Condition Monitoring of Cold Stamping Presses Based on Fiber Optic Sensors

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Abstract. The work presented in this paper is part of the LEVEL-UP project, which aim is to develop a platform for monitoring the production lifecycle of Large Industrial Equipment (LIE). One of these LIE involved in the project is cold stamping presses for automotive components manufacturing, for which, within the framework of this project, it has been developed a monitoring system based on two complementary Fiber Optic Sensor (FOS) technologies. A combination of fast and high accuracy punctual Fiber Bragg Grating sensors (FBG) with multipoint Brillouin distributed sensors were selected for the monitoring system. The multi-parametric FOS monitoring system was installed and validated in the structure of three large cold stamping machines to analyze their Structural Health Monitoring (SHM), and for their Condition Monitoring (CM). During the validation, it was noticed that from the distributed sensors is possible to obtain a 3D map of the strain and temperature status of the press structure. And, from the FBGs, besides to obtain information from the strain and temperature of the points where these sensors are installed, also, they provide information about each stamping process: the applied force by the press, the frequency of manufacturing, and the number of components manufactured.

Keywords: Fiber optic sensor · FBG · BOTDA · Condition Monitoring · Structural Health Monitoring · Large Industrial Equipment · Cold stamping press

1 Introduction

The main goal of the LEVEL-UP project [1] is the development of a holistic operational and refurbishment framework applicable both to new and existing manufacturing equipment to achieve dynamic utilization and maintenance with upgraded remedial actions for sustainability. The project results will be demonstrated in seven different application driven pilot lines in metal machining, woodworking, automotive, caravanning, railway and aeronautics. The work presented in this paper is focused on the automotive sector, implemented in the ESMA (Estampaciones Mayo) pilot line [2].

ESMA is a leading component manufacturer in the automotive industry. They have cold stamping presses of up to 2,000 tones, together with equipment to manufacture

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P. Rizzo and A. Milazzo (Eds.): EWSHM 2022, LNCE 254, pp. 338–347, 2023.
https://doi.org/10.1007/978-3-031-07258-1_35

components and subassemblies. One of the aims of the LEVEL-UP project, for this Pilot Line (PL), is to develop a monitoring system able to detect and monitor the structural health of the presses, and avoid the appearance of cracking problems. The presence of cracks in the press structure is an issue that these cold presses can suffer and that has a negative impact on the manufacturing process. In the case of ESMA pilot line, they have detected some cracks in a few of the older stamping presses that they have. In such case, the cold stamping presses present visible cracking problems, with no possibility of knowing their real state, the criticality of the failures that have appeared, or their evolution. Besides, during the maintenance and repair process, problems not detected up to now were identified. The lack of CM and sensory data at structural press led to propagated damages, which could have been avoided. The encountered problems lead to an increase in the time required to complete the repair, increasing the unforeseen downtime.

One of the main objectives of LEVEL-UP in the ESMA case is to have an analysis and monitoring system of cracks, for identifying their appearance and subsequent evolution in situ. In addition, the *CPSisation & Modernization* of the machines will allow monitoring and control their operation through the *Strategies* to optimize their performance against their known condition. At the end of the project, a functional diagnosis would support ESMA to evaluate the defective parts and their economic impact.

The success of stamping process depends on more than forty associated variables [3], hence, off-line analyses cannot accurately predict all these faults, therefore, online monitoring is preferred [3]. Up to now, sensors were not usually installed in the structure of the stamping machines to CM. Although, in last few decades, the monitoring experienced evolution regarding the development of sensors, signal processing techniques, and feature extraction has led to the implementation of monitoring systems in the stamping presses. The progress on stamping press monitoring was focused on the digital tools [4, 5], to simulate the press efforts, the design of the stamping tools, and recently, with the age of Industry 4.0 upon us, on the press kinematic monitoring [6, 7]. Although, in the last years, much progress has been made in the CM of the cold stamping presses, there are still some detected blind spots in their CM, particularly, in the structure monitoring of old presses, where sensors have not been installed because of the monitoring system cost or difficult to customize. In the LEVEL-UP project, a monitoring system based on fiber optic sensors for structural health monitoring and CM, focused on crack detection and monitoring, was designed, developed, integrated, and validated in new and old cold stamping presses.

There are many references works and commercial FOS adapted to SHM or CM to monitor buildings, civil infrastructures, power plants, etc. [8]. But, for industrial components and machine monitoring, FOS technology was not so much validated at relevant environments [9], and nothing related with the use of FOS in SHM of stamping press, unless we know.

