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EXPERIMENTAL RESIDUAL STRESS ANALYSIS BY THE HOLE-DRILLING METHOD ON PLASTIC MATERIALS

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Abstract

This paper describes the testing method and measurement system developed for automatic measurement of residual stresses in plastic materials. Unlike in traditional application of the hole-drilling technique to metal materials, in plastics the heat produced by the drilling process can cause high errors of measurement. These can be minimized through the choice of drilling parameters and by giving the strain gage signal time to stabilize before being recorded.
An accessory has been developed for the well-established Restan MTS3000 automatic measurement system which essentially consists of a very low-speed electric motor and an electronic control system. The measurement system may be remotely operated thus avoiding any thermal effects caused by the presence of operators during testing.

Sommario

La memoria descrive il metodo di prova ed il sistema di misura sviluppati per poter eseguire in modo automatico la misura delle tensioni residue su materiali plastici. Rispetto alla tradizionale applicazione della tecnica del foro ai materiali metallici, per i materiali plastici la produzione di calore durante il processo di foratura può determinare elevati errori di misura. La minimizzazione di questi errori può essere effettuata attraverso l'opportuna scelta dei parametri di foratura e del tempo di stabilizzazione del segnale estensimetrico prima di effettuare la sua registrazione.
E' stato sviluppato un accessorio del consolidato sistema di misura automatico Restan MTS3000 che è costituito essenzialmente da un motore elettrico che gira a velocità molto bassa e la sua elettronica di comando. E' possibile il comando a distanza del sistema di misura che evita i potenziali effetti termici dovuti alla presenza delle persone durante le prove.

Key terms: Tensioni residue, metodo del foro, materiali plastici, Restan, MTS3000.

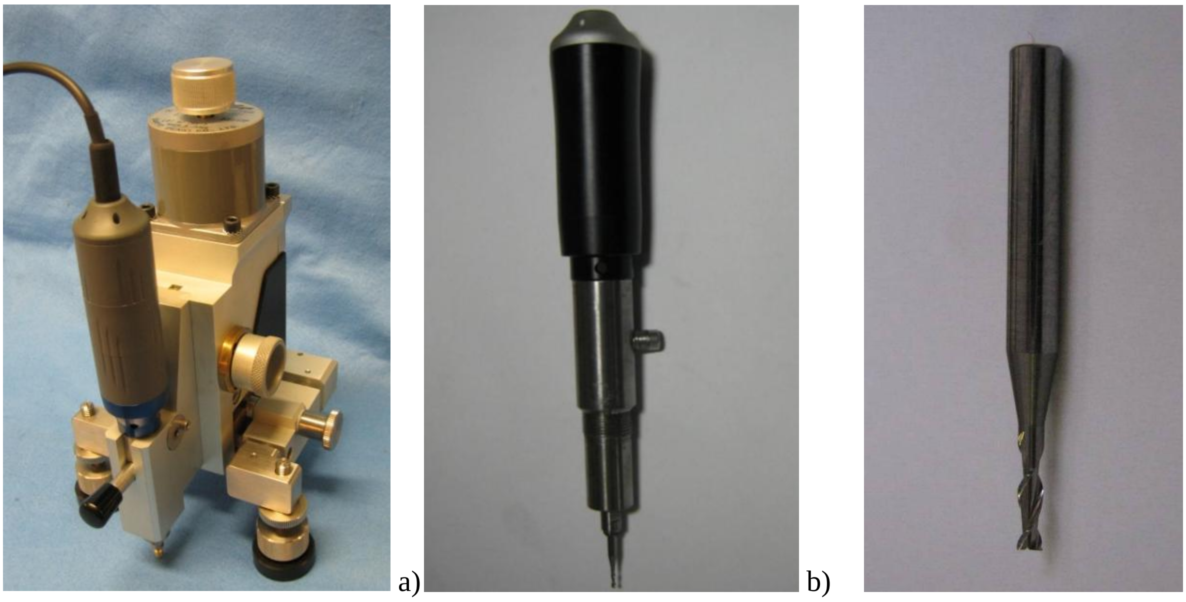
1. INTRODUCTION

Over the last fifty years the plastics industry has developed greatly, outstripping the steel industry also in technical applications. This has led to new synthetic substances progressively replacing traditional materials and to a formal rethinking of structures, ergonomic shapes and production processes.
What has made use of these materials become so widespread is essentially the fact they are cheap, light, easy to work and it is possible to design the desired mechanical properties. Increasingly accurate and in-depth mechanical characterization is therefore necessary and it is in this context that the need arises to know and study the value of residual stresses induced by machining processes in these materials.
Also polymer melt flow, pressure distribution, non-uniform temperature field, and density distribution all cause residual stresses in polymer injection moldings and these stresses affect the mechanical properties of plastic parts, can alter the final shape and significantly reduce the life expectancy of the product in addition to increasing the likelihood of dimensional instability and environment stress

