An Automated Test System for Spearfishing Rubbers Characterization

Francesco Adamo, Filippo Attivissimo, Giuseppe Cavone, Giampaolo Cice

Politecnico di Bari – DEI, Via Re David 200, attivissimo@misure.poliba.it

Abstract* – This paper describes the realization of an automated system for rubber characterization in spearfishing applications. These materials, once lengthened, thanks to their ability to shrink very quickly, are used as dart propellers in fishing spears. The system permits the evaluation of the rubber behavior getting its stress vs. strain curve, allowing also the study of the effects of one or more parameters change like the maximum percentage elongation and the time elapsed between the stretching and shrinking phases at which the device under test is subject.

I. INTRODUCTION

The study, design and engineering of new materials has always had as its objective the improvement of their performance and of the products in which they are used. This aspect is also well established in many different sports, including the diving. Underwater fishing is heavily involved in running new technologies and use of innovative materials; the hostile environment and initially rudimentary facilities have required a more efficient use of the limited resources available. In the last decade, especially in Italy, some big companies have been gradually supplanted by much smaller ones, but more and more specialized on certain well-defined products. The latter, stimulated by an increasingly demanding market, using technologically advanced instrumentation, have made large efforts to improve the technical performances of their products. Relevant is the case of rifles, which are of great interest in apnea fishing enthusiasts and undertake companies in a relentless race and continuous innovation.

Weapons for underwater hunting are classified according to the propulsion system; the two main categories are *i)* pneumatic spears in which the dart is accelerated by the expansion of a compressed volume of air and *ii)* elastomer-based spears which make use of the contraction of one or more pairs of elastic materials previously stretched and hooked on the dart. Each of these two types of weapons has its strengths and weaknesses but over time both have been subject to improvements and new interpretations. Overall, though thanks to the simplicity of operation and structure, as well as the recent development of new techniques useful to the efficient ejection of the arrow thus increasing the range of use, the elastic spear is certainly the dominant and most widely used.

The propulsion technique is very simple but, at the same time, its actual performance is strongly dependent on the characteristics of the materials used for this purpose. The mechanical properties of the elastics, in fact, play a key role in assessing the quality of the weapon on which they are used and are of fundamental importance to be able to make the right considerations at the time of the setting.

Thus having an automated test setup for elastomers able to test them measuring all the parameters that characterize the behavior of these materials could prove useful to technological growth of the numerous Italian companies in the industry and already world leaders in this field.

II. PRINCIPLE OF OPERATION AND BEHAVIOUR UNDER TENSION OF A CURED ELASTOMER

The elastomer-based fishing speargun has ancient origins and is much simpler than the compressed air-based model. Over time, however, this device has undergone significant changes in terms of materials used for its construction. Nowadays the most common ones are manufactured with suitably treated aluminum, carbon fiber or wood; the latter is adopted on models equipped with high-performance elastics and heavy rods in order to absorb the substantial recoil generated during firing. Compared with the compressed air type, this hunting tool has a series of peculiarities. First, it can fire darts with diameter up to 9 mm; furthermore, it is possible to use one or more pairs of elastics, so as to take advantage of a greater power when shot, compared to a fractionation of the load in the armament phase. These two features together, give the possibility to make wooden drums to properly balance the gun, making them much more flexible and adaptable to the fisherman’s needs. Also, it should be not overlooked that the dart is resting directly on the stem, allowing the shooter to align it with the target in a much more instinctive and clean way.

The resilient elastomeric material used as thrusters are stretched during the loading phase, accumulating energy which is then transferred to the dart when the trigger is pressed (Fig. 1). In the firing phase there are many interacting factors, such as the characteristics of darts and types of steels used, the shape, the size, the material with which the stems are designed and especially the

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characteristics of elastomers.

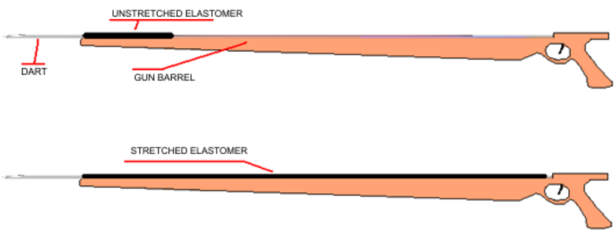

Fig. 1 - Schematic of a speargun and stretching of the elastic phase of armament.

In order to obtain a balanced device it is therefore essential to estimate the amount of energy that the elastomer is able to accumulate and, of course, the percentage of it that will be returned to the dart when fired; also the manner in which the elastic returns the stored energy is a relevant parameter that hides any effects of hysteresis and lost energy.

