SIMULATION OF MICROSTRUCTURAL PROPERTIES OF WASPALOY RINGS USING FORGE 2007®

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Summary

Waspaloy is a metallic material which elevated Cr and Co content and low Fe content difficult forging procedures: non adequate procedures promote surface cracking, affecting forging soundness. To overcome these characteristics, elevated forging temperatures are required to improve alloy toughness, but affecting microstructural properties like grain uniformity.

Use of Finite Element Methods (FEM) to simulate forging processing on Waspaloy components is an important effort to reduce resources and efforts when new developments must be done. Despite some FEM software are available in the market, the use of FORGE 2007® to simulate microstructure evolution on Waspaloy forging, show significant improvements respect another sources.

Introduction

Developed since 1950 decade, Waspaloy is a common alloy used for turbine-engine components. Since this alloy present important properties at elevated temperatures like strength and oxidation resistance, it is used for the manufacture of rotor discs, shafts, spacers, seals, rings and casings. This alloy, a nickel-base, age hardenable superalloy, can promote such properties when appropriate methods of manufacture are performed.

Ring rolling of Waspaloy components present interesting challenges, especially when contour shapes are considered: metal flow patterns must be homogeneous to ensure microstructure uniformity and, after appropriate heat-treatment processes, mechanical properties shall be uniform thru the forging cross section.

FEM techniques are revealed as an important tool to support understanding of key alloy characteristics, like grain structure (size and orientation), saving time and money during components developments.

This job summarizes preliminary results when FEM is considered to develop forging procedures of Waspaloy contour rings and their effects on alloy properties.

Waspaloy ring rolling

Waspaloy can be considered as a complex material to forge. Due to its metallurgical characteristics, parameters like forging temperature and deformation ratios shall be carefully defined, especially when a uniform microstructure is desired. Then, it is extremely important to characterize alloy behavior when ring-rolling operations are considered to produce components of this material.

Typical forging problems related to Waspaloy are surface cracking and grain size heterogeneity. Depending on forging temperatures, precipitation phenomenon can arise as soon as forging is extracted from furnace, promoting toughness losses and surface cracking is common if this variable is not controlled. Related to grain size control and uniformity, the number of steps and deformation ratios of every step is crucial to avoid duplex structures.

A market demanding lowering of production costs is a factor which impulse forging contouring: raw material savings for this kind of alloys justify investments on tooling, particularly when shape of projected forgings are complex.

Traditionally, the development of such tooling requires several trials, where a number of forgings must be sacrificed to evaluate tools effectiveness to promote material flow and desired microstructures. These procedure demands important quantities of money and time; in general, analysis of results is slow and a single design improve can take weeks. In this scenario is where FEM techniques are essential to speed up developments giving an extraordinary opportunity to save time and money: in general, after an appropriate modeling, just one forging can be sacrificed to validate the modeled forging.

Experimentation

Several Waspaloy contour forgings, with a weight between 50 – 100 Kg were developed for industrial purposes. Parameters like forging temperature, soaking times, deformation ratios and number of operations were defined for each component.

These forgings were then segmented to evaluate material flow and evaluate their effects on dynamic re-crystallization phenomenon. In order to obtain this data, metallographic evaluations were performed; after this, information was analyzed and used to characterize alloy behavior for this considered window of operation. Some process improvements were suggested and implemented.

FEM software selected to perform modeling is FORGE 2007®, a Transvalor product designed and developed for the modeling of hot, warm and cold forming of metallic alloys. The information generated during the forging of involved components was analyzed to determine alloy characteristics to be simulated and adjust software model to actual alloy properties.

Improvements to process were executed and production trials on other forgings were performed. Meanwhile, simulations of these parameters were also performed to compare results.

Simulation results from previous and actual conditions were reported: as expected some differences on grain size and microstructural uniformity were observed. After forging of components according to improved conditions, involved forgings were segmented and evaluated by metallographic techniques.

FEM Considerations and Results

As mentioned, this job is focused to validate algorithms to predict grain size during ring-rolling operations of Waspaloy. In order to perform simulations, two constitutive models are considered; results of these simulations are directly compared with forgings produced on industrial conditions.

For this research, it was considered grain size after rolling operations can be affected by next variables:

Deformartion ratio, ε

Deformation rate, $\dot{\varepsilon}$

Deformation temperature, T

Initial grain size, d_0

For the characterization of Waspaloy, data related to processing of this alloy will be the input for the software, which consider a re-crystallization model. Such model is a group of equations which can describe the microstructure of the involved alloy for a certain moment and considering known values of ε, $\dot{\varepsilon}$, T and d_0.

