Università degli Studi di Palermo

Meccanica dei Materiali e delle Strutture
Vol. 1 (2010), no.3, pp. 13-23
ISSN: 2035-679X
Dipartimento di Ingegneria Civile, Ambientale e Aerospaziale - DICA

EXPERIMENTAL CHARACTERIZATION OF DACRON© 360 WOVEN CONSTITUTIVE BEAHAVIOR

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Key words: Dacron, Constitutive behavior, Woven.

Parole chiave: Dacron, Comportamento costitutivo, Tessuti.

Abstract. *In the present paper some experimental analyses of Dacron© 360 woven aimed to characterize its 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 and cyclic tests, clearly show the orthotropy features of the material, its high strength and deformability. Finally, the examination with optical microscope of the tested specimens allows to evidence how the warp and weft yarns interact.*

Sommario. *Nel presente lavoro vengono presentate alcune indagini sperimentali mirate alla caratterizzazione del 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 manufatturiero. Le prove di trazione e cicliche realizzate mostrano le caratteristiche di ortotropia del materiale, l'elevata resistenza e la notevole deformabilità. Infine, l'analisi dei campioni testati al microscopio ottico consente di mettere in evidenza la interazione tra i fili di ordito e di trama.*

1 INTRODUCTION

The science, engineering and manufacturing of textiles have played a very important role in the development of man history since its beginning. The ability of manufacturing yarns and textiles more and more reliable from many point of view (mechanical, weight, thermic isolation and so forth) can be regarded as a fundamental step in many human technological developments, e.g. the exploration of subsea and spatial environment. In the last century the science and engineering of textiles have recieved a very important impulse due to the introduction of non-natural fibres such the synthetized and carbon ones. Thanks to the introduction of such new fibres, to decreased costs, due to production improvement and even to the knowledge of their mechanical behavior, it is nowadays possible to obtain textiles with an almost infinite range of performances and, as a consequence, useful for a very large range of applications. In this paper attention is focused to the experimental study of Dacron© woven for three fundamental reasons: the first one is that Dacron© woven applications ranges from medical apparatus (such cover of pacemaker as well as cardiovascular prothesis), until to sailcloth manufacturing; the second one is that a deep knowledge of mechanical behavior is a fundamental step for a right numerical mechanical model which is the core of an optimization algorithm; the third one is that the manufacturing process of Dacron© woven is more complicated than that of a conventional woven. Since Dacron© wovens are available in a very large variety of weigths, in this paper the attention is focused on to Dacron© 360 woven, the number indicating the weigth in grams for square meter. This woven belongs to the family balanced woven, that is the yarns are the same diameter and weight in warp and in weft directions. In the following, after a brief overview of Dacron©, the performed mechanical tests (tensile and cyclic ones) are reported and the results discussed and commented. Furthermore, a first insigth in the interaction between warp and weft yarns is also reported.