cracking. Although the residual stresses are commonly found in plastics their magnitude can be difficult to predict as it depends upon a wide range of variables including the mold design, material and processing parameters. Consequently, it is important to have a reliable technique to evaluate the stresses existing in plastic components.
Three techniques are available for the residual stress measurements in Polymeric Moldings: Chemical probe technique, Layer-removal technique, and Hole-drilling technique [1].
The chemical probe technique involves applying chemicals to the surface of a polymer and measuring the time taken for the polymer to fracture. It is a quick and simple technique, suitable for use in quality control applications. The higher the residual stresses in the polymer the quicker it will fracture due to environmental stress cracking. The main disadvantage of this technique is that it can detect only tensile residual stresses, while polymer injection moldings pressures frequently present compressive stresses.
The layer-removal technique consists in measuring the curvature introduced into flat plate samples by the removal of thin layers from the surface of the specimen. By measuring the curvature in the specimen, the strain can be determined and hence the residual stresses that are present in the layer that is removed. This technique is accurate but has the disadvantage of requiring much time and it is often difficult to apply because it can be used only on flat surfaces.
The hole-drilling strain gauge method allows residual stress to be measured in wide range of plastic moldings. It has the advantage that the measurements can be made over a smaller area. A special strain gage rosette is bonded to the surface of the specimen and a hole is drilled precisely through the centre of the rosette. The strains measured at the surface correspond to the stresses relaxed during the drilling process. Using the measured strains and appropriate models (i.e. ASTM E827 [2]) it is possible to calculate the stresses along the two principal axes and their direction.
This paper describes application of an automatic hole-drilling residual stress measurement system to polymeric moldings. An accessory has been developed for the Restan MTS3000, an automatic measurement system, essentially consisting of a very low-speed electric motor and an electronic control system. The measurement system also has remote control which avoids the potential effects of temperature due to the presence of operators during testing. The drilling and data acquisition method allows less heat to be generated during drilling and the signal to stabilize before the strains are read.

2. MEASUREMENT SYSTEM

A description follows of the main features of the measurement system developed for automatic analysis of the residual stresses existing in plastic materials.
The high sensitivity of the plastic material under analysis requires an automatic system for drilling and acquisition of strain data.
The mechanical setup of the drilling system is shown in figure 1a. It is based on the consolidated Restan - MTS 3000 system developed by SINT Technology and marketed in collaboration with HBM.
Figure 1b shows the specially designed drilling tool that allows holes to be drilled at under 200 RPM.
This speed minimizes local heating and residual stresses induced in the material to be analyzed.
The cutting tool is shown in figure 1c. It is a twist drill with two cutting edges perpendicular to the direction of advancement, 1.6 mm in diameter, which produces flat-bottom holes at modest feed rates.
The drilling system is powered and automatically controlled by the electronic control system and drilling control software, thus making the drilling process fully automated. The whole measurement apparatus may be remotely operated: this option is advisable as it allows the external influences of the operator to be minimized during the measurement process. Figure 2 shows the measurement process.


a) b) c)
Figure 1: a) modified MTS3000 system for measurement of residual stresses in plastic materials, b) specially designed drilling tool, c) drill with 2 cutting edges