The elastics, marketed as bushed or "per meter" (Fig. 2), are not all equal and their behavior strongly depends on the quality of the raw material used, i.e. natural rubber as well as a series of stages in the manufacturing process and handling; Of fundamental importance are for example the addition of powders and additives, and the step of crosslinking or vulcanization [1].

Fig. 2 - Examples of elastics for fishing spearguns: bushed and "per meter"

A common feature of all the elastomeric materials is represented by the presence of long polymeric chains interconnected by cross-link points; in general, it is possible to delineate qualitatively the behavior of a vulcanized rubber subjected to a traction stress.

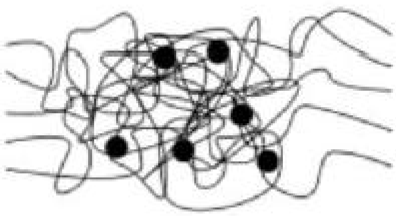

Fig. 3 - Schematic of the elastomeric chains in the undeformed state

When the polymer is at rest, the chains are folded and curled up on themselves (Fig. 3), while under the effect of an external stretching force they tend to modify their spatial distribution, aligning themselves parallel to the direction of elongation.

When the chains are stretched, due to their natural tendency to return to the original conformation, the macromolecules exhibit a return force (elastic recovery) of the same direction but opposite to the stretching one (Fig. 4).

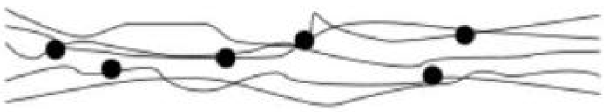

Fig. 4 - Schematic of the elastomeric chains subjected to deformation

Deforming the material and consequently extending the macromolecules, the number of accessible conformations decreases until there is only one possible conformation with each chain fully extended. Removing the external force that caused the deformation, each polymer chain tends to recover its original shape. This behavior of the vulcanized rubber during the extension phase is observable on the stress-strain curve (Fig. 5).

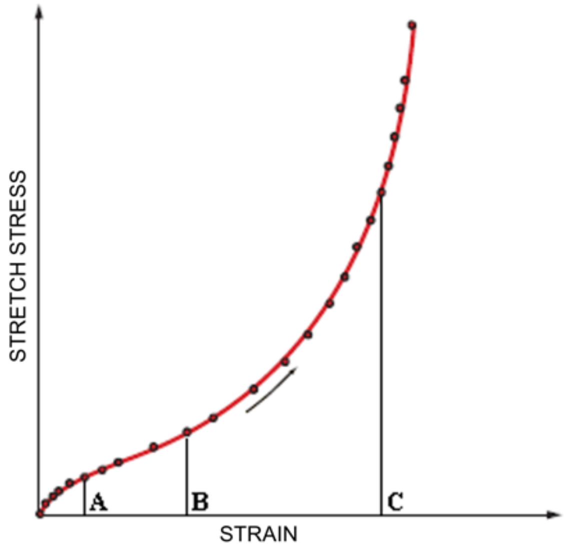

Fig. 5 - Typical stress-strain graph of a vulcanized elastomer

Excluding the first few values of applied strain, the stress value assumes an almost linear trend with respect to abscissa values, that is the sample follows the well-known Hooke's law:

$$\sigma = E \cdot \varepsilon \quad (1)$$

where E is the elasticity (or Young's) modulus (Fig. 5, section AB).

Over a certain stress range, however, the curve tends to bend upwards: the progressive decrease in the number of accessible conformations and the increasing number of elastically active chains that reach the maximum of its capacity to extend, requires the application of an effort progressively more intense (Fig. 5, segment BC). In some cases, achieved high strains, with an elastomer structure particularly neat, the material can crystallize: this phenomenon, not always reversible, causes the need to apply an even greater effort to further deform the material (Fig. 5, taken from C onwards). In this last phase of deformation the sample does not show any more a linear behavior nor an elastic one. Obviously, continuing the stretching action brings the material to a rupture.

The application in question, however, requires quite modest stretches; in most cases, in fact, elastics used on fishing spearguns work with elongation factors oscillating between 250% and 400% of the length at rest; therefore, as regards their characterization, it is not required to consider intervals in which the behavior is plastic and, even less, those next to the rupture of the specimen.

The curve that describes the behavior during the discharge cycle is qualitatively very similar to that of the traction cycle, but the values assumed are generally lower than those which have characterized the elongation phase, giving rise to a hysteresis which is indicative of a loss of energy.