2 DACRON© BRIEF OVERVIEW

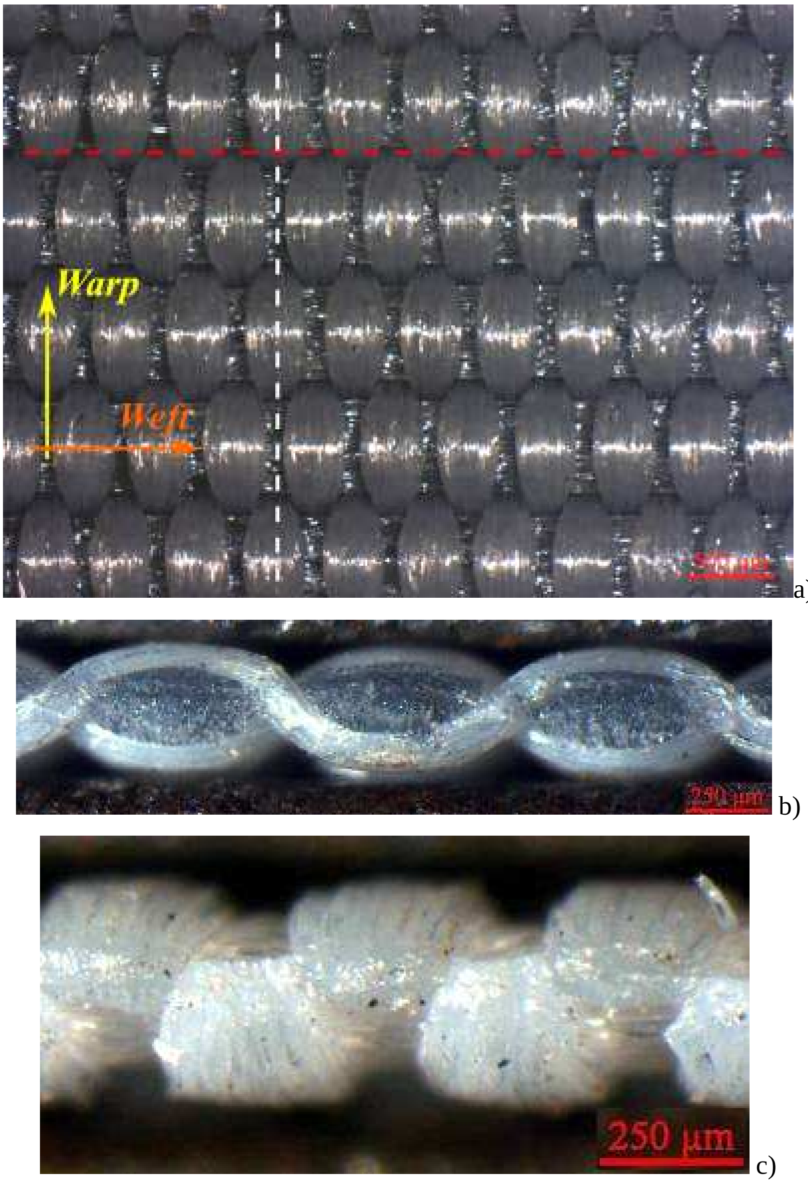
Dacron© is one of the fiber trade names of polyethylene terephthalate (PET) products and it is widely utilized in manufacturing industry. It is worth noticing that PET belongs to the polyesters family in which naturally-occurring chemicals, such as the cutin of plant cuticles can be also found. Natural polyesters and a few synthetic ones are biodegradable, but most of the synthetic polyesters are not. Depending on the chemical structure polyester can be a thermoplastic or thermoset, however the most common polyesters are thermoplastics. Fabrics woven from polyester thread or yarn are used extensively in apparel and home furnishings, from shirts and pants to jackets and hats, bed sheets, blankets and upholstered furniture. Industrial polyester fibers, yarns and ropes are used in tyre reinforcements, fabrics for conveyor belts, safety belts, coated fabrics and plastic reinforcements with high-energy absorption. Very important industrial applications of Dacron, as already mentioned, are in medical equipments (such pacemaker and vascular prothesis), in sail manufacturing and in making "plastic" bottles. Fabric woven from synthetic fibers usually shows superior water, wind and environmental resistance compared to that woven from plant-derived fibers.