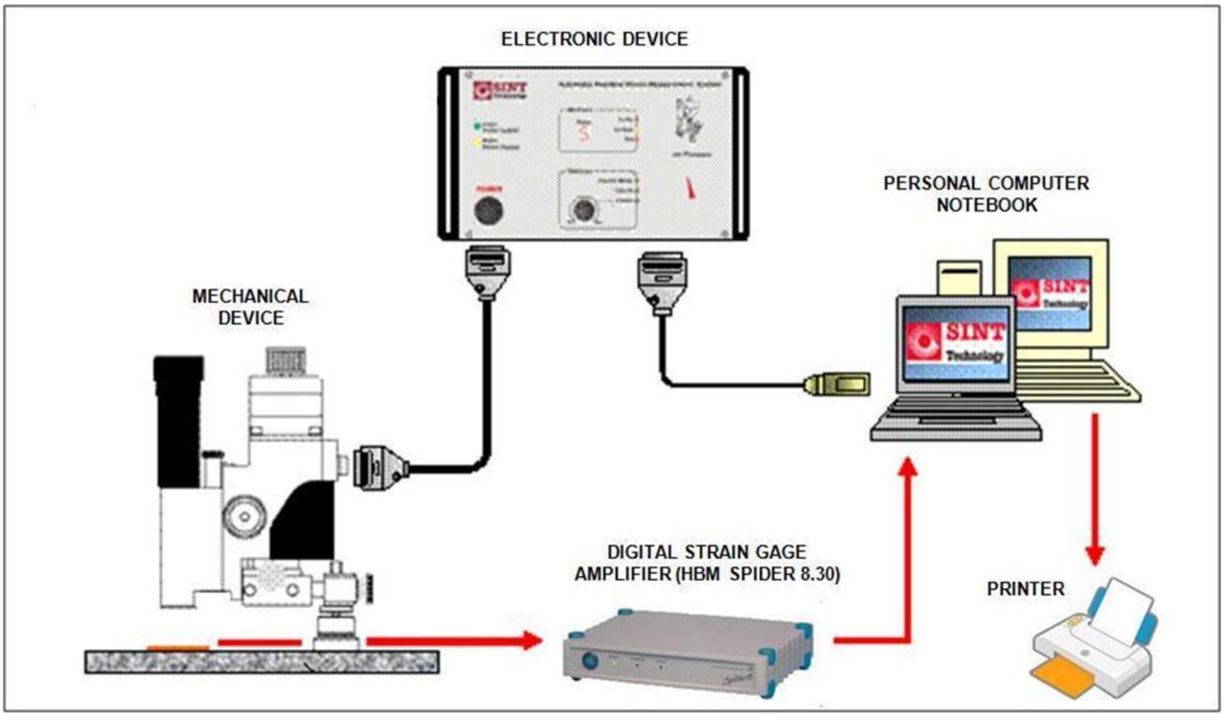


Figure 2. Measurement process

Figure 3 shows a three-element strain gage rosette of the prewired type, which is preferable for the tests as it not only makes it faster to install but also means no heat is generated by welding wires. The rosette is connected to the strain gage amplifier by the three-wire connection.
The residual stresses existing in the test component are determined starting with the strain values measured by the grids of the strain gage bonded on the surface of the component.
The acquired data was processed using a special version of the EVAL software, produced by SINT Technology srl, specifically for processing the strains in plastic materials. This version applies an initial optimized polynomial interpolation of measured strains. [3]
The strain measurements are processed in conformity with the provisions of standard ASTM E837-08 [2].

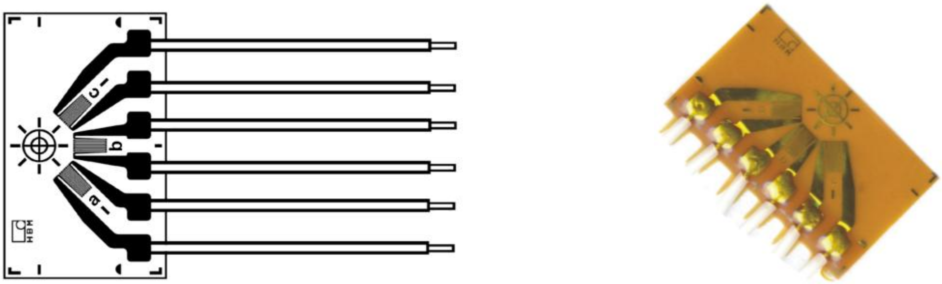


Figure 3 - Rosette: HBM K-RY61-1.5/120R-3 prewired

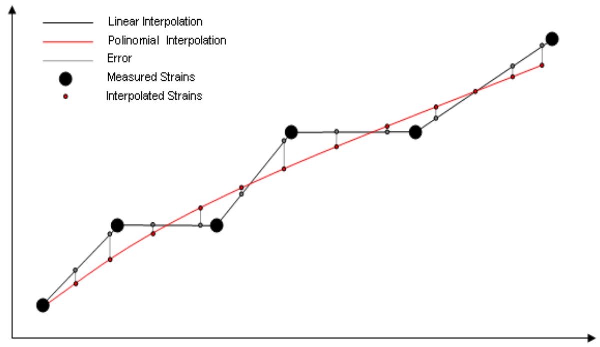


Figure 4a. Optimized polynomial interpolation of strains strategy.

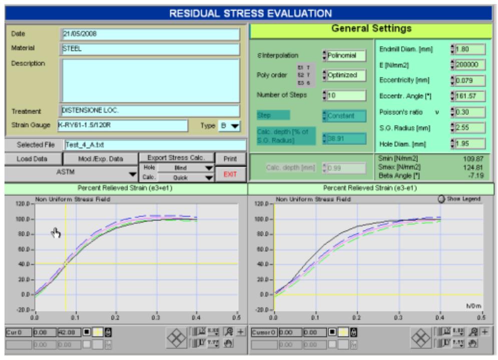


Figure 4b. Eval strain data processing software produced by SINT Technology.

3. TEST PROCEDURE

The main operations to be carried out when applying the hole-drilling strain gage method to plastic materials are described here below.