This loss is mainly due to the phenomenon of relaxation of the polymer chains that constitute the material and will be much more pronounced the more the amount of elongation and the time in which the sample remains in a state of extension are high.

The area under the curves represents the energy that the elastomer stores in the load phase, and releases in the discharge phase. Equivalently, the two energies represent the work that the fisherman should carry out to stretch the elastic up to a predetermined value and the work that the elastic performs on the dart during the discharge phase:

$$L = \int_0^{l_{max}} F \cdot ds \qquad (2)$$

These two energy values allow obtaining the resilience of the rubber in specific examination [2]. The way in which the material accumulates and releases energy during the two cycles is largely deduced from the shape of the curves. In the range of elongation values that characterize the application on fishing spearguns (250% - 400%), three types of behavior can be summarily identified, which in turn identify a type of rubber (Fig. 6) [3].

The first type of elastics (curve A) has a behavior very similar to that of a spring of harmonic steel: in fact it offers a direct proportionality between the applied stress and the strain for most part of the dynamic range; this behavior, however, is always confined to a limited range of strain values.

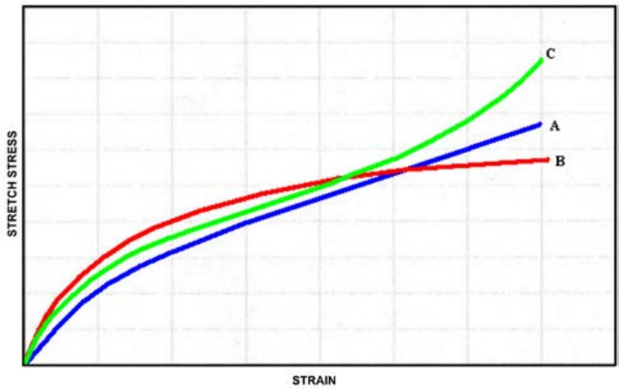

Fig. 6 - Comparison between three types of elastics. The diameters and the rest length are equal.

Curve B represents a type of elastomer which requires a greater force in the initial elongation, beyond which it stretches more easily even for small increments of the applied force. This type of elastic gives a slower but progressive pull to the dart.

Finally, the third type of elastics (curve C) is characteristic of materials hard to stretch: in the final phase, the curve shows a plastic behavior; at this stage the increase in the elasticity modulus is a sign of the fact that the applied force must grow greatly even to obtain limited extensions and this requires a large muscular energy to attach the bow to the trigger mechanism. Generally, during the firing phase, this type of elastic provides a strong but brief initial thrust action.

Finally it should be emphasized that to date the ideal elastic has not yet been realized; the three categories described above are all potentially valid, but they should be used judiciously, examining carefully the intended application.

III. EXPERIMENTAL SETUP

The electro-mechanical setup designed to test the elastic materials was built using a recirculating balls screw bar driven by a stepper motor (Fig. 7). One end of the specimen under test is attached to the moving head of the linear actuator and the other end is attached to a load cell used to detect the load and return force expressed by the tested elastomer.

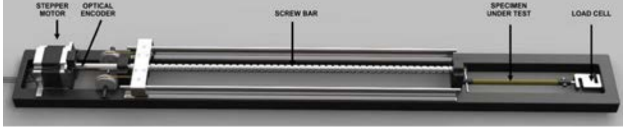

Fig. 7 – Photo of the mechanical section of the test system

The stepper motor was selected considering the torque required applying a maximum force of about 1000 N to the specimen under test at a high enough step-rate. The load cell was selected with a maximum working load of

1960 N and a sensitivity of (3 ± 0.003) mV/V in order to ensure both maximum linearity in the range of actual operation and a good signal to noise ratio to the input of the conditioning electronics; the total uncertainty declared by the manufacturer of the load cell is equal to 0.03% of full scale.

The system is completed by two custom designed microcontroller-based electronic cards; the first one (Fig. 8A) dedicated to the control of the stepper motor, the other (Fig. 8B) is dedicated to the conditioning and digitization of the signal of the load cell.