2 Fiber Optic Sensor Monitoring System

The FOS monitoring system developed in the LEVEL-UP project combines distributed and punctual FOS able to show a 3D map of the strain and temperature status of the press structure, and also, to monitor some parameters related to the manufacturing process at real time. The goal of the proposed monitoring system is to predict, and in consequence avoid, the appearance of cracks (or other damages), their location, and their growth, through specific algorithms developed for this purpose. A combination of fast and high accuracy punctual Fiber Bragg Grating sensors (FBG) with multipoint Brillouin distributed sensors based on Brillouin Optical Time Domain Analysis (BOTDA) technique were selected because of the intrinsic and unmatched properties offered by optical fibers in terms of size, EMI immunity, multiparametric and multiplexing potential, and their adaptability to design an ad-hoc fiber optical sensing network able to cover all the critical points defined. The FBG sensors will be able to monitor at a very high acquisition rate, with high accuracy, and sensitivity at the critical points defined to monitor. These sensors, in addition to temperature and strain measurements, can detect vibrations, an early sign of a potential component fault or defect, and cracks appear or its growth evolution. To complement the FBG sensors network, the Brillouin distributed sensors were used. They offer a multipoint and multiparametric network, distributed along the press structure. With this technology is possible to monitor strain and temperature on a fiber up to around one hundred km with a spatial resolution between 0.5–5 m, which offers thousands of measurement points for only one optical fiber. The major difference with the FBG sensors is the acquisition rate (BOTDA distributed sensors are slow, a few mins for each measurement) and the cost of the datalogger equipment (interrogator), which in the case of distributed equipment is 4–5 times more expensive than the FBGs interrogator.

2.1 Fiber Bragg Grating Sensors

FBGs are punctual sensors, corresponding to a portion (3–10 mm) of the optical fiber long, where the core was modified by a laser to have a periodic variation of the refractive index. This periodic refractive index variation reflects a wavelength (0.2–0.6 nm wide) through the so-called Bragg diffraction phenomenon, and transmits all others, acting as an optical notch filter in transmission, as depicted in Fig. 1. The FBGs multiplexing is very straight forward, many gratings can be deployed longitudinally in the same optical fiber as long as their reflected wavelength is different, avoiding crosstalk. Since strain or temperature variations affect the period and refractive index of the FBG, the reflected wavelength varies too. FBGs are the best option for point monitoring of strain and temperature, as they are the equivalent of a mix of strain gages and thermocouples regarding their application. Temperature and strain measurements are coupled, so to discriminate between strain and temperature, several techniques can be used: encapsulations that avoid strain in the fiber, deploying two fibers, only one being sensible to strain and the other loose (not affected by strain), using coated fibers with different sensibilities, etc. In the LEVEL-UP project, to avoid the FOS cross-sensitivity between strain and temperature, the temperature sensors will be encapsulated in a metal capillary tube to insulate them from the strain variations.

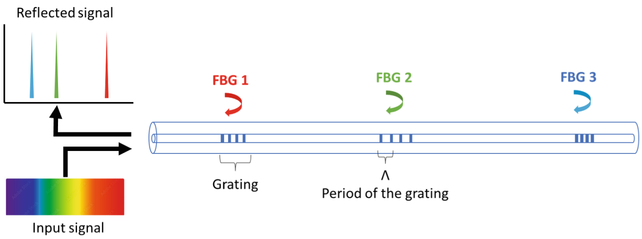

Fig. 1. Principle of FBG sensor.

2.2 Brillouin Distributed Fiber Optic Sensors

Distributed fiber sensors are based on a physical phenomenon that appears in optical fibers when light is propagating through them. This effect is known as scattering, and when it appears in optical fiber it can show itself in three different ways (Rayleigh, Brillouin, and Raman), giving place to three different categories of distributed sensors. Each one of them has its own properties, and therefore, they are employed in different applications, for instance, sensors based on Raman scattering are only sensible to temperature variations, hence their applications are limited to temperature monitoring. However, Brillouin, and also Rayleigh sensors, are sensitive for strain and temperature variations, making those applications related to SHM, where both magnitudes must be measured, suit better for them. All distributed sensor technologies have a great advantage in comparison with other sensing solutions: the entire fiber acts as the sensor, in contrast with FBG that only measures at only one point. Consequently, these sensors can provide thousands of measurements points depending on the spatial resolution employed, and the length of the sensing optical fiber. Another great advantage with respect to other types of fiber sensors is that it is not necessary to make modifications into the fiber to measure strain and temperature, being even possible to use standard telecom fibers previously installed for other purposes.