In sailing industry Dacron© plays a very important role. The earliest sailcloth was constructed of woven flax; afterward, in XIX century flax has been replaced by cotton (American cotton and later Egyptian cotton). Since four decades Dacron© replaced cotton as the primary sail material and currently, most woven sailcloth is still constructed out of Dacron©, although other fibers such as Kevlar©, Spectra© and Pentex© are incrementing their use. It is just to be emphasized that nowadays a new kind of sail materials, known as laminate sail materials composed by layers of film, scrim or taffeta glued together, is widespread due to their performances. In woven industry it is usual to refer to three different directions characterizing the manufacturing process and, as a consequence, the woven mechanical behavior: weft (fill) is the direction across the width of a sail fabric, warp is the direction along the length of a sail fabric, directions at a significant angle to the warp and fill are all called the bias, but the common one is that at 45° with respect to warp and weft. These terms come from the weavers' names for the two directions of thread in the loom. Dacron© woven is a fill-oriented weave, in which the warp fibers (running from the upper left to the lower right) are woven over and under the straight fill yarns. In this construction, all of the crimp is in the warp and stretch in the fill direction is minimized. Four primary factors affect the quality of Dacron© sailcloth: yarn quality, yarn content, tightness of the weave and type of finish. Yarn quality depends on its tenacity (breaking strength), modulus (resistance to stretch), creep (long term stretch) and "weaving quality"; yarn content relates to the aspect ratio of the particular sail. Lower aspect sails require a more balanced weave, with fibers of similar denier and count in the warp and fill. Higher aspect ratio sails, such as blade jibs, require more heavier fibers along the load lines and fewer across the sail. The tightness of the weave varies for a number of reasons, including the size and the shrinkage of the yarns employed, the smaller the yarn denier, the tighter the weave. Higher shrink yarns will produce a tighter weave than lower shrink yarns. The tighter a sailcloth is woven, the better it will perform. The type of finish used on the sail greatly affects the "hand", or feel, of the material. Also, highly resinated materials often rely on the resin for stability and when, after extended use, the resin begins to break down, the sail begins to change shape. Resin quality and quantity greatly affect the overall quality and cost of the sailcloth. Other parameters affecting the quality of the sailcloth are flex life, UV-resistance, elongation and flutter stability. From mechanical point of view sail fabric properties, especially stretch, are not isotropic, (that is, they vary with direction), fabric orientations are significant.

In literature is reported that Dacron© fabric is manufactured in four different phases: in the first one the fabric is impregnated with formaldehyde resin in order to be plasticized; in the second one the fabric is heated in such a way that it shrinks of about 10% in order to improve its consistency; the latter is further incremented in the third phase, the calendering one, in which the fabric is packed between heated rollers; the final phase is that of dressing in which the finishing of the fabric is improved by epoxy resins.

3 EXPERIMENTAL ANALYSIS

The first step in the experimental analysis has been the investigation of the material under examination focusing the attention to the geometric characteristics of the cross-section related to weaving. In figure 1 a microscope photo of the surface of a specimen is reported together with two other photos of the typical cross-section in the weft and warp direction, respectively. An examination of these figures immediately reveals the particular form of the cross-sections which are different each other and very different to the rectangular one. A first remark is that the yarn cross-section is not circular but very close to an elliptic or lenticular one; this is a peculiar characteristic of high tightly woven and it can be fundamentally ascribed to the different phases of manufacturing described above. In literature these particular forms of cross-section are well known and they have been studied by Pierce[1] and Shanahan et al[2]. In order to evaluate the mechanical characteristics of the material under investigation it is necessary the evaluation of the area of the cross-section. After a simple analysis with an appropriate software it has been deduced that the cross-sections in the weft and warp directions can be evaluated equal to about 50% and 60% of the corresponding bounding rectangular one, respectively. In literature, however, due to the small value of the thickness of woven these differences are usually neglected and the results are reported in terms of load divided the width of the specimen. Another remark is that, strictly speaking, the above described cross -sections are not constant along the length and the width of the specimen. This remark suggests to adopt in the following of the paper as reference cross-section the bounding rectangular one and to consider the obtained results as an underestimation of the real ones. Another important aspect is related to the mechanical interaction between warp and weft yarns but it will not faced in this paper, leaving it to a successive development of the research. The fundamental geometrical characteristics of the woven under tests are the following: thickness equal to 380 μm,warp yarn width equal to 350 μm,weft yarn width equal to 535 μm.



a) b) c)

Figure 1: Microscope photos of the specimen - a) 20x particular of the specimen. b) 40x particular of the cross-section in the weft direction. c) 40x particular of the cross-section in the warp direction.

