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Procedia CIRP 38 (2015) 143 – 146
www.elsevier.com/locate/procedia

The Fourth International Conference on Through-life Engineering Services

The use of infrared thermography for maintenance purposes in the production process of components for automotive alternators

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Abstract

This work reports an investigation concerning the employment of infrared thermography in the production environment of claw pole alternators, aimed for early detection of anomalies during the stamping stage at the press. The investigated process consists of a number of steps, starting from a raw workpiece in the form of a star, sheared from a low carbon steel plate, is brought to its final shape through bending and coining operations, using a progressive die. The process is characterized by a high production rate since the component is destined for the automobile market, therefore the controlling of both the die conditions as well as the mechanical press is crucial in order to reduce unexpected stops of the process.

After having analysed each production stage, a series of experimental tests have been carried out and a series of thermal snapshots were taken during the normal production run and analyzed in order to detect any process signature which were capable of giving information concerning the process conditions. An FEM model has also been developed for each step of the process in order to characterize the material flow and, in addition, the thermal field related to the transformation of the mechanical energy into heat, due to plastic deformation of the material and frictional effects. Correlations between the geometry resulting from material flow and thermal maps detected in the production environment have allowed to address of the maintenance activity in order to eliminate defects which can affect significantly the functionality of the product as well as the die life.

Peer-review under responsibility of the Programme Chair of the Fourth International Conference on Through-life Engineering Services.

Keywords: Infrared thermography; Maintenance; Finite element simulation; Claw pole alternator;

1. Introduction

One of the most common type of alternator used in modern automotive production is the claw-pole. These kind of alternators, with an inductor based on the Lundell circuit, have a rotor constituted of two opposed polar impellers, partially interpenetrated with a single ring coil, as depicted in Fig. 1. The claw pole can be manufactured in different ways, namely by bending of an n-pointed star blanked from a thick plate or by hot forging and, more recently, by warm forging of a billet. However, the latter two technologies still requires high investment costs; therefore, the more traditional process is still a valid solution for those enterprises which possess a long established experience at such a technology. A very important rule in modern industry is to reduce sudden breakage of the mold and consequently machine stops and to evaluate process parameters with non-contact and non-destructive techniques.

Fig. 1. 8-poles rotor used for claw pole alternators.

Peer-review under responsibility of the Programme Chair of the Fourth International Conference on Through-life Engineering Services.
doi:10.1016/j.procir.2015.08.087

Infrared (IR) thermography has been used for non-destructive controls for many years, over various applications, however only recently its applications have become effective and more widespread in industrial fields. Jin-Woo [1] used thermography to detect fractures caused by an unexpected temperature distribution in underneath layers structures of glass fiber reinforced plastic. Park et al. [2] conducted a study of detecting crack defects caused by stress corrosion in a pipe welded with dissimilar metals. In [3], Chen et al. investigate the possibility to evaluate the re-manufacturing of tools, before failing or becoming obsolete. Thanks to the maturity of IR thermography, Bagavathiappan et al. [4] focused their study on the advances reached by this technology as a non-contact and non-invasive tool for monitoring in civil structures, electrical installations and welding processes. In [5] IR thermography has been used to register the temperature field in electrical equipment, in which the reliability is strictly related by temperature, besides in [6], Huda and Taib, studied the effects of temperature distribution in electrical equipment proposing an artificial neural network model to find defects. Ren et al. [7] propose a method to evaluate impact damage defects, while Benmoussat et al. [8] studied a fully automated model based on the use of IR thermography to detect surface and sub-surface anomalies like cracks and notches in industrial metallic parts.

In literature, the studies regarding 8-poles claw pole rotors are mainly focused on the electrical properties. In [9] Jadin et al. studied the effects of thermal condition on electrical equipment. For example, Chen et al. [10] illustrates the effect, not yet analyzed in other scientific contexts, of the permanent magnets on the saturation of the magnetic field. In [11], Guo et al. investigated the application of composite magnetic materials in electrical machines for realizing a small claw pole permanent magnet motor. Doege et al. [12] presented different tools to realize the claw pole, while Quin et al. [13] elaborated a model to describe net-forming by injection forging to predict flow-dependent flaws.

In this work, the IR thermography has been used, together with an automatic 3D thermo-mechanical FEM model of the whole process, in order to reach a deep understanding of the process aimed to schedule appropriate maintenance activities for the tooling.

2. Analysis and Finite Element modeling

A 3D thermo-mechanical FE model with about 300,000 tetrahedral elements has been developed, using DEFORM-3D software, in order to study the workpiece behavior in some critical zones, especially in the upper part of the hips and during the blanking operations, as shown in Fig. 2. By taking advantage of the symmetry characteristics, only one fourth of the blank was modeled. The workpiece material is a low carbon steel, which has been characterized by means of tensile tests to assess the cold mechanical properties. The resulting constitutive law is reported in the following equation:

$$\bar{\sigma} = 89 \cdot \bar{\varepsilon}^{0,165} + 220 \quad \text{(MPa)} \qquad (1)$$

where $\bar{\sigma}$ and $\bar{\varepsilon}$ are the equivalent von Mises stress and plastic strain, respectively.

