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▶ **To cite this version:**

Damien Mauduit, Marion Le Fournier, Kevin Grondin, Thomas Pottier, Yannick Le Maoult. Industrial applications of the superplastic forming by using Infra-Red heater. ICTP 2017 - International Conference on the Technology of Plasticity, Sep 2017, Cambridge, United Kingdom. pp.1898-1903, 10.1016/j.proeng.2017.10.958 . hal-01655007

HAL Id: hal-01655007

https://imt-mines-albi.hal.science/hal-01655007

Submitted on 2 Apr 2019

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Procedia Engineering 207 (2017) 1898–1903

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on the Technology of Plasticity, ICTP 2017, 17-22 September 2017, Cambridge, United Kingdom

Industrial applications of the superplastic forming by using Infra-Red heater

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Abstract

The superplastic forming is used in aeronautics in order to manufacture titanium parts with complex shapes. Regarding to others forming processes, it is important to save costs of superplastic forming. Using Infra-Red lamps to heat directly the blank is an economic way to raise the temperature as the heating time is cut to a few minutes instead of 24 hours. The tool core is not completely heated anymore, leading to greater efficiencies.

Radiative flux model was developed and complex thermomechanical simulations have been used as a predicting tool of the infra-red lamps power. The lamps power is adjusted throughout the forming step in order to obtain an optimized flux and thus to ensure a homogeneous temperature of the blank during the superplastic forming. Through these simulations, several TA6V sheets with a size of 500x500 mm^2 were successfully formed by using this technology. The microstructure is not affected by the quick heating phase. Secondly, an aircraft part with a size of 1500x1000 mm^2 were likewise formed which demonstrates the efficiency of the IR heating for the industrial superplastic forming.

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Keywords: SPF, Titanium, Aeronautical part, Simulation

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10.1016/j.proeng.2017.10.958

1. Introduction

TA6V is widely used in jet engines and airframe structures. It is a α+β type alloy which can exhibit a good superplasticity thanks to this dual phases microstructure. Superplasticity is the ability exhibited by some fine-grains materials to be elongated a great deal with no failure. Mechanism of superplasticity is known as grain boundary sliding and also dislocation creep. The superplastic deformations are possible in a narrow gap of temperature (850°C to 920°C for TA6V for fine grain and can be reduced to 750°C for Ultra Fine Grain alloys). Then, it is necessary to keep a homogeneous temperature of the sheet during all the forming phase. The deformation rate needs to be controlled too and maintained near $10^{-4}s^{-1}$. The titanium alloys combined with the SPF process offer large possibilities for complex part and can reduce assembly to a single part.

A classical titanium alloy superplastic forming production run is conducted in several steps. The first one is the heating of the metallic or castable die till 900°C nearly by conduction inside the press-furnace. The second step consists in removing the die out of the press and placing the titanium sheet on it. As a third step, a holding time is needed to return to an isothermal configuration. The forming period is during one hour more. Finally, the formed titanium sheet is taken off the press. The heating platen technology is responsible of the duration of the global forming process (heating and forming phase). Therefore, the total heating time are much greater than the forming cycle time. The first heating time is needed to get the tools and press platen up to 900°C which can last 48h depending on the mass of the tools. The second heating time is used to re-heat the tool after unmolding the part and can last 1 or 2 hours. The shorter the heating time is, the higher the saving costs will be.

Several technics have been developed in order to reduce the heating time and avoid the complete heating of the die. The direct heating of the sheet is possible by using induction [1] or infra-red lamps [2]. Aurock and Institut Clément-Ader (ICA) base their research in the development of the Infra-Red heater. The main issue is to ensure the homogeneity of the sheet temperature along the process. Aurock chooses to manage the temperature of the sheet with a numerical PID (PID means Proportional Integral Derivative –patented [3]) which takes into account the displacement of the sheet during forming and all the thermo-optical exchanges in the furnace.

2. Experimentation, superplastic forming test

To experiment the Infra-Red heating and to bear out the simulations, a laboratory device was developed in Institut Clément-Ader to form 500x500 mm^2 sheets. It is a press-furnace equipped with 8 IR lamps of 3540W each and diffuse reflectors on the top and the side. The maximum hydraulic pressure available is 100Tons. Argon gas is used to form the sheet and to prevent oxidation. The maximum argon pressure available is 40bar. A second device was developed by Aurock to form industrial size sheets (1500x1000 mm^2) with an equivalent heating device but containing 44 IR lamps. For both devices, the die is not heating before the forming phase: the sheet is placed on a cold die and it is directly heating. The pressure cycle and lamps intensity cycle can be programmed in the machine of the press-furnace. Those cycles can also be modified during the forming. A feedback is available from the pressure and temperature sensors in the die. The laboratory device is equipped with non-contact sensors to check the sheet temperature during the forming. Due to SPF conditions, the sheet temperature can lonely be measured locally. Therefore, the non-contact sensors cannot be used to control the power of lamps during the forming.