BOTDA sensor systems are the most employed technique in the field of Brillouin distributed sensors. BOTDA sensors are based on a non-linear scattering process called Stimulated Brillouin Scattering (SBS). In SBS, the Probe wave is amplified through the coherent addition of a reflected Pump wave through Bragg diffraction on the refractive index perturbation generated through an acoustic wave. The composition of the optical fiber, its temperature and strain, while giving the frequency at which the Brillouin amplification is maximum. The measurements consist of an array of values of this frequency, named Brillouin Frequency Shift (BFS), for each location along the optical fiber. This parameter, BFS, is related to strain and temperature variations along the sensing fiber. In BOTDA, the Probe wave is a continuous wave, and the Pump is a pulse travelling in opposite directions, so the interrogation works as a time-of-flight technique. As depicted in Fig. 2, the Pump pulse amplifies the Probe wave along the fiber. At the opposite end of the fiber to where it was launched, the Probe wave exits as a signal containing the spatial information of the Brillouin gain along the fiber. The separation between locations is given by the spatial resolution that is defined by the temporal width of the Pump pulse. The smaller is the spatial resolution, the more spatial detail we get in the measurement [10].

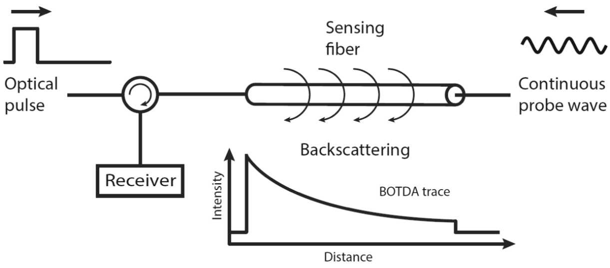

Fig. 2. Time of flight BOTDA operating principle.

3 Fiber Optic Sensor Installation

The FOS monitoring system was defined, designed, developed, and integrated in three stamping presses (Fig. 3). Two of them were old presses (from the 80s) and the third was a new press (from a few years). The new press has many commercial sensors installed, such as accelerometers, thermocouples, force sensors, etc. for its CM. The old presses are twins, and both presented cracks around the weld rings of the structure of the gears, but they didn't have any sensor installed for CM or SHM. The cracks from one of the old presses were repaired, replacing the cracked structure with a new one without welds, but the second old press, was not repaired, so, it still presents the cracks on its structure.

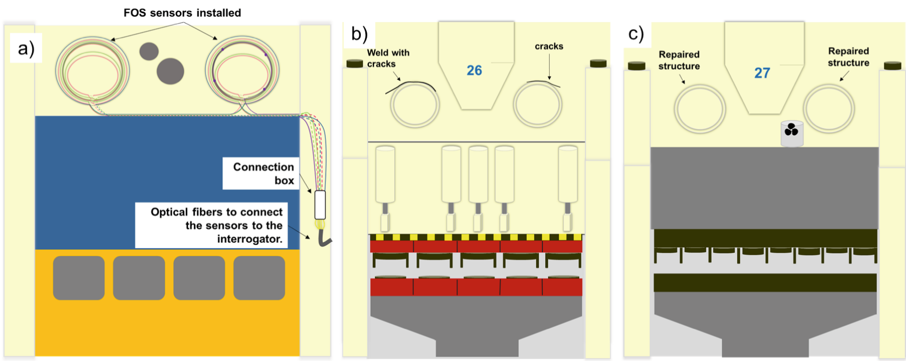

Fig. 3. Stamping presses monitored. a) New press. b) Cracked press. c) Repaired press.

In the new press, the aim is to monitor the strain on the structure of the press to study the press efforts during its operation, especially in the zone where the cracks have appeared on the old presses, to prevent the appearance of the cracks. In addition, the FOS data will be used to complement the commercial sensors to feed the CM system, to compare and complement the commercial sensors data, and to develop the maintenance prediction models and digital twins of these LIE. The FOS monitoring system defined to be installed in the new stamping press was composed of three distributed fiber optic sensors and 4 punctual FBG sensors. They were installed on the critical points of the front gear structure (Fig. 4). Two strain distributed sensors were placed around the external gear structure, both sensors have the same disposition, three loops equally separated, being one of them placed at the weld and the others inside and outside. Each sensor employs a different spacing between the loops, 0 mm (over the weld), 25 mm and 50 mm (from the weld). The third distributed FOS installed was a temperature sensor, which had only one loop per gear, and it was glued at 80 mm from the weld of the gears, as temperature sensor reference. According to this layout, the fiber length of each FOS to be monitored is 32 m for the first strain sensor, 33 m for the second, and 21 m for the temperature sensor. The monitored spatial resolution employed was 0.5 m, so, more than 150 measured points are monitored on this press structure. Besides, four punctual FBG multiplexed sensors were glued around one of the gears welds, as one of the strains distributed FOS loops.