- Clean the surface with a suitable cleaning agent for removing any dirt that can prevent the strain gages from bonding to the surface of the polymer. Care is required in choosing the cleaning fluid as some fluids can attack the polymer or induce plasticization which influences the distribution of residual stresses.
- Attach the strain gages to the surface of the polymer using an adhesive that has no affect on the properties of the polymer. A cyanoacrylate adhesive is suitable for many applications.
- Use prewired strain gage rosettes as much as possible. They eliminate the effect of welder heat on the distribution of residual stresses in the polymer. Should this not be possible, it is advisable to use backing and minimize welding time.
- Fix the drilling system to the specimen and ensure that the drilling axis is perpendicular to the surface on which the strain gage rosette is applied.
- Using an optical microscope, align the cross reticle so that it is exactly in the center of the rosette.
- Replace the microscope with the drilling tool and drill precisely through the center of the rosette.
- Install conductor tape, of a set thickness, on the strain gage taking care not to cover all the reference markings.
- Advance the drilling tool until it reaches the surface of the conductor tape. Start the cutter again and advance it until it cuts through the conductor tape and rosette backing material. This point corresponds to “zero” cutter depth.
- Record the readings from each strain gage with the cutter on the surface, after waiting sufficient time to allow the signal to stabilize (delay time).
- Set the established feed rate, maximum depth, number of drilling steps, and delay time in the automatic system. Holes are usually made in depth increments of approx. 0.05 mm in compliance with the provisions of standard ASTM E837-08.
- The three strain gage readings and hole depth are recorded for each drilling step.
- Replace the drilling system with the microscope and measure the hole diameter and eccentricity, effecting four translations on two perpendicular axes.

3.1. Surface preparation and bonding

The chemical affinity of each plastic material with the solvents and adhesives used in installation needs to be analyzed and taken into account. Unsuitable bonding agents can actually damage the strain gage installation or even the component under analysis. A mechanical surface treatment method is advised for cleaning the surface.
Purely by way of example, table 1 indicates the requirements for correctly installing a strain gage on a plastic material.

Material	Sanding	Marking	Surface cleaning	Adhesive
Polycarbonate	320 - 400	Yes (*)	HBM RSM-1	HBM Z70
ABS	320 - 400	Yes (*)	Isopropyl alcohol	HBM Z70
Polyethylene	400	Yes (*)	Isopropyl alcohol (**)	HBM Z70

(*) If possible, lightly mark around the strain gage backing material.
(**) Surfaces can also be cleaned with ordinary detergent and rinsed with water.

Table 1 . Preparation for installing strain gages on some plastic materials.

3.2 Determining the contact depth (zero setting)

Determining the starting depth is a key aspect of a correct measurement of residual stresses with the hole-drilling method.
This point is determined in metal materials by electrical contact. Totally automatically, the MTS3000 system stops the cutter when the drill reaches the surface of the component after cutting through the polyamide backing of the strain gage rosette.
Whereas the zero point in plastic materials cannot be determined simply by electrical contact as they do not allow electric conductivity.
Nevertheless, some operations can be used to determine the "zero" point.

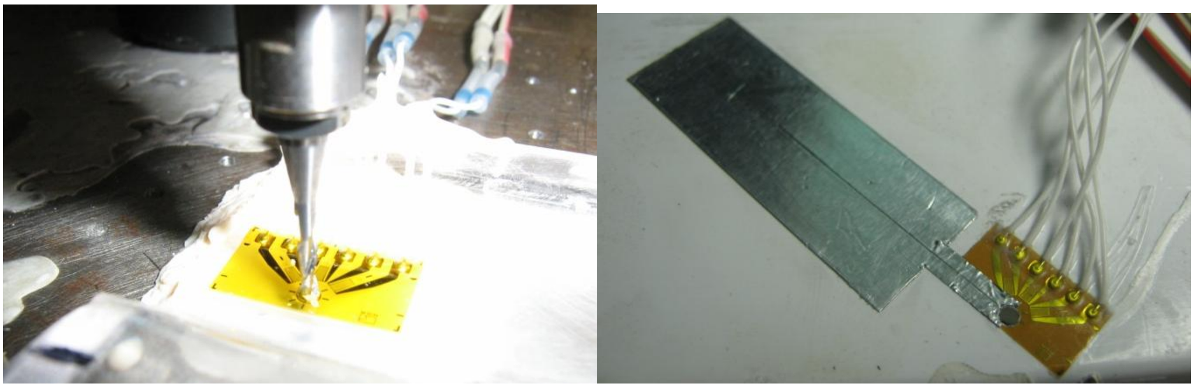


Figure 5. Techniques for determining the initial drilling depth.

