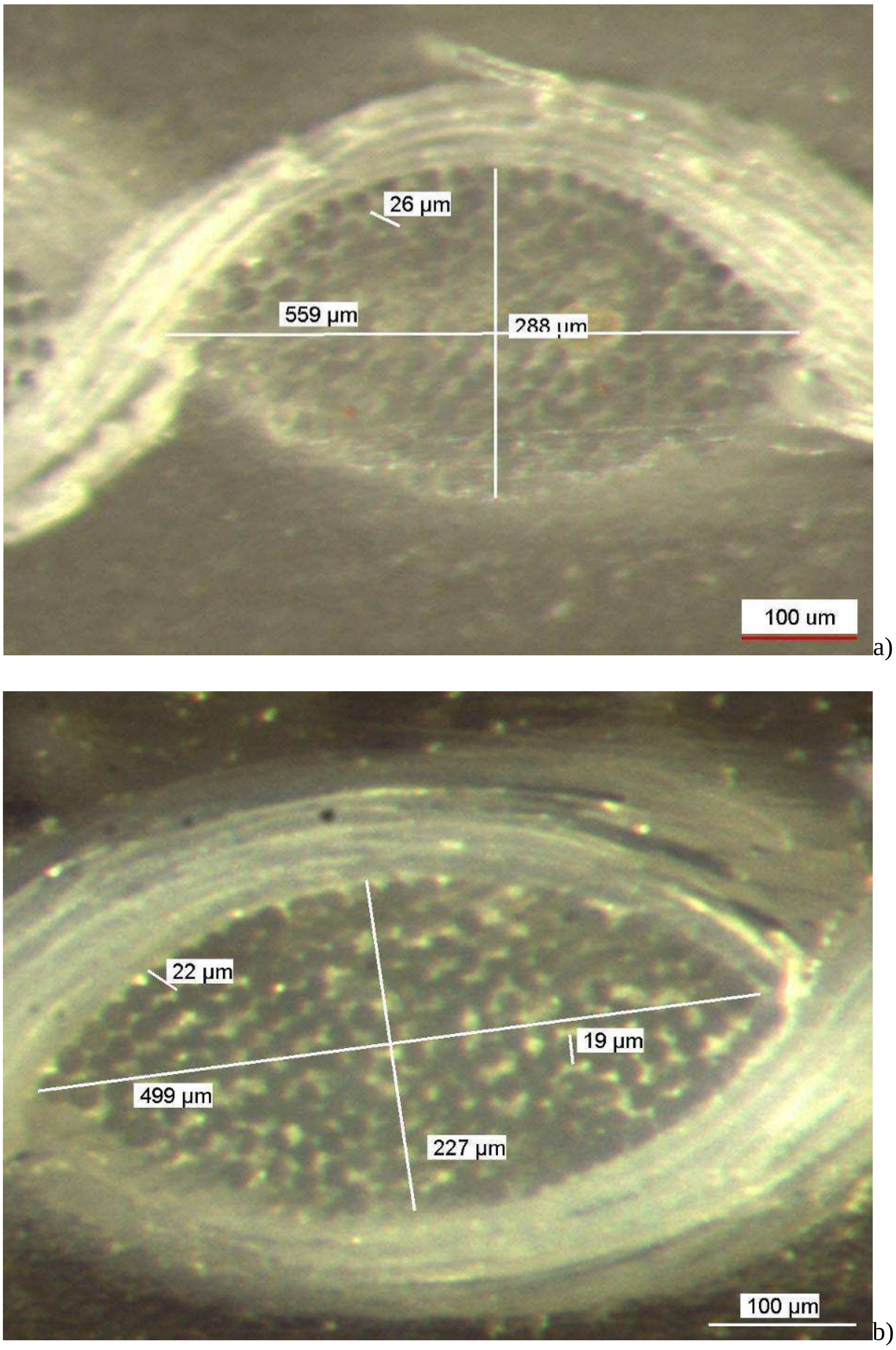


Figure 7: Microscope photos of the woven warp cross-section - a) 400x particular of woven with no finish. b) 400x particular of woven with MTO finish.

3 MECHANICAL ANALYSIS

In order to analyze the constitutive behavior of the material under examination and to identify the effect of the treatment a standard tensile test has been performed on specimen of both cloth. In particular, the aim of this test is to evidence the effect of the treatment on the ultimate stress and strain as well as the Young modulus of the material. All the described tests have been performed with Zwick&Roell Z600 testing equipment handled by TextXpert v11.02 software. The selected specimen is a strip of 300 mm length and 50 mm wide. The dimensions of the specimen have been selected making reference to UNI EN ISO 13934-1 standard[4]. In figures 8 a photo of the selected specimen with and without rubber shim (following the adopted standard) and one of the experimental set-up are reported. In order to evaluate the constitutive behavior of the material, it is required to define the stress acting on the specimen during the test. However, from an examination of figures 5 and 6, it can be easily recognized that the cross -sections are not constant neither along the length nor along the width of the specimen. In order to overcome this problem in the following of the paper the bounding rectangular cross-section has been adopted as reference one considering the obtained results as an underestimation of the real ones.