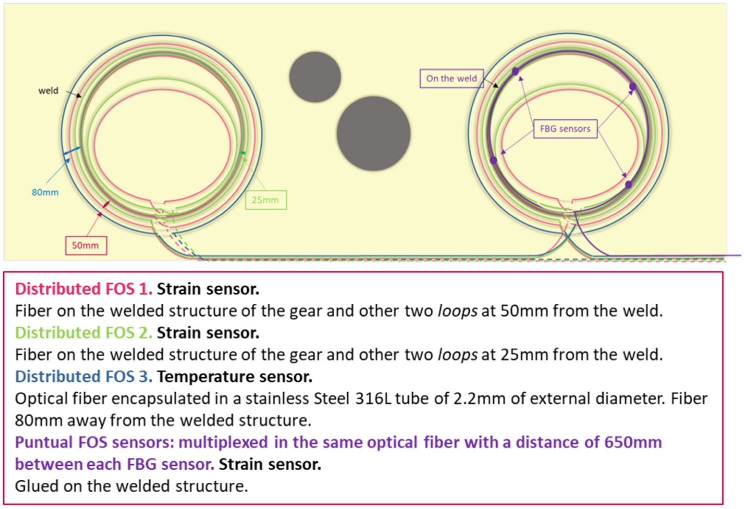

Fig. 4. FOS distribution installed in the new press.

In the old presses only FBGs were installed, because in this case, a higher spatial resolution, accuracy, and acquisition rate was aimed. The FBGs were distributed along the weld rings of each old stamping press (Fig. 5). In the cracked press, a higher number of FBG sensors (18) were installed to cover the whole cracks zone, in order to obtain a higher resolution and sensitivity to know the cracks evolution.

The FBGs distribution was the following (Fig. 5a): on the first welded ring (1) 2 FBGs on the cracks out of the weld, 4 FBGs on the cracks in the weld, 3 FBGs on the rest of the welded ring, and 1 temperature FBGs on the press structure (out of weld) were installed. On the second welded ring (2), 1 FBGs on the cracks out of the weld, 4 FBGs on the cracks in the weld and 3 FBGs on the rest of the welded ring were installed.

Regarding the repaired press, the FBGs distribution strategy was the same used in the new press, a total of 8 FBGs were installed around the welded structure. The FBGs distribution in this press was the following (Fig. 5b): on the ring (3): 4 FBGs on the welded ring were integrated. On the ring (4), 3 FBGs on the rest of the welded zone and 1 temperature FBGs on the press structure were integrated.

All the FOS were glued on the cold stamping presses structure by an adhesive resistant to industrial environment, and the temperature sensors were encapsulated in a metallic capillary tube of 1.2 mm of external diameter.

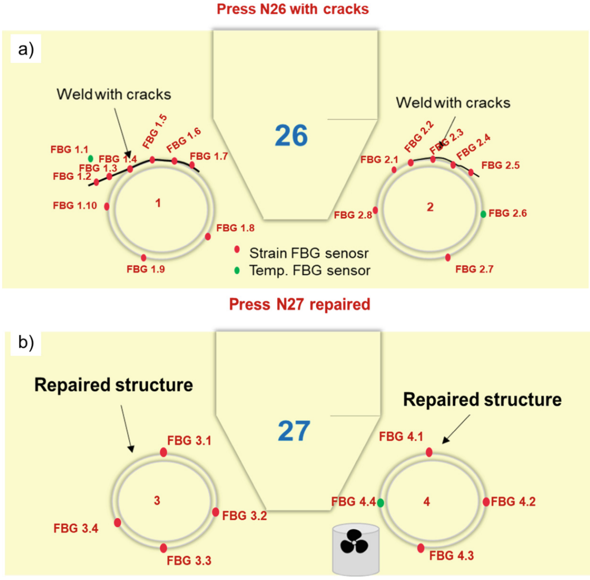

Fig. 5. FBGs distribution for the old presses. a): FBGs installed in the cracked press. b): FBGs installed in the repaired press.