In order to analyze the constitutive behavior of the material under examination, a wide plan of experimental investigations has been defined. In particular, this plan includes two different types of experimental investigations: 1) the first one is the standard tensile test in order to check the ultimate stress and strain as well as the Young modulus of the material; 2) the second one is a standard cyclic test in order to check the material behavior for slowly time varying loads. Dynamic tests are planned in a future development of the research. 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 [3]. In figure 2 a photo of the selected specimen and one of the experimental set-up are reported.

a) b)

Figure 2: a) adopted specimen. b) Experimental set-up.

3.1 Tensile test

The tensile test has been conducted following the UNI EN ISO 13934-1 standard. The length of the strip put between the grips has been fixed equal to 50 mm and 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 two 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 warp direction; in the second set the specimens have been obtained with their length aligned with the weft 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 two different displacement rates (v_1 = 5.0 mm/min, v_2 = 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 3 the results of the tensile test are reported in terms of nominal stress vs nominal strain, that is not taking into account the reduction of the cross-section. An examination of this figure immediately shows, as it can expected, that: 1) the nominal strain range is very high (up to 65% in the bias direction) due to the chemical structure of the yarn material; 2) the loading rate influences the results of the test. In particular, the loading rate influences both the resistance (about 10% except that in the bias direction) and the stiffness, the latter meaning that at a given nominal stress the nominal strain is lower for an higher loading rate. An examination of the first part of these graphs allows the evaluation of the nominal Young modulus of the material, that is about 2 GPa in the weft direction, about 0.8 GPa in the warp direction and about 0.5 GPa in the bias direction. Another important remark is that the reported graphs show an high nonlinear behavior which is different between the weft and bias direction with respect to that of the warp direction. The formers present two concavities, the first one negative and the second one positive while the latter only a negative one followed by a very large linear behavior; further the concavity in the weft direction is higher than that in the bias direction. It has to be emphasized that the reported results for warp and bias differ from those reported in literature[4] for a conventional woven, confirming the peculiar characteristic of Dacron©. Finally, it is worth noticing that all the tested specimens showed a brittle rupture usually near the grips.

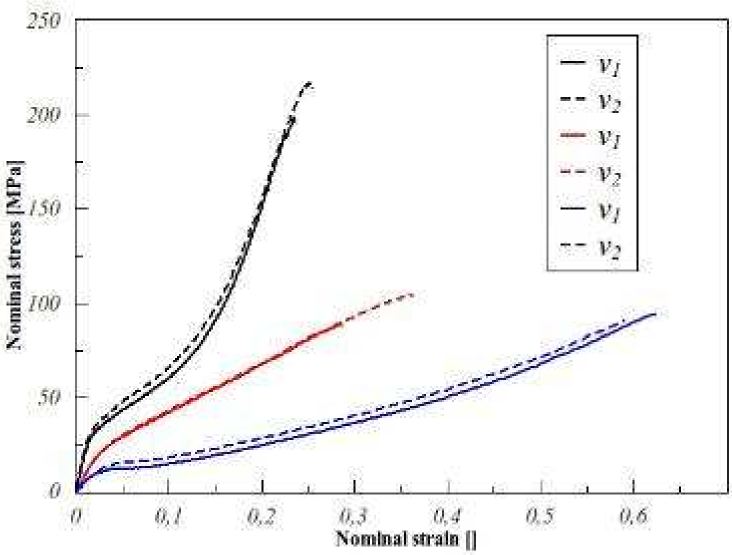


Figure 3: Tensile test results: (black lines) weft direction; (red lines) warp direction. (blue lines) bias direction.

3.2 Cyclic tests

Two other sets of specimens have been prepared following the same indications described in foregoing sections, in order to be put under cyclic tests. These tests have been performed in displacement control with a selected rate equal to 1 mm/min and each test is characterized by ten cycles. Since no indications have been found in international standards, two different cyclic tests have been performed, differencing each other for the maximum allowable load: in the first test the maximum load is equal to the rounded value of the one half of the ultimate load obtained in the corresponding tensile test, while in the second one the ultimate load has been divided by 8. In Table 1 the adopted maximum load are reported.