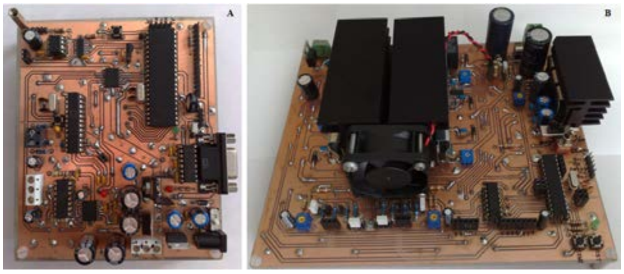

Fig. 8 - Electronic card system

Card B is also able to measure the elongation of the specimen under test by means of an incremental optical encoder positioned coaxially with the axis of rotation of the actuator. The motor control algorithm is based on a PI regulator tuned on the basis of motor parameters declared by the manufacturer and depending on the desired response time. Moreover, the controller has been fitted with an efficient procedure to limit the wind-up phenomena, i.e. the maximum output overshoot in response to a discontinuity in the set-point value. The analog-digital conversion of the signal coming from the load cell is performed by a 16-bits ΣΔ converter.

Thanks to a user interface implemented in LabVIEW®, the operator can determine whether the parameters of the specimen, as well as those that characterize the measurement cycle to be performed are correct. From the Front Panel the operator can set the desired maximum elongation, the velocity profile at which the sample will be stretched, the number of complete cycles to execute, and the time during which the sample will be left under tension and under relaxed state.

The whole process can also be configured to implement a set of tests in which one of the variables mentioned above in each complete cycle is incremented by a predetermined amount.

The user interface is also fitted with many useful indicators to report the status of the procedure, such as the successful calibration, the temperature at which the system is working and the number of cycles already performed. The operator interface has also been equipped with a display in which he can view the complete set of measurements obtained, and analyze in detail the results of the individual cycles. For each of them, in fact, the implemented algorithm identifies the accumulated and the released energy, the value of resilience and the loss curve.

Finally, at the end of the procedure, the test results, along with the values of the parameters characterizing the measuring cycles can be saved on a file so that they can be used in subsequent analyses.

IV. EXPERIMENTAL RESULTS

A series of specimens of elastic materials all long 20 cm but of different diameters and compounds and characterized by the presence or not of the co-extrusion process were prepared. The tests were carried out varying the applied strain and the waiting time in traction, both according to the configured values; all the other parameters however were kept at fixed values. Once a complete cycle (consisting of a charge, a waiting and a discharge phase) was executed, as a result of deformation, the elastomeric chains retain a certain degree of residue tension which generally decreases over time when the specimen is then maintained at rest. For this reason, between a complete cycle and the next one, the samples were deliberately left at rest for a time equal to 45 minutes in order to allow the elastic to fully recover its initial characteristics.

At the end of the tests, the data obtained from elastomers having the same sections were grouped in order to obtain load curves comparable as a function of the elongation percentage.

The experimental trends, in addition to highlight different elastic constants for the various compounds in the process of elongation (Fig. 9), have shown a significant discrepancy of values during the discharge cycles. Some compounds, much more than others, have shown a significant degradation of response magnitude with increasing elongation and stay under tension (Fig. 10). This behavior was particularly evident in the case of a specimen belonging to the 16 mm diameter.

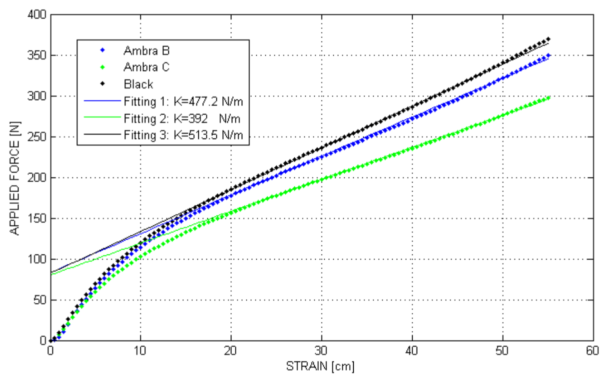

Fig. 9 - Category 19 mm. Fitting curves and identification of certain elastic constants

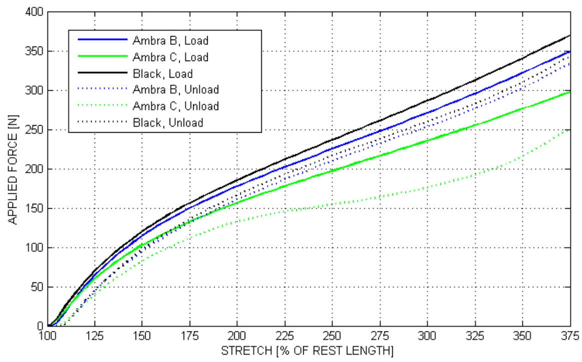

Fig. 10 - Category 19 mm. Test results comparison: despite having the same cross-sections, some compounds suffer a more pronounced elongation factor and stay in traction time

In that case, the sample has maintained a good response up to 375% elongation percentage, even for waiting times of one hour. Although the material with the elastic constant and "the values of recall" the highest for this category, for elongations over 400% the specimen showed a sudden increase of the losses (Fig. 11), then after a wait under one hour drive, his response has fallen even below the guaranteed values from one of the other samples, the performance of which were, however, always been modest (Fig. 12).