Essentially, it is possible to operate either :

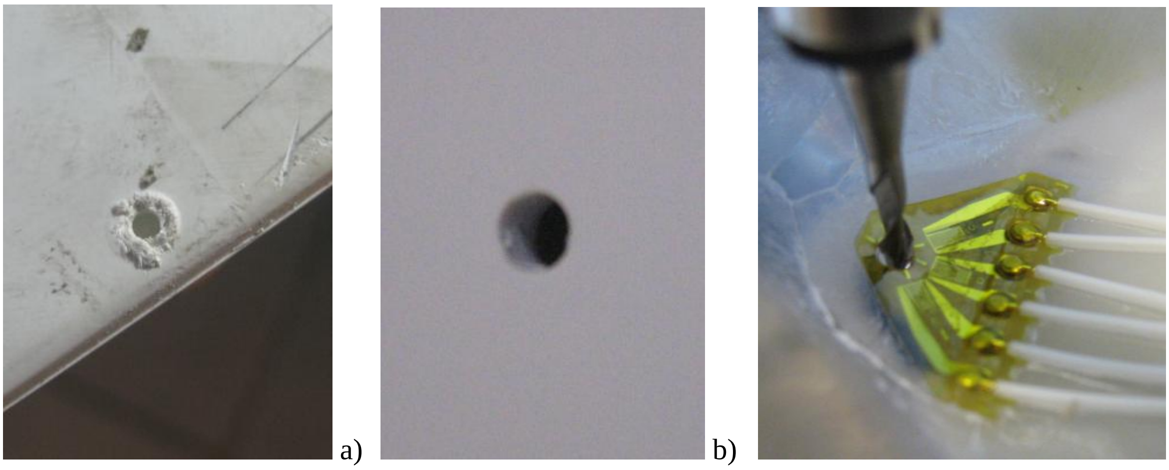
- Determining "zero" depth manually, stopping the cutter when it begins to produce plastic cuttings (figure 5, left), or
- Using a special aluminum adhesive tape so that "zero" depth is determined automatically. Once the "zero" point is determined, it is necessary to translate the system by a distance equal to the sum of the thicknesses of the strain gage rosette and special aluminum tape. (figure 5, right).

5. ISSUES INVOLVED IN MEASURING RESIDUAL STRESSES IN PLASTIC MATERIALS. DETERMINING OPERATING PARAMETERS

Measuring residual stresses in plastic materials with the hole-drilling method involves very different aspects from applying the same method to metal materials. In plastic materials the modulus of elasticity is lower and therefore measured strains are much higher, applying the same load, and the material is more sensitive to the operation of removing material. The cutting speed, feed rate, and delay time in acquiring strain readings have to be selected appropriately.

5.1. Speed of rotation during drilling

The drill speed is undoubtedly one of the parameters that most influence the measurement of residual stresses in plastic materials with the hole-drilling method. High-speed drilling with an air turbine, which is the technique normally used for measuring residual stresses in metal materials, cannot be applied as generated heat causes the plastic material to melt and considerably increases the temperature in the areas where the strain gages are applied.



a) b) c)

Figure 6: a), hole made with a turbine fed with air compressed to a pressure of 4 bars. b), hole made with an electric motor at low speed. c), strain gage during the drilling process.

By way of example, figure 6a shows a hole made in plastic material with the high-speed drilling system using an air turbine: melting of the plastic material around the sides of the hole is clearly evident. Lowering the compressed air pressure and the resulting slowing down of the air turbine can only reduce this effect but are certainly not sufficient to eliminate it.
The cutting speed, therefore, has to be very low. In figure 6b one can see the quality of a hole made with the low-speed drilling system (under 200 RPM), designed for measuring residual stresses in plastic materials.

5.2 Feed rate

Since plastic materials are highly sensitive to mechanical stresses, various experimental drilling tests have been conducted to determine the optimal feed rate.
The test results have shown that the drilling tool has to be advanced more slowly in order to reduce the time of instability after drilling. Reducing the feed rate means increasing the time it takes to measure residual stresses: the right compromise between these two aspects has led to determining the optimal speed for drilling holes in plastic materials.
Table 2 shows the time necessary for drilling and the average stabilization time for each feed rate analyzed: the best compromise is achieved with a feed rate of 0.1 mm/min.

Feed rate [mm/min]	**Drilling time** [sec]	**Delay time** [sec]	**Time per step** [sec]	**Total time** [sec]
0.05	120	60	180	6400
0.1	60	90	150	6000
0.2	30	150	180	6400

Table 2 . Time required for measuring residual stresses in plastic materials.

5.3 Choice of delay time

The delay times serves to allow strain readings to be acquired when the specimen returns to a state of thermal and mechanical balance after the hole is drilled.
Testing has shown that the thermal balance, which is affected by the drilling process, is reached with very few seconds of delay.
To evaluate the time required to attain the mechanical balance of the component, testing has been necessary to measure the trend of strains throughout the whole stage of drilling the plastic material.
Using a SPIDER 8.30 strain gage amplifier and the CATMAN acquisition software produced by HBM, it has therefore been possible to measure the trend of the strains measured during the entire drilling operation: the results, shown in figure 7, show that the system is mechanically unstable during the drilling process and that it is necessary to wait approx. 90 seconds before the system returns to stability. With a sufficient delay time, the usual strain vs.depth curves can be observed for each strain gage grid.
The curves refer to tests with a feed rate of 0.2 mm/min.