	Tensile test	Cyclic Tests	
Specimen	$F_{ultimate}$ [N]	F_{max} (cyclic 1) [N]	F_{max} (cyclic 2) [N]
Weft	3800	2000	500
Warp	2000	1000	250
Bias	1800	1000	250

Table 1: Load values adopted in cyclic tests

In Figure 4 and in Figure 5 the results of the above described cyclic tests are reported. In particular, in Figure 4a and in Figure 5a the results are reported in terms of load – elongation, while in Figure 4b and in Figure 5b the same results are reported but in normalized form, in order to obtain an easier comparison between the obtained results.

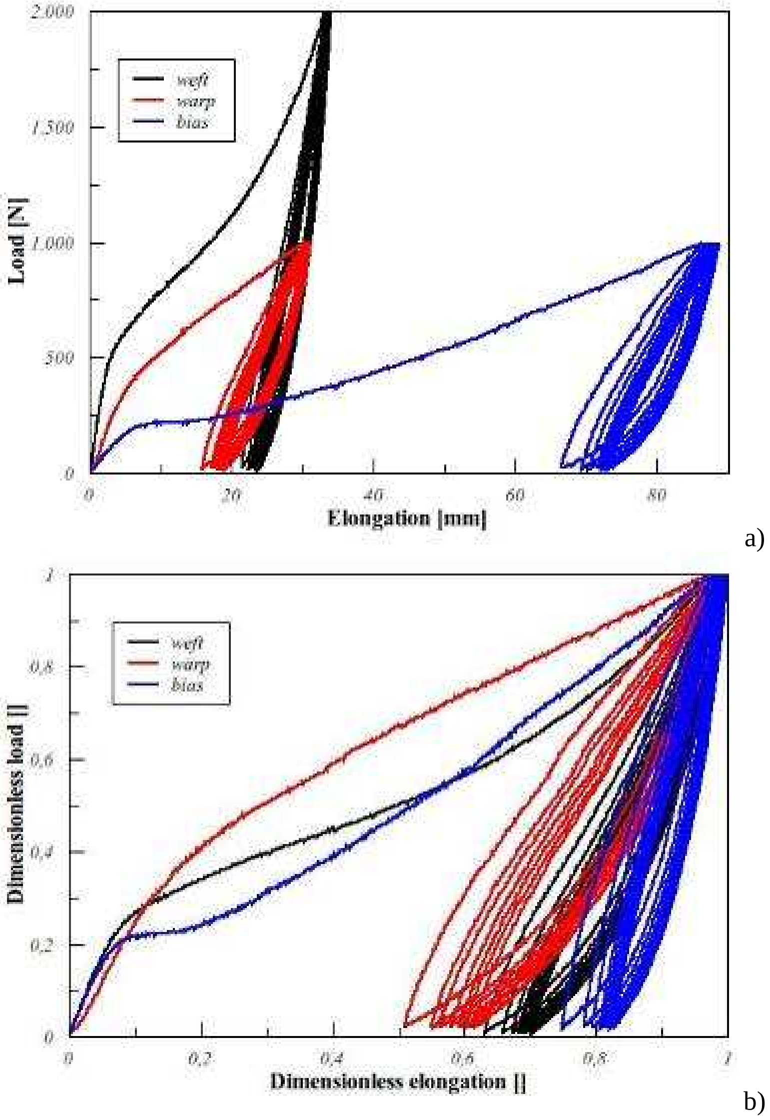
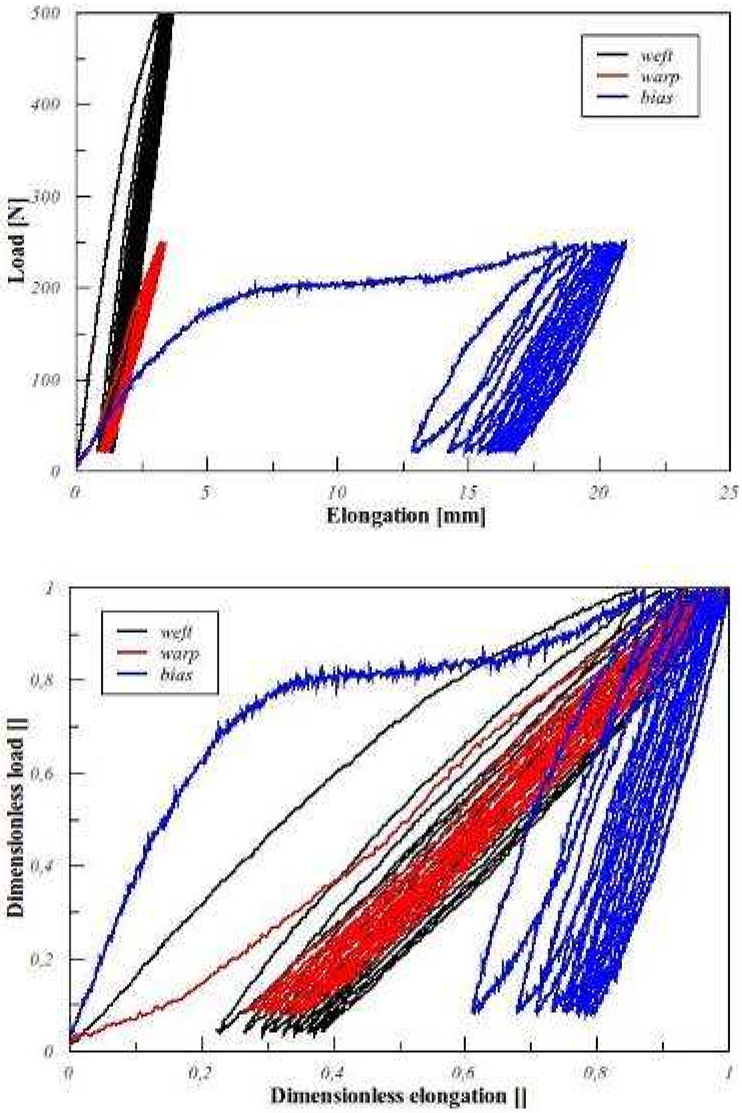