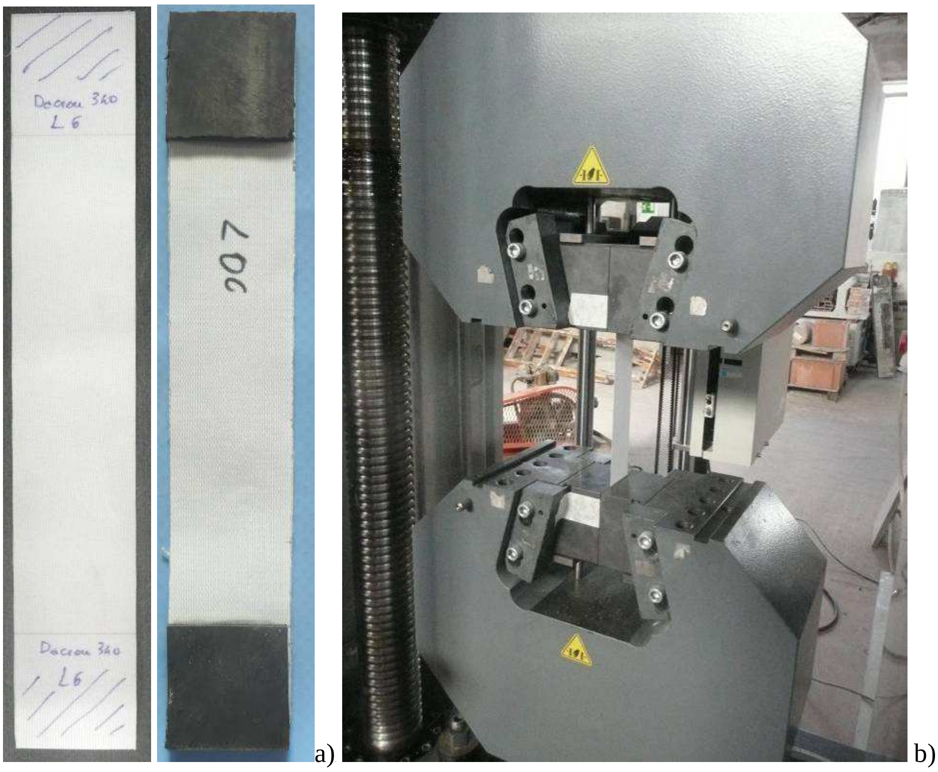


Figure 8: a) Adopted specimen without and with rubber shim. b) Experimental set-up.

3.1 Tensile test

The tensile test has been conducted following the UNI EN ISO 13934-1 standard. According to the standard, in order to avoid the rupture of the specimen near the grips, a rubber shim on both side of each end of the specimen has been glued with a polyester resin. Since the length of the rubber shim (put between the grips) has been fixed equal to 50 mm and that of the specimen equal to 300 mm, as a consequence, the free length of the specimen is equal to 200 mm. The test has been performed in displacement control, with a preload of 10 N and by selecting three different displacement rates. Three different sets (each composed of three specimens) of specimens have been tested: in the first set the specimens have been obtained with their length aligned with the weft direction; in the second set the specimens have been obtained with their length aligned with the warp direction; in the third set the specimens have been obtained with their length aligned with the bias direction, the latter being selected equal to that at 45° with respect to the warp (weft) direction. As stated above three different displacement rates (v_1 = 0.5 mm/min, v_2 = 5.0 mm/min, v_3 = 50.0 mm/min) have been selected in order to test the dependency of the material behavior on the “loading” rate. In order to test the repeatability of the results, a further set equal to the second one described above has been tested showing an almost coincidence of the obtained results whose differences can be ascribed to the intrinsic errors in preparing the specimen and in inserting it between the grips.

In Figure 9 the results of the tensile test are reported in terms of nominal stress vs nominal strain in the case of specimen length aligned with the weft direction. An examination of this figure immediately shows in a first range of nominal strain (0-0.025) treated and no-treated cloth behave in a very close way and the treated one possesses a Young modulus (equal to about 2 GPa) a bit stiffer than the no-treated one. In the subsequent range the constitutive behavior of the cloths changes: the no-treated one behaves in a way stiffer than the treated one. However it has to be observed that the ultimate strength of the treated cloth is about 10% higher than the corresponding one of the no-treated cloth, while the ultimate strain of the no-treated cloth is about 50% of the corresponding of the treated cloth. Another remark is that in the case of treated cloth the rupture of the specimen has been always a brittle one while the same is not true for the no-treated cloth. As it can expected the results show that the loading rate influences the results but this influence is not very high. Finally, the shape of the nominal stress- nominal strain curve is of both treated and no-treated cloth is different from that reported in Hu[5].