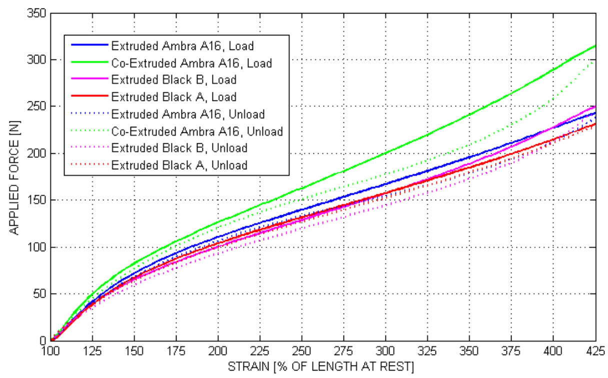

Fig. 11 – Category 16 mm: experimental curves with waiting time of 15 min before unloading

Finally, two other samples having always the same diameter but different compounds were evaluated until breakage (Fig. 13). Initially it was possible to observe a reversal of the load values at a stretch close to 325%. As the elongation increases the divergence keeps constant until one specimen has begun to show a plastic response, (starting from 625% elongation) increasing the elastic modulus until breakage, that occurred at an elongation of 725%, ensuring a measured resistance value of about 686 N. The other specimen instead has maintained a much more linear performance up to 650% of elongation, beyond which even its elastic modulus began to increase into the field of plastic response.

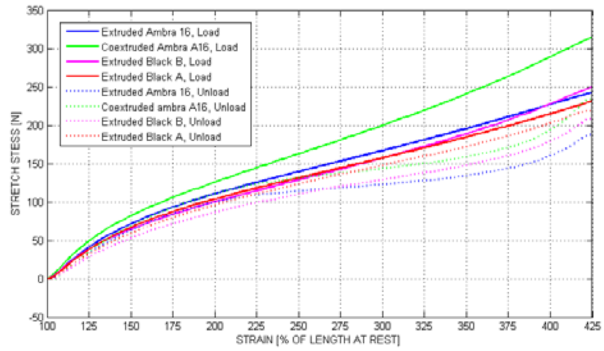

Fig. 12 – Category 16 mm: experimental curves with waiting time of 60 min before unloading

The fracture occurred at 800% elongation with a measured resistance value equal to about 872 N. The values of fatigue resistance were calculated as 163.32 J and 202.10 J , respectively.

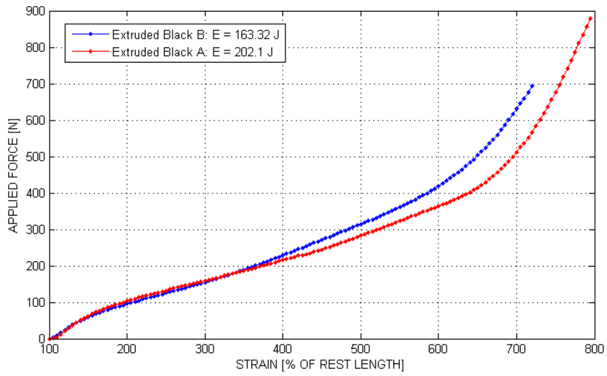

Fig. 13 – Category 16 mm: Elongation until the breakage

V. CONCLUSIONS

Nowadays the market dedicated to equipment for underwater fishing has become increasingly demanding. In order to meet this growing demand for high-end products, manufacturers are forced to a constant process of study and innovation of their products, resorting more and more to the aid of technologically advanced devices and systems.

In this context, the analysis of the behavior of elastic-based fishing spearguns used on rifles can be a pusher for Italian companies, involved in this process. To this end, we implemented a simple and low cost test system, which can help manufacturers in the construction or purchase of artifacts more reliable and guaranteed specifications. Moreover, the systematic collection of meaningful data could allow the implementation of mathematical models able to identify the correlation between the various factors at play in the interests of greater effectiveness and efficiency of the fishing gear. This would avoid gross errors in the earliest phase of balancing and prototyping of the speargun, avoiding long periods of tank tests and limiting them only to a fine-tuning of the device, to the benefit of both companies (for the lower production time) and of the experienced user (who might be able to set up in a "more aware" way his speargun).

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