Considered re-crystallization model is based in the Metallurgical Model, developed by Sellars and co-authors. Main aspects of this model are described as follows:

Zener-Hollomon constant

$$Z = \dot{\varepsilon} e^{\frac{Q}{RT}} \quad (1)$$

Considering T < 1010ºC,

$$\varepsilon_p = 5.375e - 4{d_0}^{0.54} Z^{0.106} \quad (2)$$

Considering T > 1010ºC,

$$\varepsilon_P = 1.685e - 4d_0^{0.54} Z^{0.106} \quad (3)$$

If T < T_{solvus}

Considering T < 1010ºC,

$$\varepsilon_{0.5} = 0.1449 d_0^{0.32} Z^{0.03} \quad (4)$$

Calculating fraction of grain dynamically re-crystallized

$$X_{drx} = 1 - e^{-ln2\left[\frac{\varepsilon}{\varepsilon_{0.5}}\right]^3} \quad (5)$$

1010ºC < T < 1030ºC,

$$\varepsilon_{0.5} = 0.056 d_0^{0.32} Z^{0.03} \quad (6)$$

$$X_{drx} = 1 - e^{-ln2\left[\frac{\varepsilon}{\varepsilon_{0.5}}\right]^2} \quad (7)$$

Calculation of dynamically re-crystallized grain size

$$d_{drx} = 8103 Z^{-0.16} \quad (8)$$

If T > T_{solvus}

T > 1030ºC,

$$\varepsilon_{0.5} = 0.0356 d_0^{0.29} Z^{0.04} \quad (9)$$

$$X_{drx} = 1 - e^{-ln2\left[\frac{\varepsilon}{\varepsilon_{0.5}}\right]^{1.8}} \quad (10)$$

$$d_{drx} = 108.85 Z^{-0.0456} \quad (11)$$

Meta-dynamic re-cristallization for T > 1030ºC

$$t_{0.5} = 4.54e - 5\varepsilon^{-1.2815} d_0^{0.5062} \dot{\varepsilon}^{-0.0729} e^{\frac{9703}{T}} \quad (12)$$

$$X_{mdrx} = 1 - e^{-ln2\frac{t}{t_{0.5}}^{1}} \quad (13)$$

$$d_{drx} = 14.56 \varepsilon^{-0.44} d_0^{0.325} Z^{-0.0258} \quad (14)$$

Grain-size coarsening

Considering holding times, t_{hold} < 30 min,

$$d^3 = d_0^3 + 2e26 e^{\frac{-595000}{RT}} t \quad (15)$$

Considering holding times, t_{hold} > 30 min,

$$d = 4.85e - 63 T^{20.58} \quad (16)$$

Described model allowed simulation of contour forgings showing good correspondence between simulations and forgings produced on industrial conditions. Figure 1 and Figure 2 present examples of FORGING 2007® simulations.

Conclusions

Considering exposed information, it is possible to enounce next comments:

1) Waspaloy is a complex alloy to forge, especially when contour shapes are considered.
2) Defined forging parameters are needed to avoid surface cracking and promote appropriate material flow for Waspaloy contour forging processing.
3) Simulation of contour rings was developed to predict grain size and its distribution thru the cross section of several forgings.
4) Validation of these simulations was performed by industrial production of several forgings, which were evaluated by metallographic techniques.
5) Reported results show excellent correlation between predicted (simulated) microstructure and promoted microstructure during industrial trials.