3. FEM simulations and radiative flux model

Lamps intensity cycle is obtained from FEM simulations, modelling the process forming, coupled with a numerical PID (developed in Fortran subroutines and already published [3][4]). For each numerical increment, Fortran subroutines give the intensity of lamps depending on the calculated sheet temperature during the forming. The process simulation needs to be modelled as close as possible to reality in order to determine the optimal power of lamps cycle. However, it was necessary to develop, in first time, a relevant radiative flux model in order to strictly describe the heat absorbed by the sheet along the forming steps. Indeed, in the superplastic forming, the temperature of the sheet has to be uniform and constant to ensure a correct forming. An incorrected model could bring local overheating on the sheet and damage the microstructure. The absorbed flux per element is calculated during the FEM simulation of the forming. Several studies [5] which calculate a radiative flux emitted by infrared lamps have already been done and used the equation (1).

$$\Phi_{Absorbed}(x,y) = \frac{(1-\varepsilon)Q_0 H}{2\pi^2 L\alpha}\left(\frac{\beta_+}{\alpha^2+\beta_+^2} - \frac{\beta_-}{\alpha^2+\beta_-^2} + \frac{1}{\alpha}\left(arctan\left(\frac{\beta_+}{\alpha}\right) - arctan\left(\frac{\beta_-}{\alpha}\right)\right)\right) \quad (1)$$

With, in the equation (1): $\alpha = \sqrt{x^2+H^2}$, $\beta_+ = y + L/2$, $\beta_- = y - L/2$, L and H are respectively the length (m) and the height (m) of the lamp, Q_0 is effective radiative power of the lamp (W), x and y are the position of the sheet element and ε the emissivity of the material. In this formulation, the emission of the lamp is supposed isotropic, and its diameter is considered small relative to its length and other dimensions of the system (1D model of the lamp). Furthermore, the deformation of the plane are not considered and likewise the multiple reflections influences.

The variation of the thermo-optical properties of TA6V from room temperature to forming temperature was also quantified as the thermo-optical properties of the IR heater and the cover. The thermal contact resistance of the sheet on the die was also determined. All data and phenomena are integrated in the FEM simulations to build the most relevant models and to assess the lamps intensity cycle.

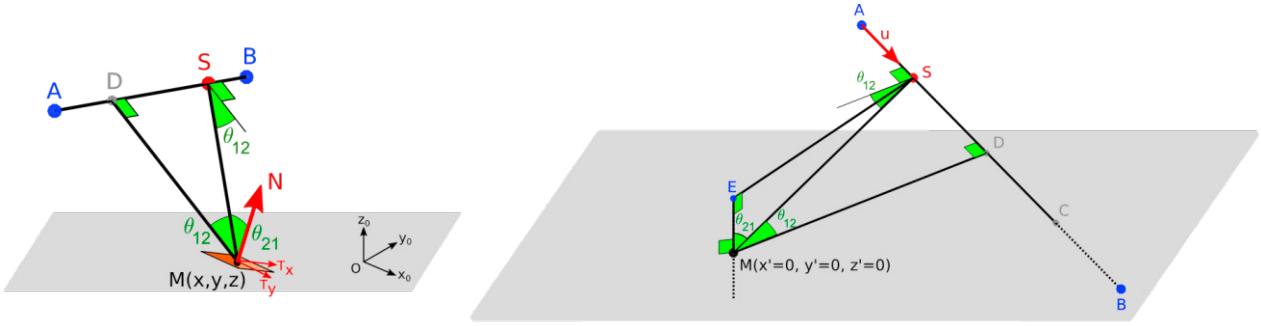
4. Results

FEM simulations

The equation (1) is only relevant for a plane sheet, In the case of a non-plane sheet, the direct incident flux must be recalculated by integrating the incident flux emitted by an elemental length ds of the lamp (1D model) and received by an elemental surface of the sheet which has a normal vector $\vec{N}$ (equation (2)).