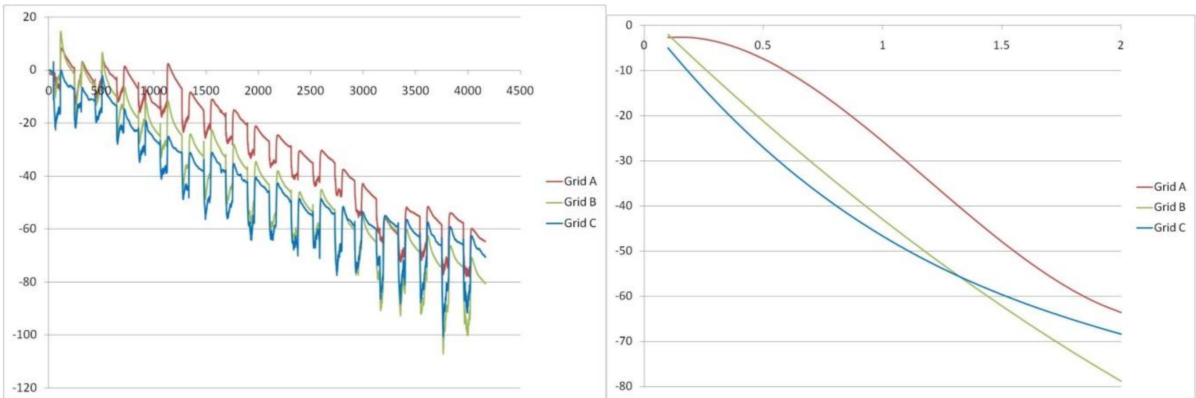


Figure 7. On the left, acquisition of strains in time. On the right, strains versus drilling depth.

The same experimental tests have been repeated also during the drilling of metal materials (steel and aluminum: the results have shown the behavior of the system but with a faster stabilization time (3-5 sec). In Figures 8 and 9 it is possible to observe the detail of the trend of strains in a metal material (Steel) and a plastic material (Polycarbonate).

5.4 Verification of temperature variation on the plastic component

Once the drilling system was designed, the temperature on the plastic (polycarbonate) component during the drilling process was measured. A 2mm. deep hole was then made and the temperatures on the specimen were then acquired with a type K thermocouple installed at the same distance from the hole as the strain gage grids, positioned opposite grid 2 (or B).
Figure 10 shows the position of the thermocouple and figure 11 temperature versus hole depth. Twenty seconds was set as the delay time between drilling steps and a feed rate of 0.2 mm/min (standard rate for tests on metal materials such as steel) was chosen for the test.

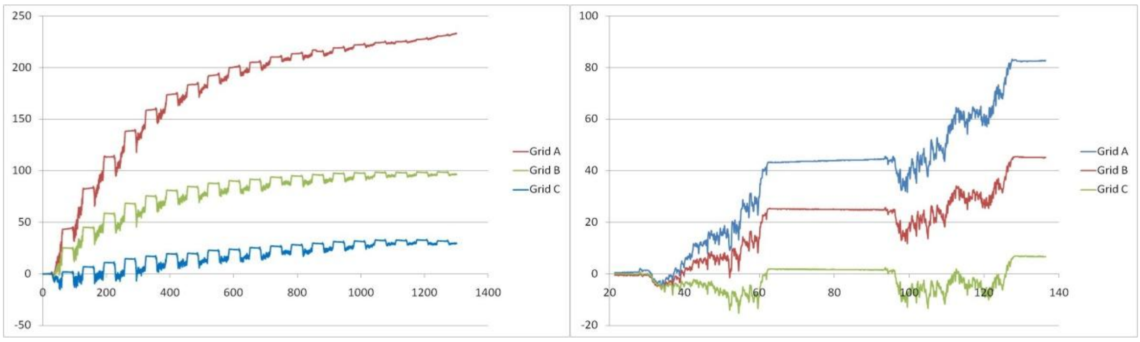


Figure 8. Strain trend during drilling on metal material.