References

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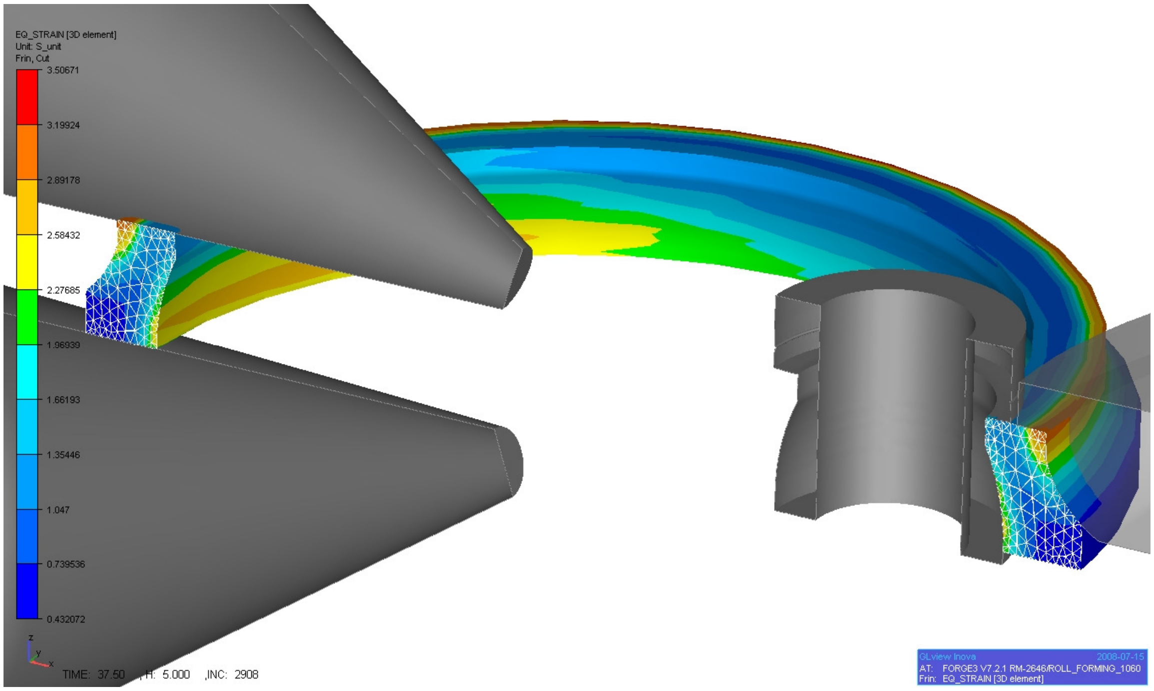

Figure 1 Simulation of Reduction ratios on a Waspaloy contour ring.

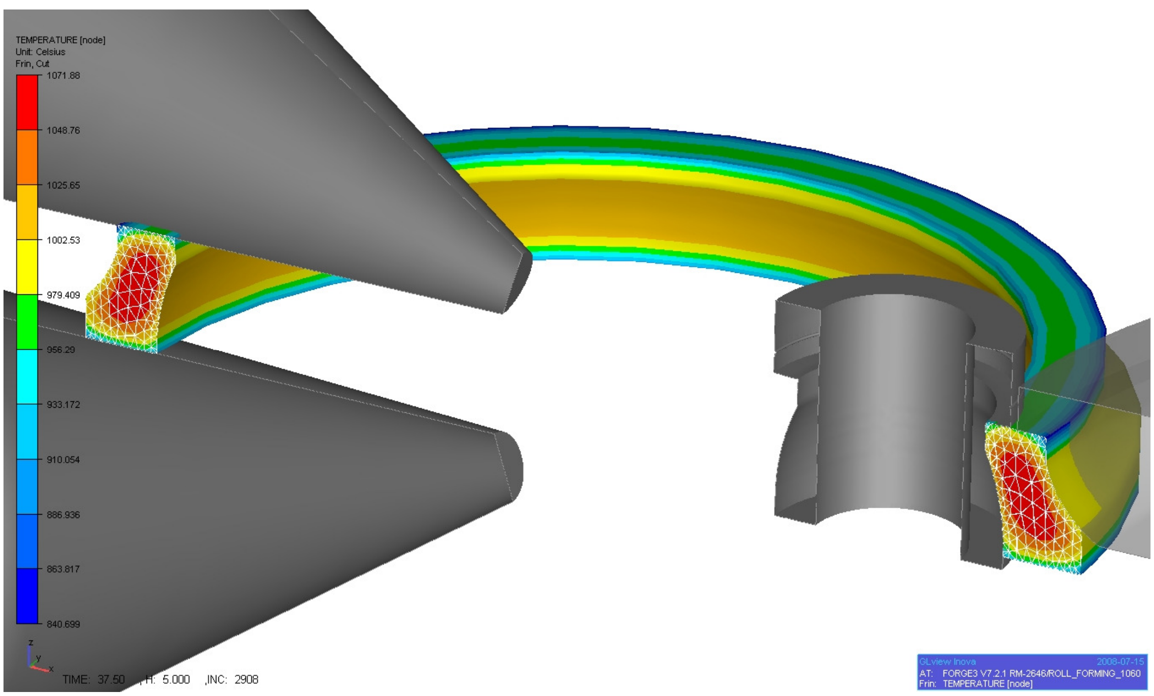

Figure 2 Simulation of temperature gradients on a Waspaloy contour ring.