Figure 4: Cyclic test 1 results: a) Load vs elongation; b) Dimensionless load vs dimensionless elongation.

The examination of these figures allows the following remarks: 1) the behavior of Dacron© is highly nonlinear even at low load value (cyclic test 2); 2) in cyclic test 1 the behaviors in warp and bias directions are close each other but different to that in the weft direction; 3) for cyclic test 2 the behavior is different in all directions; 4) hysteresis loops are very large for all directions in cyclic test 1 while in the case of cyclic test 2 only bias direction shows large loops; 5) as a consequence of the previous characteristics the amount of elongation due to cyclic tests is very high, revealing an high accumulated plastic strain even in cyclic test 2. In Table 2 the values of elongation for each direction due to cyclic tests are reported.

	Warp	Weft	Bias
Cyclic Test 1	1,2	1,4	2,7
Cyclic Test 2	0,25	0,6	2,8

Table 2: Elongation values in mm due to cyclic tests.



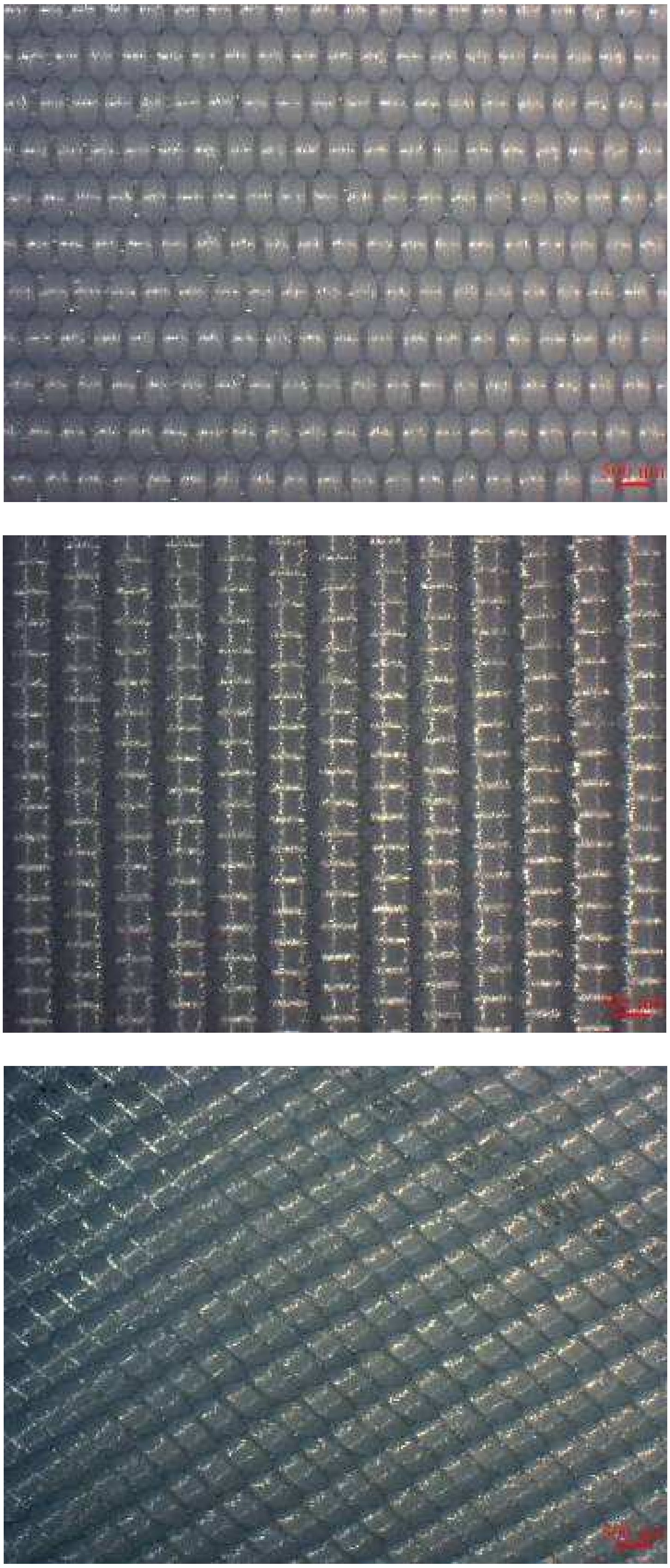
a)

b)

Figure 5: Cyclic test 2 results: a) Load vs elongation; b) Dimensionless load vs dimensionless elongation.

3.3 Remarks

At the end of the described tests the specimen have been examined with the optical microscope in order to analyze the effects of the test in the fabric pattern. In Figure 6 the images (10x magnification) of the specimens in the weft, warp and bias directions after the tensile tests are respectively reported. An examination of these figures together with a comparison with Figure 1a immediately reveal that no effects in the fabric pattern are evident in the specimens in the warp and bias directions, while in the case of weft direction it is possible to observe many “holes” which decrease the compactness of the fabric evidencing some stress concentrations. In Figure 7 a portion of Figure 6 is reported with a magnification factor equal to 40 from which it is very clear the presence of the above referred holes. In order to check whether the above described behavior is a material characteristic or not, also the specimens after the cyclic tests have been examined with the optical microscope.



a)

b)

c)

Figure 6: Optical microscope images of tested specimens (10x magnification): a) Weft direction; b) Warp direction; c) Bias direction.

