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Study of the dynamic recrystallization of Inconel 625 alloys through cogging

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Abstract

The dynamic recrystallization of Inconel 625 superalloys has been studied through cogging tests performed both on a screw press and a hydraulic press. The microstructure observed in different areas of the part are associated to thermomechanical parameters (i.e. strain, strain rate, temperature) obtained by the numerical simulation of the process. The equivalent plastic strain, $\varepsilon$, and an averaged Zener-Hollomon ($\dot{Z}$) have been implemented for the complete thermomechanical process characterization with regard to the DDRX. It has been found that the recrystallization domain in the ($\varepsilon, \dot{Z}$) processing plan is similar for both part forged respectively on the screw press and the hydraulic press despite the difference in terms of strain rate, and strain per pass of the two processes. The use of the average Zener-Hollomon parameter seems relevant to synthetized the combined effect of temperature and strain rate on discontinuous dynamic recrystallization of Inconel 625. Moreover, it has been showed that experimental tests made on industrial presses combined with numerical simulation allows to determine DDRX initiation and evolution of Inconel 625 with a reduced number of experiments. These are encouraging results for the prediction of the microstructural evolution in more complex parts with more complex forging path.

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1. Introduction

The nickel based Inconel 625 superalloy is widely used in aeronautical, petrochemical and nuclear industries for its good mechanical properties at high temperature and its excellent resistance to corrosion and oxidation. However, these properties are directly related to the material microstructure this last one depending on the thermomechanical path undergone all along the forming route. Therefore, the forming route needs to be designed so that the geometry and the microstructure meet the part requirements.

In order to control the microstructure of Inconel 625 superalloy during hot forming, two recrystallization mechanisms are generally used: discontinuous dynamic recrystallization (DDRX) and post-dynamic recrystallization (PDRX). While DDRX occurs during the hot deformation, PDRX corresponds to the continuation of the recrystallization after the hot deformation has stopped. PDRX includes meta-dynamic recrystallization (MDRX) which is the growth of nuclei produced during the DRX, and static recrystallization (SRX) which corresponds to new germination and growth of grains induced by initial straining and high temperature.

DDRX is mainly influenced by the stacking fault energy, the initial grain size and the thermomechanical process [1]. The thermomechanical process can be characterized by the strain ($\varepsilon$), the strain rate ($\dot{\varepsilon}$) and the temperature ($T$). Many studies have already focused on modeling the impact of the thermomechanical process on DDRX of Inconel 625. Experiments are generally conducted on thermomechanical simulators, like Gleeble simulator, by hot compression tests under constant temperatures and strain rates [2],[3],[4].
However, the relevancy of an isothermal, single stroke test to model complex thermomechanical paths can be discussed [5]. Lindh et al.[5] showed that in case of deformation brought by tension followed by compression, the effect of the compression strain on recrystallization is minor due to the reversed load. Embury et al.[6] also showed that unidirectional and multidirectional forging of pure aluminum produce different recrystallization fraction for a given total strain. Sidtikov et al[7] showed on multi-pass rolling that the strain per pass can also influence the recrystallization behavior of aluminum alloys. Gardner et al[8] showed that multiple strokes compression test produce bigger grain size than one stroke compression with the same strain due to grain growth between strokes.

Recently, the development of mean field[9],[10] and full field[11] models have improved the accuracy of prediction when considering complex thermomechanical paths[12]. However, the numerical cost of these methods is not adapted to model whole parts.

The present study proposes a method to determine DRX evolution of Inconel 625 superalloy through cogging with a thermomechanical path close to that of industrial parts in order to predict the microstructure of the industrial part with a reduced cost. The method used combines experimental results and numerical simulations to determine recrystallization rules. A similar approach has already been suggested by Irani and Joun[13] on single compression tests. The use of an averaged Zener-Hollomon parameter to simplify the evolution of temperature and strain rates characterization through all the process is investigated.

2. Material and Methods

2.1. Methodology

In order to determine a recrystallization law, microstructural parameters like grain size have to be associated to the thermomechanical path. With simple tests, like isothermal compression, constant strain rate and temperature can be applied making easier the relation between the thermomechanical path and the structure parameters. For more complex parts, the temperature and the strain rate is heterogeneous and evolve during the stroke. The local values are difficult to measure and can be assessed only by simulation. The methodology proposed in this paper, detailed in Fig. 1, is based on an experiment-simulation approach. First, an Inconel 625 billet cogging is performed with an instrumented press. Crystallographic analyses are then performed in order to obtain the grain size and the recrystallization fraction distribution within the cotted part. In parallel, the forming process is simulated with a Finite Element Software Forge®.NxT. The experimental crystallographic measurements are then associated to numerical thermomechanical data in order to draw a processing map.

2.2. Experimental Procedure

A Ø70mm Inconel625 superalloy bar at annealed state was provided by Böhler. The chemical composition of the alloy is given in Table 1. Two specimens of Ø70x200mm were heated to 1100°C during 100min in a forging furnace and then cogged respectively on an industrial screw press and on a hydraulic press, both cogged samples being then water quenched in order to freeze the microstructure. The screw press has a 680mm/s maximum speed for an energy of 31.5kJ. The hydraulic press has a constant 30mm/s ram speed for a maximum force of 600 tons. Manipulation of the billet during cogging is ensured by a 6-axis robot manipulator. Cogging consists in 4 passes with 14mm bites on the screw press, and 2 passes with 40mm bites on the hydraulic press.
After forging, the parts are cut for metallographic characterization. The metallographic specimens are polished and etched by a solution of 66ml HCL, 33ml H$_2$O and a few drops of H$_2$O$_2$ with a 30% concentration. The recrystallized fraction is then determined from the optical micrograph by a point counting method. Numerical Simulations

The forging process is simulated by finite element method with Forge NxT software. The position of the billet and the height of each stroke are determined from the experimental measurements made by the robot manipulator and the instrumentation of the press ram. Thermal parameters are adjusted to match the initial and final experimental temperature measured by a bichromatic pyrometer. The material behavior of the Inconel 625 is modeled by a Hansel-Spittle law with 5 parameters.