In order to consider the heat exchange with the environment, dies and molds, the thermal properties given by literature for each material were used, while the frictional coefficients were determined by experimental tests. Given the real displacement of the mechanical press in term of strokes per minute of the real crank system and the starting relative positions between workpiece and dies, it was possible to obtain a reliable result in term of force-time given by the press.

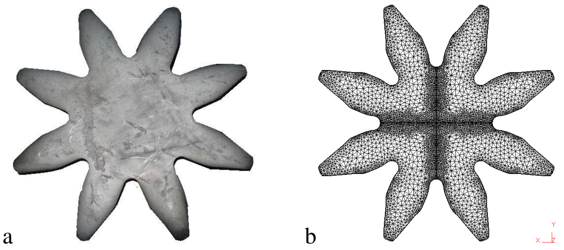


Fig. 2. (a) blank sheared from a thick strip; (b) spatial discretization employed for the FEM analysis.

To achieve a comprehensive understanding of the process, the correct set of parameters and their values were obtained and studied by comparing the results obtained with data obtained in real production, until the attainment of an automatic FEM model, which, for given process parameters, allows to quickly predict the final geometry of the workpiece. The FE model obtained is therefore useful to simplify in a realistic way the forming process and therefore to predict what occurs to the process in terms of thermal effects. The model, in fact, knowing dies material properties as well as the workpiece properties, lubrication status and the thermal exchange coefficients, can predict the die zones areas most subjected to failure, and therefore it has proven to be a valid tool for maintenance.

Based on experimental observations at the manufacturing level, we concentrated the attention to the die zones where horns are formed. This step is the most expensive in terms of energy of the whole process, as can be seen in Fig. 3, which depicts the trend of the mechanical energy converted into heat inside the material during this step. Indeed, in a very short time, the coiner exerts a very high force, in order to form the 8 horns of the rotor into their final geometry.

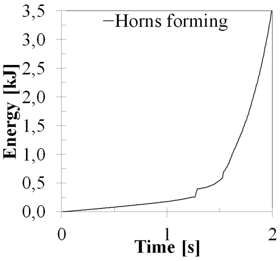


Fig. 3. Mechanical energy expended for material deformation during the horn- sizing step.

The coiner have 8 pits into which the rotor tips are forced to enter for reaching their final geometrical form. Fixing the workpiece centering on the mold, due to very high angle of the pits and to the lubrication conditions, the coiner experiences a significant stressing temperature distribution with an abrupt change at the mold opening. Therefore, the coiner is usually the component most subjected to failure, as confirmed by experimental tests. This is the most critical and expensive part of the die, since the coiner is manufactured by EDM technology. The FE model developed, compared with the thermal analysis, was therefore useful to understand the behavior of the critical zones and therefore to redesign and improve the coiner.

3. Experimental tests

To produce a claw pole with 8-poles, a number of forging steps carried out by a mechanical press are employed. After each step, the workpiece is collocated by brackets in the mold of the next station, until the final product exits out of the press for further operations. Thermal measurements were carried out by employing the system ThermaCAM S65 HS by FLIR.

After a first analysis concerning the forces and material properties, it was possible to set a reliable FE model of the process.

In Fig. 4, the temperature distribution after the blanking operation of the central hole is shown. The temperature map is continuously detected by the thermograph and the image shown in Fig. 4 was captured when the die was just opened. As expected, the inner surface of the hole (SP11), which is the only one to be worked in this step, reaches the highest temperature (56 °C). In the figure, the temperature values in other single points of interest are also evidenced.

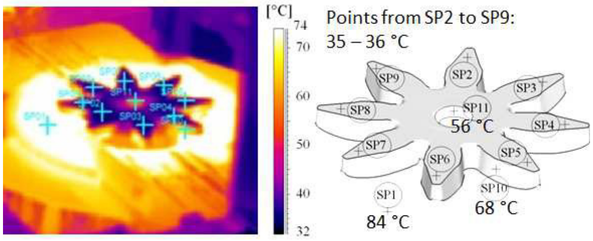


Fig. 4. Thermogram detected after the blanking operation.

As it is possible to observe, the temperature distribution is nearly constant, at about 35 °C, at the upper surface of the blank, while the die block upper surface (SP1) shows the highest temperature (86 °C). The lateral surface of the horns, (e.g. SP10 at about half thickness) exhibits a relatively high temperature, due to the heat flow from the die block to the workpiece during the operation.

In Fig. 5, it is shown the most expensive step in term of energy required by the mechanical press. This operation is devoted to forge the claw-pole horns, giving them the final geometrical tolerances. Due to the high stroke rate of the press, a high area involved in deformation and also to the high friction coefficient, temperatures reach very high values, causing significant alteration of oil lubrication.

In the central zone, which does not undergo deformation in this step, the temperature tends to remain constant at about 36 °C, i.e. the same exhibited at the end of the previous step (points from SP02 to SP08 in Fig. 5).