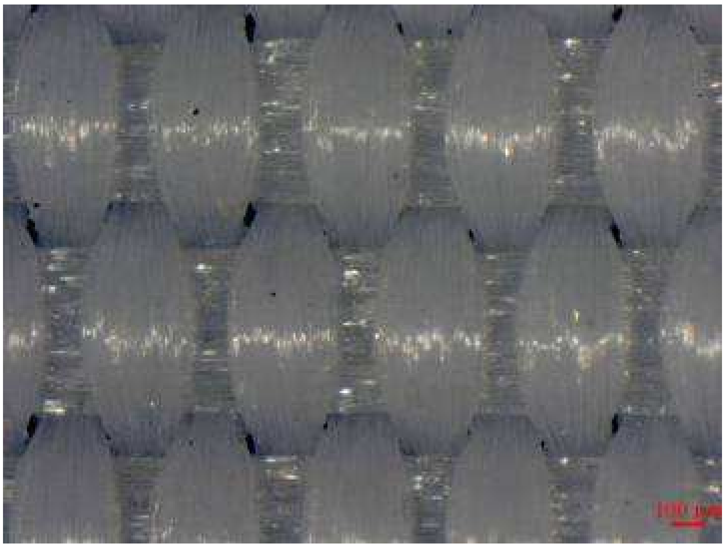


Figure 7: 40x magnification optical microscope images of tested specimen in weft direction (tensile test).

For sake of brevity in Figure 8 only the image (40x magnification) of the specimen in the weft direction after the cyclic test 2 is reported. An examination of this figure confirms the presence of the holes which are now of smaller dimensions. This remark suggests that the presence of the holes is due to the stress concentration which depends on the load intensity: higher the load, bigger the holes. It is to be emphasized that no holes are present in the specimens in the warp and bias directions after both tensile tests. The above described remark suggest that weft yarns mechanically interact with warp yarns while the contrary is not true. This can be related to the stitching effect of the warp yarns reported in literature[4].

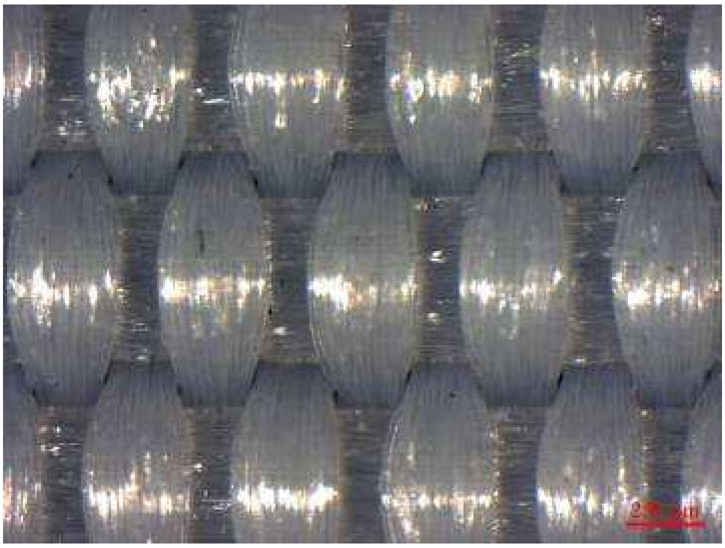


Figure 8: 40x magnification optical microscope images of tested specimen in weft direction (cyclic test 2).

4 CONCLUSIONS

In the paper some experimental analyses of Dacron© 360 woven aimed to characterize its constitutive behavior have been presented. The analyses have been performed by means of mechanical tests (tensile test and cyclic tests with different maximum loads) on strips of woven whose longitudinal direction coincides with the weft, warp and bias directions. Further observations have been performed with optical microscope. The analysis confirmed the orthotropy of the woven, with very different behaviors in the three fundamental directions and that in the weft direction, when the material reaches a certain stress level, some holes arise in the woven pattern. This confirms the interaction effect of the warp yarns with respect of the weft ones. Future developments of this research are to adopt some kind of dynamic tests, biaxial tests as well as to extend the analysis to creep tests. 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. Giuseppe Seminara, Erasmo Cataldo and Dr. Alessia Camera for their support during the research. The fundamental support of Mi.Me. s.r.l. and in particular that of Ing. Antonino Cirello is gratefully acknowledged.

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