4 Results

The LEVEL-UP project is still on-going then, the FOS monitoring system is still recording data and the prediction models and Digital Twin, which include the FOS information, are still under development. Therefore, in this section, only the results obtained from the FOS data processed is showed.

4.1 Results from the New Press

From the FBGs response is possible to monitor the temperature variation of the press structure due to its normal operation, as is depicted in Fig. 6. During the working hours the temperature of the structure increase and during the night or weekend drops. The unusually low temperatures showed around the day 100, was because of a snow squall in Spain. There is some lack of data because of connection problems.

In Fig. 7a, a detail of the FBGs response (in raw data) for one week is showed. Besides the temperature variation, which is clear for the FBG4 response, the other monitored signals of the FBGs show some peak variations during the working stamping press hours. This is due to each stamping cycle of the press. In Fig. 7b the response of the FBGs

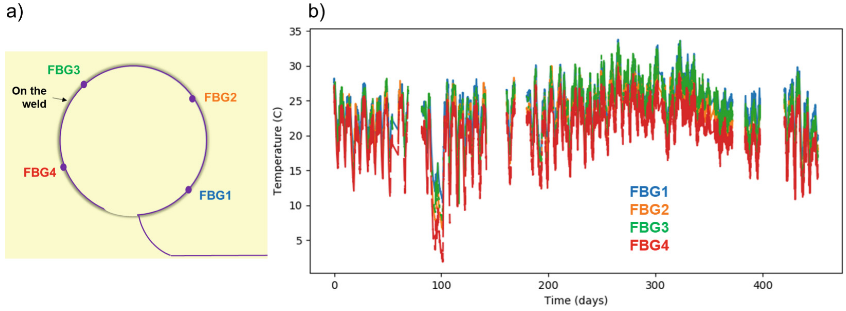

Fig. 6. FBGs temperature response for 450 days.

for one stamping cycle is showed. It is possible to observe that depending on the FBGs location around the welded ring, the stresses experienced by each sensor are different. The FBG2 experiments a higher impact than the others, then, this part of the structure is more stressed. Also, the FBGs located at the top of the ring suffer traction and the located at the bottom suffer compression. The shape of the FBGs response for each stamping cycle match with the commercial force sensors installed.

In addition to this, from the FBGs response is possible to know the number of components manufactured and the manufacturing frequency, detecting and counting the peaks on the signals and making a Fast Fourier Transform (FFT), respectively.

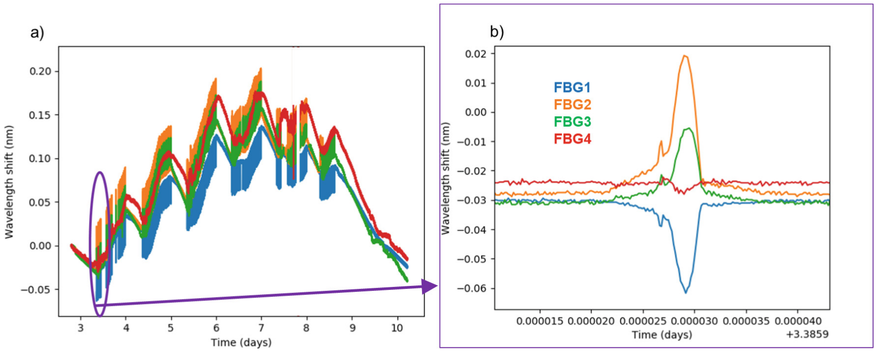

Fig. 7. FBGs response in raw data. a) FBGs response for one week. b) detail of the FBGs response for one press stamping cycle.

Finally, using the FOS distributed sensors is also possible to monitor the temperature variation of the structure, obtaining a detailed 3D map of the temperature distribution along the stamping press structure, as is depicted in Fig. 8a.

BOTDA distributed sensors employed are not able to monitor the stamping cycle effect on the press structure due to their slow acquisition monitoring rate (a few minutes). Nevertheless, it will be possible to detect permanent strain variations which would be a sign of the appearance of a defect on the press structure. Figure 8b shows a comparison of the responses of strain sensors and the temperature sensors, as it is possible to see, the responses are very similar because for so far no damages have appeared on the structure, and they are all monitoring only temperature variations.