$$\Phi_{Absorbed}(x,y) = \frac{(1-\varepsilon)Q_0}{\pi^2}\int_0^1 \frac{\cos(\theta_{12})\cos(\theta_{21})}{\left\|\overrightarrow{MS}\right\|^2} ds \quad (2)$$

In order to simplify the calculation of equation (2) and to obtain an analytical formula for all points of the sheet, the coordinate system is changed from the global coordinate system R_0 to the local coordinate system R (Figure 1). The problem thus becomes a flux calculation for a plane sheet and a lamp non-parallel to the sheet .It also deals with the situation when a part of the lamp is hidden (in the case θ_{21}>90° on the Figure 1). This new radiative flux model is used to calculate the absorbed flux for each elements of the sheet along the simulation of the forming process. The model, coupling with the PID controller, is implemented in Abaqus by several subroutines.



a. Global coordinate system R_0 b. Local coordinate system R

Figure 1: (a.) View factor from a point S in lamp [AB] to a point M on a non-plane sheet with a normal vector $\vec{N}$. (b) Lamp and sheet after changing the global coordinate system $\mathcal{R}_0(O, \overrightarrow{x_0}, \overrightarrow{y_0}, \overrightarrow{z_0})$ for the local coordinate system $\mathcal{R}(M, \overrightarrow{T_x}, \overrightarrow{T_y}, \vec{N})$.
In some case, the lamp may cut the plane z'=0: the intersection is noted C. The part [BC] of the lamp is hidden and does not send flux to the point M.

Each other relevant phenomenon is modelled: the friction coefficient between the sheet and the tool, the thermal exchange (radiative and convective) between the sheet, the tool and the internal atmosphere of the press-furnace, and the thermal exchange of the cover with the outside at room temperature. For the simulation, a double symmetry is considered (Figure 2a). At the beginning of the simulation, all the components are at room temperature. Then the sheet is heated up to the forming temperature, then the optimized pressure cycle is applied. The intensity is controlled for each lamp and the temperature is assessed for each nodes facing the lamps. This simulation will give the lamp intensity cycle to ensure a constant temperature in the sheet during the forming. The target temperature is 870°C during all the forming. An example of lamp intensity cycle obtained by the simulation for a 500x500 mm^2 is presented in Figure 2b.

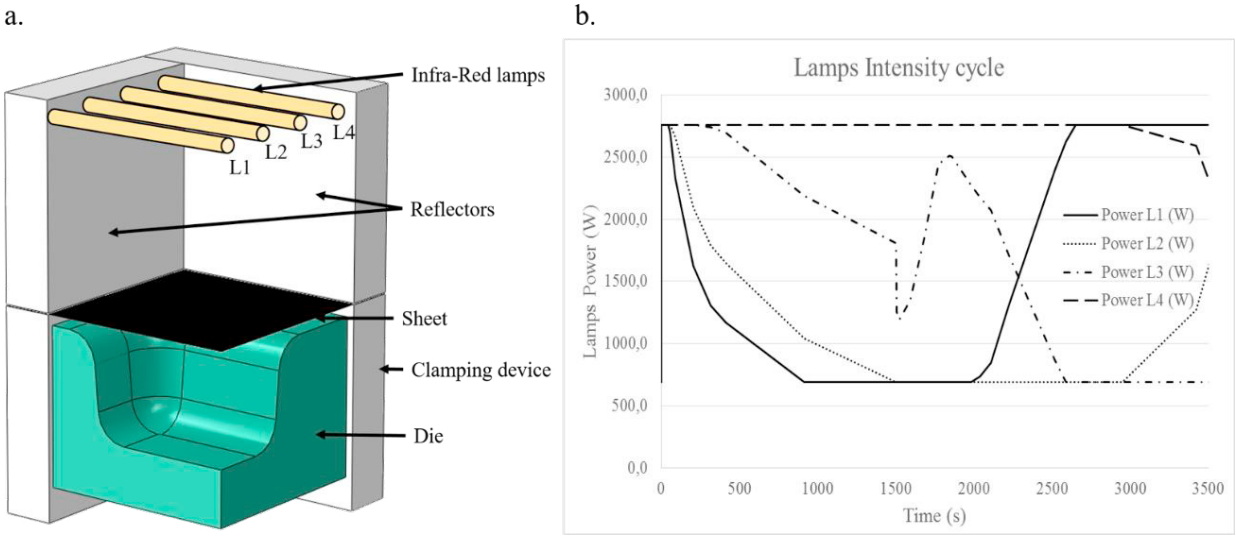


Figure 2: (a.) Schema of the laboratory device (only a quart of the device is represented) and (b.) lamps intensity cycle for the forming of a TA6V 500x500 mm^2 sheet obtained from the FEM simulation, coupling PID and new radiative flux model.