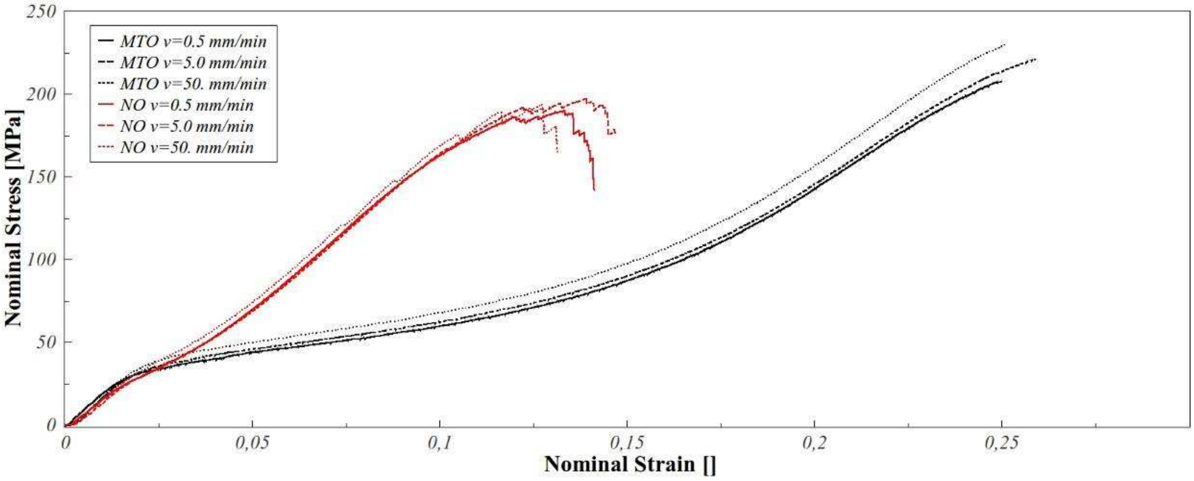


Figure 9: Tensile test results in weft direction: (black lines) woven with MTO finish; (red lines) woven with NO finish.

In Figure 10 the results of the tensile test are reported in terms of nominal stress vs nominal strain in the case of specimen length aligned with the warp direction. An examination of this figure immediately shows a very different behavior of treated and no-treated cloth. The no-treated cloth behaves almost linearly for almost the examined range of strain while the treated one shows a behavior close to that described above in the case of the weft direction. The Young modulus can be evaluated equal to 0.8 GPa and to 0.2 GPa, in the case of treated and no-treated cloth, respectively. As it has been already evidenced above, the ultimate strength is higher (of about 20%) in the case of treated cloth, while in the case under examination the strain range is very close for both type of cloth, being that of the treated one a bit higher. The kind of rupture is the same described in the case of test along the weft direction.

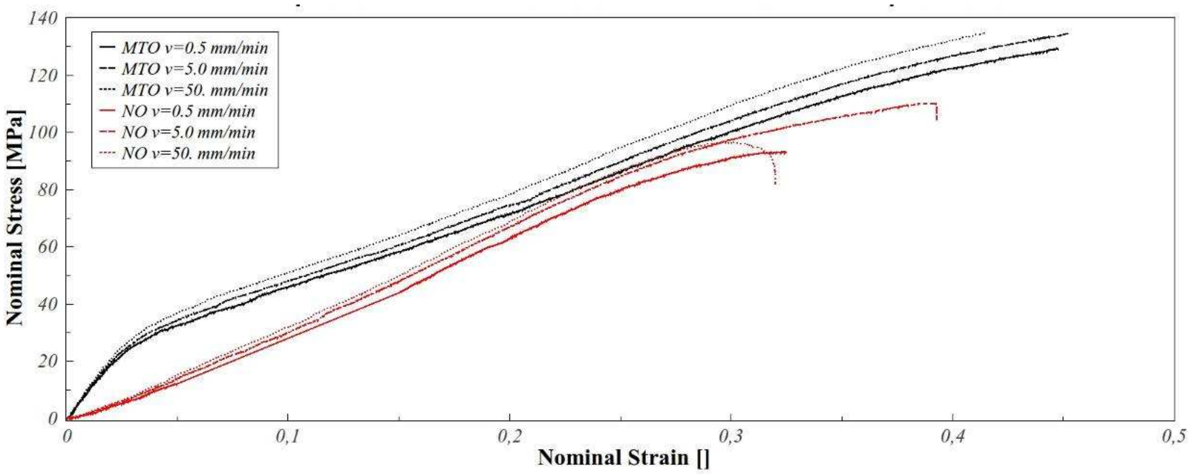


Figure 10: Tensile test results in warp direction: (black lines) woven with MTO finish; (red lines) woven with NO finish.