After computation, sensors are placed in the simulation at each point where micrographic measurement are made. The evolution of the equivalent plastic strain, $\varepsilon$, the equivalent plastic strain rate, $\dot{\varepsilon}$, and the temperature during the thermomechanical cycle is calculated. The Zener-Hollomon $Z$ parameters is then calculated by the following relation

$$Z = \dot{\varepsilon} \exp \left( \frac{Q}{R T} \right). \quad (1)$$

where $Q = 425000 \text{kJ/mol}$ is the activation energy and $R$ the perfect gas constant. The Zener-Hollomon parameters is then averaged on all the deformation stage to obtain a single value, $\bar{Z}$, assumed representative of the complete deformation process.

$$\bar{Z} = \frac{1}{\varepsilon_{\text{max}}} \int_{0}^{\varepsilon_{\text{max}}} Z \varepsilon \, d\varepsilon \quad (2)$$

3. Results and discussion

3.1. Microstructural analysis

The initial microstructure of the annealed Inconel 625 is measured by the supplier between 10 to 20µm. The microstructure of Inconel after 100min heating is measured on the forged billet in un-deformed area. The microstructure before forging consists of equiaxed grains exhibiting many twins and with an average grain size of 160µm (see fig 2a)

Cogging induces a gradient of strain from the center to the skin of the billet (see fig 3a), which result in a gradient of recrystallized fraction of Inconel 625. On the skin, friction causes low deformation and the microstructure is un-recrystallized. In the middle of the billet, the microstructure consists of homogeneous ultrafine grains with a mean diameter of 10µm (see fig 2c). In the transient zone, the microstructure is partially recrystallized. Fig 2b is an example of 50% recrystallized structure. New ultra fine grains have formed at previous grain boundaries and twins. The necklace mechanism is typical of DDRX commonly observed in low stacking fault energy alloy like Inconel 625 [14].

![Image](a)

![Image](b)

![Image](c)

Fig. 2. (a) Optical micrograph of Inconel 625 in un-deformed state; (b) Inconel 625 partially recrystallized; (c) Inconel 625 fully recrystallized.

3.2. Processing map

The fig 4a shows the evolution of the recrystallized fraction $X_{\text{DRX}}$ for different couple of parameters ($\varepsilon$, $\bar{Z}$) measured in the cogged billets. Data from the part forged on
screw press and on the hydraulic press are plotted in the same graph. The strain measured on both part varies from 0 to 2 but the applied strain rates are roughly different, this explaining the difference in $\bar{Z}$ for the two processes ($\bar{Z} > 5 \times 10^8 \text{s}^{-1}$ for the screw press and $\bar{Z} < 2 \times 10^9 \text{s}^{-1}$ for hydraulic press).

For single stroke, isothermal compression, the Zener-Hollomon parameter is often used to combine the effect of strain rate and temperature. In recrystallization model, like the JMAK approach [20] or semi-physical models [21], the critical strain to initiate DRX [19] and the DRX evolution can be expressed as a function of $Z$. But for multi stroke processes, $Z$ can be different for each stroke and therefore is difficult to use in its initial formulation (eq 1). The use of an averaged Zener-Hollomon (eq 2) parameter to characterize the combined evolutions of the temperature and the strain rate during the complete thermomechanical process seems relevant. Two processes with radically different forging sequences produce a quite continuous recrystallization map. For the study of DDRX, the thermomechanical path characterization can be reduced to two parameters which are the equivalent plastic strain and the averaged Zener-Hollomon parameter.

Data show that higher the strain and lower the Zener-Hollomon parameter, the higher is the recrystallization fraction of Inconel 625. These observations are in accordance with the general knowledge on DDRX [1],[15],[16] and other observations made on Inconel 625 [17],[18],[19].

The use of cogging to study the dynamic recrystallization has a major interest. The total strain and strain rates that can be reached with this process are much higher than that of the thermomechanical simulators and are more relevant to the industrial processes. Moreover, the thermomechanical heterogeneity in the part allows to map a larger domain of strain and strain rate with a single test.

However, the method used is not as accurate as Gleeble tests. Results highly depends on the accuracy of the finite element simulation, this last one mainly depending on the accuracy of the material behavior, the thermal exchange and friction laws. But the lack of accuracy of the method can be balanced by the high number of conditions that can be studied in a single experiment. Fig 3b show a processing map plotted thanks to the experimental values where the domain of recrystallization is easily identifiable. This graph can be utilized to optimize the forging sequence to ensure a fully recrystallized microstructure.
4. Conclusions

This study presents a method to determine the DRX behavior of Inconel 625 through a cogging test. The experimental procedure is combined with the numerical simulation of the process in order to identify the thermomechanical parameters associated with the microstructure observed experimentally. An average Zener-Hollomon parameters is used to characterize the combined evolution of temperature and strain into a single scalar value. The method shows that two billets forged using different presses with different adjusted forging sequences can produce a continuous recrystallization mapping. Thus, in the case of similar load case (bi-axial in cogging), the use of \( Z \) seems relevant to characterize the thermomechanical process with regard to the dynamic recrystallization, even in multi stroke forging. However, the method and the use of \( Z \) as DDRX thermomechanical representative parameter has to be validated for multi directional forging process other than cogging.

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