The pressure and the lamp intensity cycle are the recipe of the forming, used for the experimental tests.

Superplastic forming tests

In order to validate the simulation approach, two recipes are determined for each of the two parts geometry: the PID controller and the process simulations give the lamps intensity cycle and the pressure cycle. Forming tests are conducted with the laboratory and the industrial devices. The recipes are programmed and followed by the machines. The sheet temperature is not controlled by sensors during conventional SPF forming. However, for the adjustment and testing steps for IR heating device, the blank is unusually equipped with a few thermocouples. Unfortunately, they are often destroyed during the forming especially because of the pressure intensity and they only gave partial information about the sheet temperature. Figure 3 presents the global evolution of measured temperatures by the less damaged thermocouples during a forming test. It shows that the temperature stays in the [850°C 920°C] defined interval, even with the arrival of the gas pressure around 1500s which decreases the blank temperature. For both devices, the sheet are successfully formed, as seen on Figure 4.

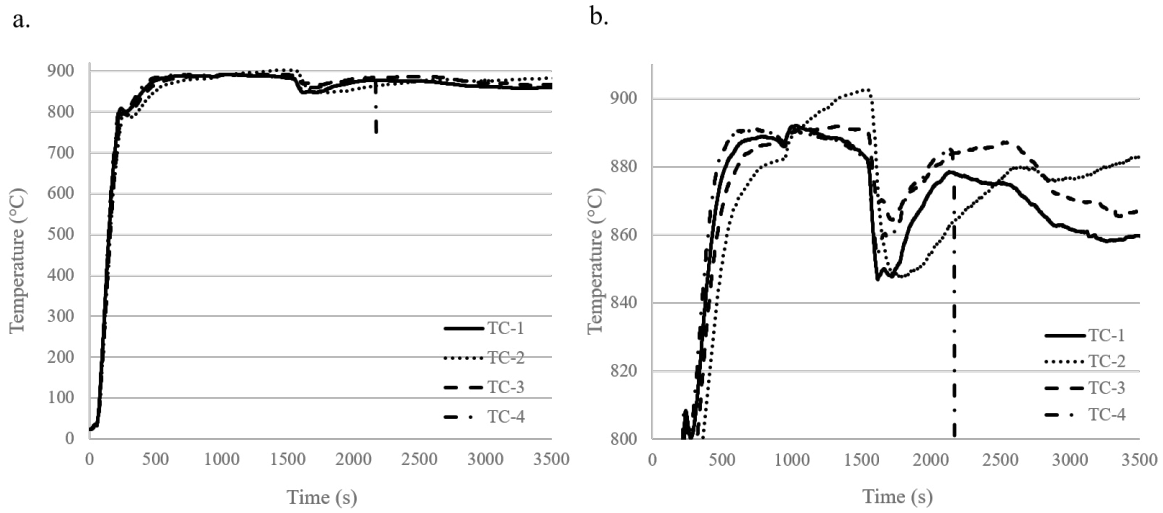


Figure 3: Sheet's temperature measured by some thermocouples (TC) during a forming test: Global evolution (a.) and details of the temperature variations (b.).

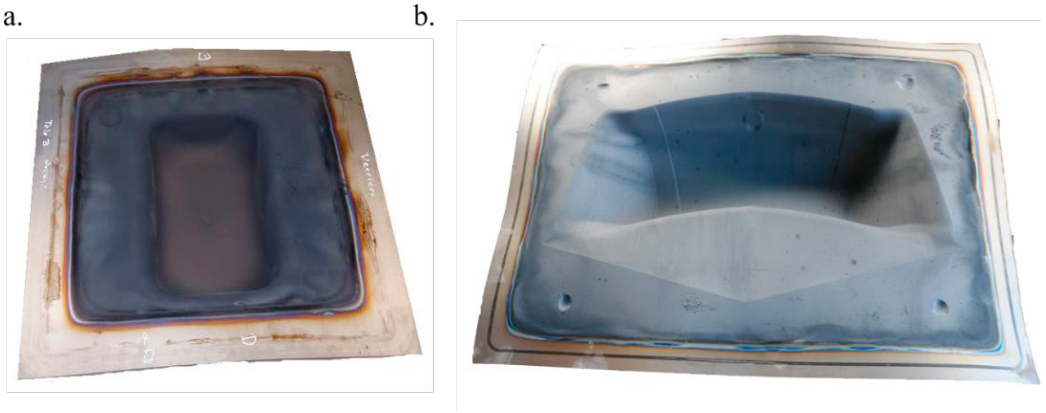


Figure 4: Examples of sheets of 500x500 mm^2 (a.) and 1500x1000 mm^2 (b.) formed by superplastic forming using Infra-Red lamps.