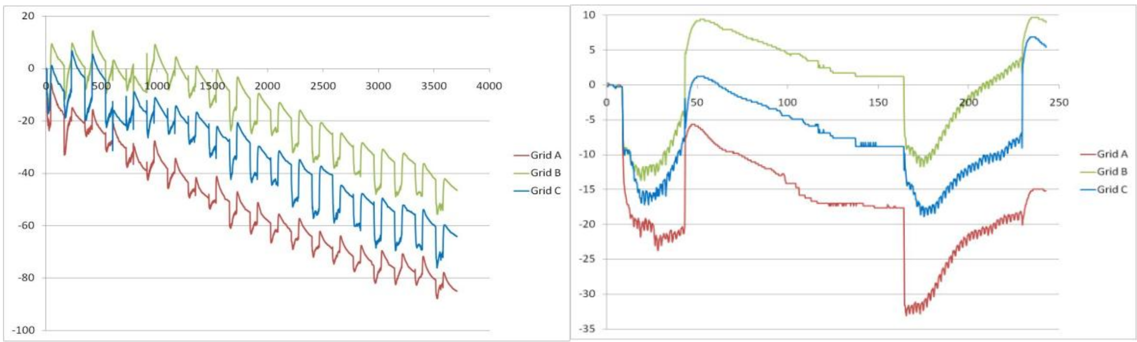


Figure 9. Strain trend during drilling on plastic material.

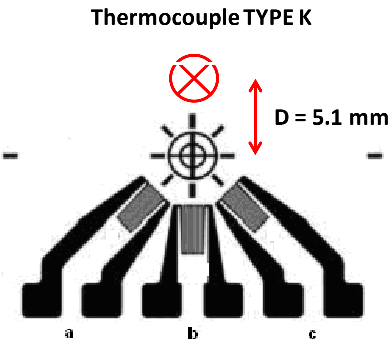


Figure 10 – Position of the thermocouple in relation to the strain gage rosette

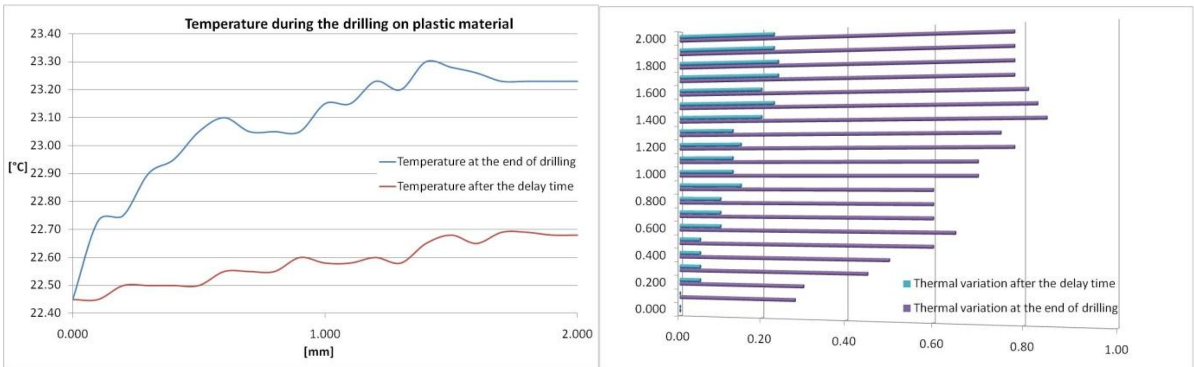


Figure 11: On the left, measured temperature trends. On the right, maximum temperature variations measured for each drilling interval.

The results demonstrate that the drilling tool does not generate excessive heating at the strain gage grids. The maximum temperature variation recorded is at the end of the drilling step and is under 1° C. In addition, during the delay time a rapid reduction of the temperature of the component and return to the initial temperature is observed. In fact, after 20 seconds it may be seen that the temperature attains the initial values: the maximum variation measured in relation to the initial temperature is 0.24°C.

6. CONDUCTED TESTS AND RESULTS OBTAINED

A plastic component of a polycarbonate household electrical appliance was tested. A Young's modulus of 2650 MPa, a Poisson's ratio of 0.37 and a tensile strength of 80 MPa were considered for this material.

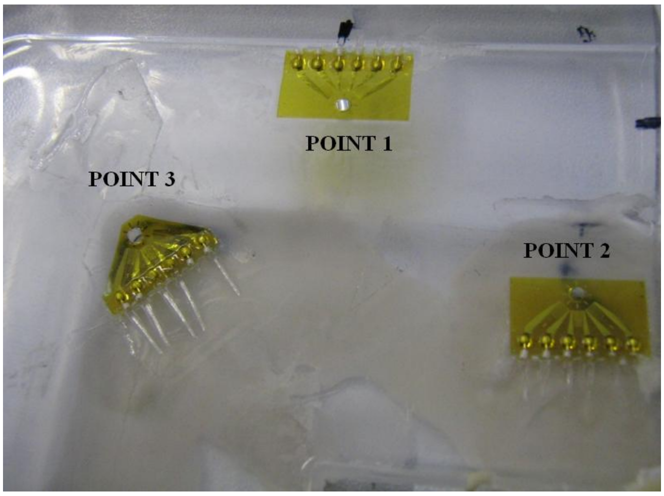


Figure 12. Positions of the measuring points in the tests conducted with polycarbonate.