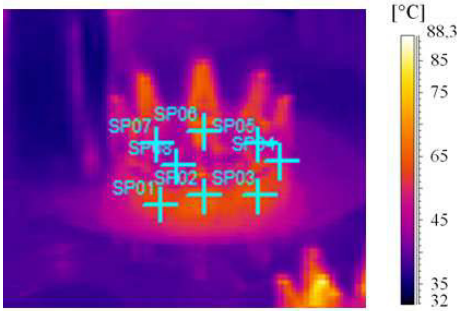


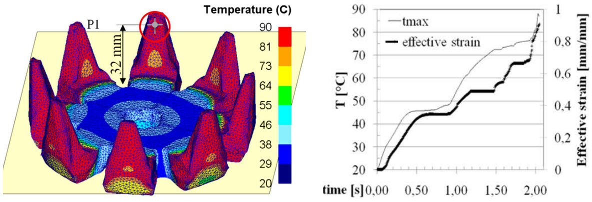
Fig. 5. Thermal map of the claw pole at the end of the last forming step.

Conversely, the temperature of the horns increases, due to plastic deformation in the coiner and frictional effects. In the case reported in Fig. 5, the temperature of the point SP01, at the external surface of a horn, about one third of the height below the tip, is about 85 °C.

From the above observations, it can be said that thermography can add important information about all the forming steps in the production process of the claw pole, which offers the possibility to evidence the most stressed zones as well as possible anomalies, both in the workpiece and tooling.

4. Results and discussion

Thanks to the experimental tests repeated for a large number of parameters in order to set the optimized ones, it was possible to obtain a model which reproduces the real temperature distribution, as shown in Fig. 6a. In Fig. 6b, the temperature trend and the effective strain at the reference point P1 as a function of the process time are reported.



a b

Fig. 6. (a) temperature distribution at the end of the last step obtained with the FE analysis; (b) temperature trend during the step and effective strain at point P1.

The reference point used to conduct this measurement is located at 32 mm from the ground plane of the claw pole, i.e. approximately at the same height of point SP01 of the experimental tests. As can be seen in Fig. 6b, the temperature increases during the horn forging, due to the plastic deformation of the material as well as to frictional effects related to the sliding of the material against the internal surface of the cavity of the coiner, as already said when commenting the previous experimental results.

The effective strain shows a similar trend, which is coherent with the temperature increase; i.e. as a consequence of the larger deformation, the temperature trend increases due to the transformation of the mechanical energy into heat. However, some differences may occur in the trends which could be attributed to both the changing of the thermal exchange along the horn as well as to the changing of the frictional effects between the horn and the die cavity. Such changings may be due, for example, to the separation between workpiece and die caused by wear and/or lubrication defects caused by the die wear.

Further accurate investigation carried by FEM simulations showed that a small depression occurred during the last forming step, as depicted in Fig. 7, which shows a section of a horn with a radial plane passing in the middle.

Due to the geometry of the die, when the last part of the vertical stroke approximates, the horn cannot completely fill the cavity and the upper part stops. The die continues its vertical stroke, but the claw pole is also constrained on the mold surface and therefore the horn experiences a bending as evidenced in Fig. 7. Due to the high force applied by the mechanical press to realize this operation, the die behavior in this step can be highly influenced by the temperature, which in turn influences the effectiveness of the lubricant and, as a consequence, the maximum force exerted by the press.

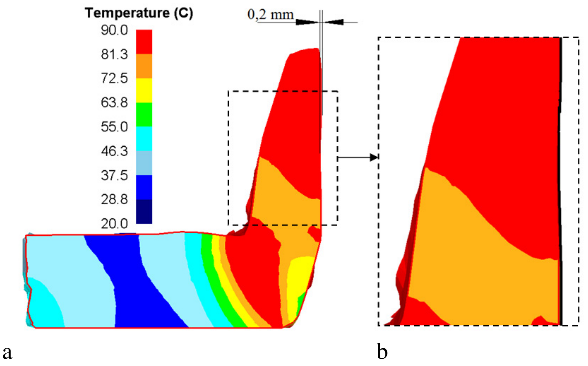


Fig. 7. (a) temperature distribution in the middle horn section; (b) particular of the horn bending (external surface).

The above considerations finally suggested the better maintenance action to undertake for the die, which consisted in a small variation of the geometry of the inner cavity of the coiner.

5. Conclusions

In this work, a 3D FEM model of the production sequence of a claw pole for automotive alternator has been developed. Experimental tests, concerning the temperature distribution and dimensional measurements of the workpiece, carried out in the production environment, have allowed to fit the model such as to accurately reproduce the real process, with a comparable temperature distribution. The comparison between experimental tests results and FEM model permitted a comprehensive knowledge of the process, adding important data for tooling maintenance and therefore to prevent unexpected out of tolerance of the product or even the dies failure.

In conclusion, the developed procedure, based on infrared thermography and FEM simulation, has allowed better planning maintenance of the tooling in the case of mass-produced components.

Acknowledgements

This work has been carried out in cooperation with Denso Manufacturing Italy Inc. under project POR-FESR Abruzzo, Activity I.1.1., Line B. The authors express their thanks to the team of Denso who followed the experimental tests, providing data and contributions in the discussion.

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