Although the thermocouples give an information about the temperature of sheet, it is necessary to control the thickness and the microstructure of the sheet to be sure that the forming happens as expected. Indeed, the final sheet's thickness is correctly predicted by the FEM simulation and can be used as a comparison variable as done in conventional SPF. The SPF process must not affect the initial microstructure of the TA6V. It can be impacted by the forming temperature because the α phase ratio highly decreases after 950°C.

The thickness after forming was measured with a non-destructive ultrasonic sensor. The comparisons between experimental and calculated measurements are in agreement. The main gap is located at the bottom of the vertical face and the fillet radius, but the difference never exceeds 0.2 mm (initial thickness at 1.4 mm). The microstructures of the TA6V sheets before forming (Figure 5a) and after forming (Figure 5b) are also compared by Scanning Electron Microscopy (SEM). The analysed samples are taken off the deepest part of the shape where the strains are biggest. The $\alpha+\beta$ phases are conserved after the forming as seen on Figure 5.

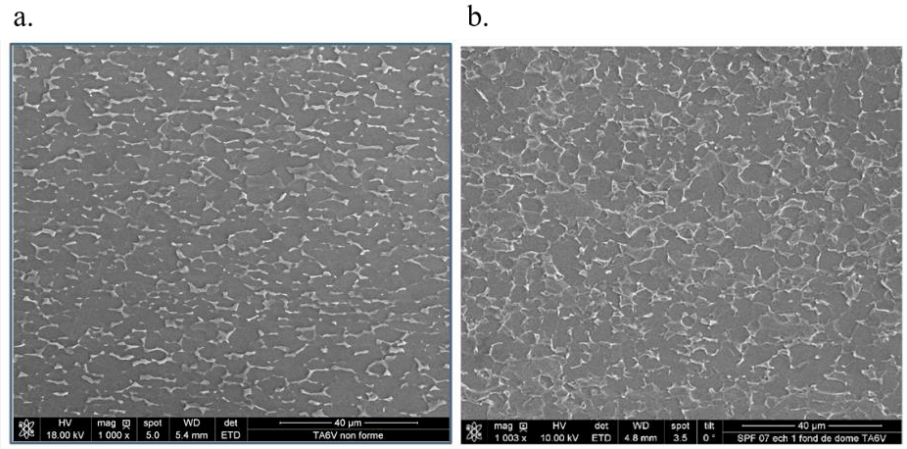


Figure 5: (a.) SEM image of the TA6V microstructure before forming shows the classical α+β phases, (b.) SEM image of the TA6V microstructure after forming shows that the α+β phases are conserved.

5. Conclusions

The direct heating of the sheet by using IR reduces the heating time and avoiding the complete heating of the die of the SPF process. A new radiative flux model and a numerical PID controller have been developed in order to control the power of the lamps taking care of all the thermal exchanges and the thermomechanical properties involved in that process. Several sheets with different sizes (500x500 mm^2 and 1500x1000 mm^2) were formed and answered to all the aeronautics quality requirement. These experimental results prove the feasibility and the relevance of Infra-Red heating device, applied in superplastic forming. The next step is the development and use of the system in industrial cadence. In order to check the industrial interest of the IR technology, a cost study was done to compare the part production costs with the conventional SPF ones. Aurock is able to do this study as the company is producing parts with conventional SPF. For IR technology, the costs are evaluated based on the knowhow of the company. The calculation is done for a part size of 1500*1000mm^2. The duration of the forming cycle is 2 hours. The batch is produced with 2 shifts (production speed: 32parts per week). Considering that, the use of IR reduces the part cost of 30%. The process has other advantages which are not easily countable. By using IR technology, the process becomes more flexible: possibility to produce a single part. The maintenance of the die is easier and the process becomes more comfortable for the operators as the die is not heated any more at 900°C. Consequently, the use of Infra-Red is also interesting to save production costs.

Acknowledgements

The authors acknowledge the financial support awarded by the "Region Occitanie", the European fund FEDER and the “Direction Générale de l’Armement (DGA)” through the RAPID financial support.

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