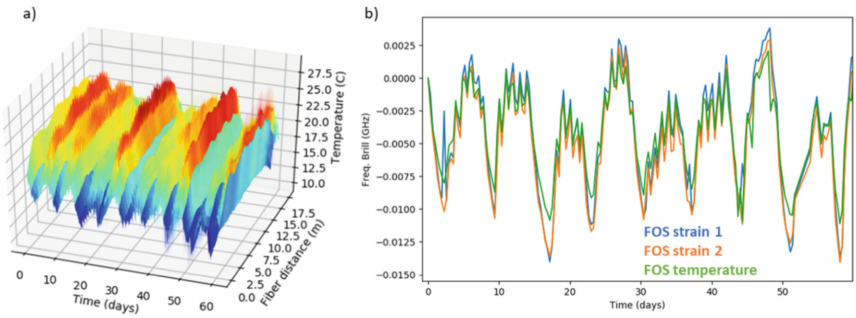

Fig. 8. Distributed FOS response for 60 days. a) Temperature response, b) Comparison between the distributed sensors response: strain 1, strain 2 and temperature.

4.2 Results from the Old Presses

In Fig. 9 the response from the FBGs installed in the older stamping presses is showed. As is explained in the previous section, from the FBGs response is possible to monitor the temperature variations of the press structure due to the normal press operation. This temperature response is depicted in Fig. 9a for the repaired press, for some of the measurement campaigns done. Furthermore, the FBGs are able to monitor the evolution of cracks and their growth. In Fig. 9b, the raw response for the FBGs installed in the cracked press is depicted. It is possible to notify the crack growth in the zone where the FBG2.4 is located because the tendency is different from the rest of the FBGs.

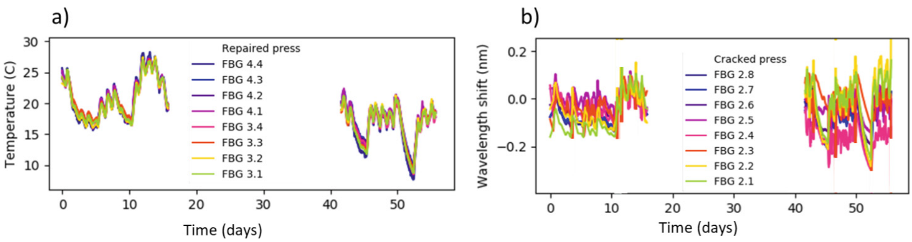

Fig. 9. a) Temperature response from the FBGs integrated in the repaired press. b) Response from the FBGs integrated in the cracked press, in wavelength shift value.

Finally, in Fig. 10 the detail of the FBGs response during a stamping press cycle is showed. While the wavelength variation of the FBGs installed in the repaired press structure is almost insignificant, which means that the structure hardly undergoes any stress during the stamping process, the FBGs installed in the cracked press experiment a high stress variation.

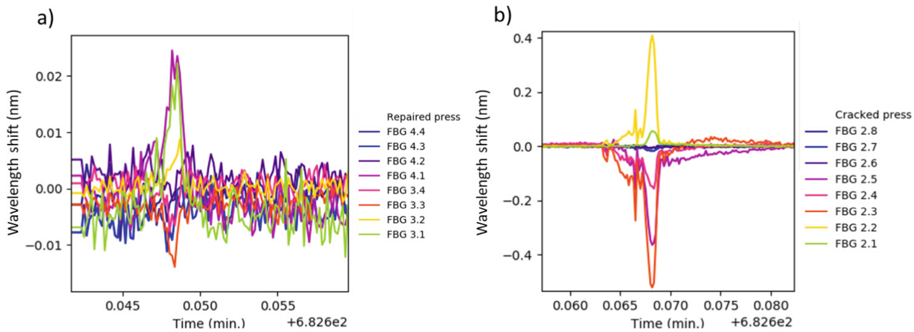

Fig. 10. FBGs peak detail due to one stamping press cycle. a) FBGs installed in the repaired press. b) FBGs installed in the cracked press.

5 Conclusions

In this section, a FOS monitoring system based on Brillouin distributed sensors and FBG punctual sensors was designed, developed, installed, and validated in old and new cold stamping presses to monitor the SHM and CM of the press. During the validation, it was noticed that from the distributed sensors is possible to obtain a 3D map of the temperature and permanent strain press structure status. And, from the FBGs is possible to obtain information from the strain, stress, and temperature of the points where these sensors are installed. Besides monitoring the evolution of the crack, but also get information about each stamping cycle: the applied force of the press, the frequency of manufacturing, and the number of components manufactured.

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