Figure 13. Drilling steps during the tests conducted with polycarbonate.

The following testing conditions were adopted for the automatic measurement system:

- Maximum depth: 2mm
- Drilling step: 0.05 mm
- Number of drilling steps: 40
- Drilling step trend: linear
- Feed rate: 0.1 mm/min
- Delay time: 90 sec.
- Strain gage rosette: HBM K-RY61-1.5/120R-3 prewired, 3-wire connection
- HBM SPIDER 8.30 strain gage amplifier

Three measuring points were set up. The positions are shown in figure 12 and two drilling stages can be seen in figure 13.

By way of example, figure 14 shows the results obtained for measurement of residual stresses at measuring point 1. The graphs show the trends of the strains, the principal stresses and the alpha angle, which were measured in accordance with the provisions of standard ASTM E837-08. Similar results were obtained at the other measuring points but are not provided solely for the sake of brevity.

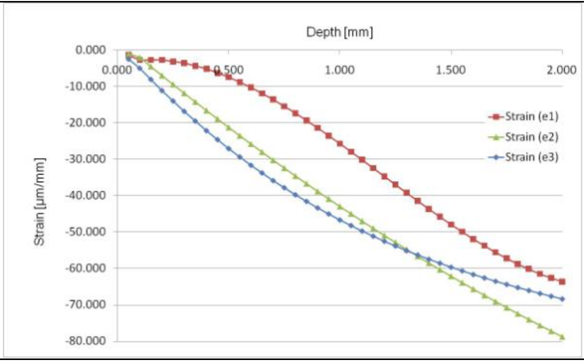


Figure 14a. Strains versus depth.

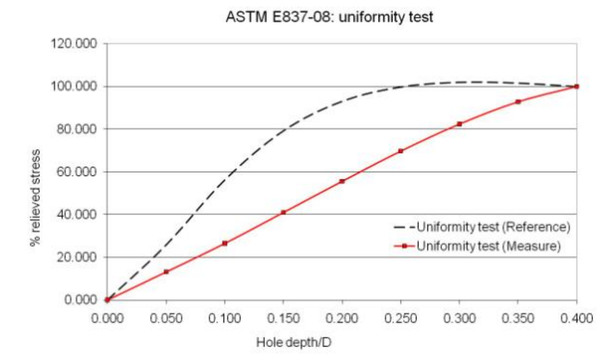


Figure 14b. Uniformity test (ASTM E837-08)

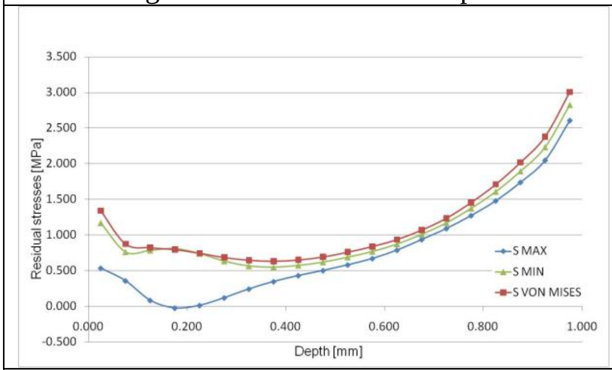


Figure 14c. Principal stresses and ideal stress versus depth.

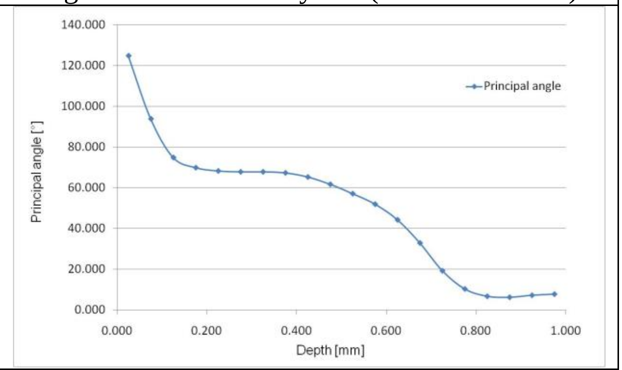


Figure 14b. Alpha angle versus depth.

7.CONCLUSIONS

Use of an automatic system for measuring residual stresses in plastic materials has proved indispensable for carrying out reliable measurements on the materials analyzed. In fact, manual drilling or high-speed drilling methods do not allow reliable measurements.

The optimal parameters have been defined for the drilling process and acquisition of strain values in applying the hole-drilling method to injection-molded plastic components. In view of high strain gage sensitivity to external factors, the remote control of the automatic drilling and data acquisition system has proved extremely effective.

8. REFERENCES

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