In Figure 11 the results of the tensile test are reported in terms of nominal stress vs nominal strain in the case of specimen length aligned with the bias direction. An examination of this figure immediately shows, as described above in the case of test along the warp direction, a very different behavior of treated and no-treated cloth. Both cloths behave in a nonlinear way, but the treated one shows a behavior close to that described in the weft direction with a negative concavity in a first range. From the other hand, the no-treated one shows a positive concavity all along the strain range. The Young modulus can be evaluated equal to 0.5 GPa and to 0.05 GPa, in the case of treated and no-treated cloth, respectively. As it has been already evidenced above, the ultimate strength is higher (of about 25%) in the case of treated cloth, while in the case under examination the strain range is close for both type of cloth, being that of the treated one higher of about 20%. The kind of rupture is the same described in the case of test along the weft direction.

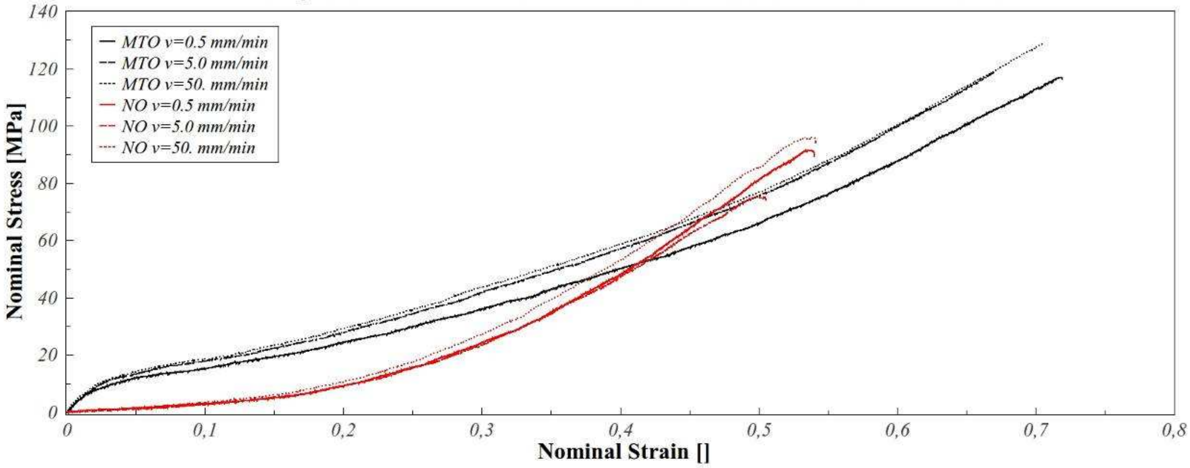


Figure 11: Tensile test results in bias direction: (black lines) woven with MTO finish; (red lines) woven with NO finish.

Finally, the shape of the nominal stress- nominal strain curve reported above no-treated cloth is close to that reported in Hu[5] while that for treated cloth no.

4 CONCLUSIONS

In the paper the effect of surface finish on the constitutive behavior of Dacron© 360 woven has been investigated by means of some experimental analyses. The analyses have been performed either by means of mechanical tests (tensile test) on strips of woven whose longitudinal direction coincides with the weft, warp and bias directions or by means of some observations performed with optical microscope. The optical image analysis reveals some peculiar features of the surface finish which changes in a very important way both the geometrical characteristics of the woven and its compactness due to the presence of melamin resin in the surface finish. The mechanical analysis reveals that the surface finish strongly influences the constitutive behavior especially in the warp and bias directions. Along these directions the surface finish changes drastically the stiffness and the ultimate strength of the material, the latter effect being present also in the weft direction. The obtained results show the positive effect of the surface finish from the sail engineering point of view which requires a material able to keep the designed shape as long as possible. The presented study opens the way for an optimization one starting from a wide plan of experimental (mainly mechanical such tensile and cyclic tests) tests towards the definition of a numerical model to be implemented in numerical design of sail. The design of the technological steps of a treatment process could also take some advantages from the reported study as well as to its developments. Another important field to be investigated as future development is that of the dynamic response of the material under investigation. Other future developments of this research are to adopt some kind of biaxial tests as well as to extend the analysis to creep tests and to environmental effects. Finally, the use of some optical full field contactless method such speckle analysis and digital image correlation is planned in order to obtain a deep insight in mechanical behavior of such materials.

Acknowledgments: Authors are grateful to Mr. Erasmo Cataldo of the Structural and Material Testing Laboratory of DICA for his support during the research. The fundamental support of Dimension Polyant GmbH and in particular that of Mr. Robert Kühnen is gratefully acknowledged.

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