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FE MODELLING OF LARGE INGOT HOT FORGING

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ABSTRACT
Hot forging of large ingots made of high temperature resistant steels is gaining renewed attention due to the increasing demand of large products mostly for the power industry. Hot forging is chosen among different manufacturing processes thanks to its potentialities in producing sound components characterized by excellent mechanical properties. Nevertheless, one of the most critical issues lies in the presence of shrinkage cavities and porosities inside the ingot that must be closed and healed completely during forging in order to avoid catastrophic failure of the component during its service life. The paper presents the FE modeling of the cogging process applied to a large component made of a duplex steel. An accurate calibration of the model in terms of material rheology and microstructure helps in quantifying the ranges of variables that are recognized to affect the closure and bonding of internal voids. A procedure is proposed to evaluate the recrystallized fraction of duplex steels which is likely to affect the goodness of such closure and bonding.

KEYWORDS: Hot Forging, Recrystallization, Void Closure

1 INTRODUCTION

In the last few years, the growth of several industrial sectors, among which construction, marine and power industries, has encouraged to search for new technological developments in those manufacturing processes that are devoted to the production of large size components. The ingots, from which these products are manufactured, are typically affected by shrinkage defects coming from casting processes. In fact, as a result of the cooling phase, the casted ingots can present cavities and porosities caused by gas entrapment and other impurities that are preferentially placed in the central portion of the ingot.

The elimination of these casting defects during the manufacturing stage represents a critical aspect for increasing the quality of the components and their service life. In the field of large components production, hot forging is the most adopted process, due to its capability of assuring great mechanical properties as well as the possibility to heal internal defects. Thanks to a proper choice of the forging process parameters, the event of unexpected and catastrophic failures, can be drastically reduced. Concerning the elimination of the internal voids that can be found in large ingots, the process of complete 'healing' can be decomposed in the succession of two stages, closure and bonding. The closure stage can be seen as the mechanical crushing of the void: this stage comes to an end when the two distinct surfaces reach a full contact.

However, in many cases, a closed void is not less dangerous than an unclosed one, since two closed surfaces can act as a crack and provoke catastrophic failures. For this reason, the second stage of bonding is essential, and must be assured. The bonding stage is accomplished when the two surfaces are welded together, in a manner that the void can be considered really 'healed', as it had never existed.

Efforts have already been made by some researchers to reach a greater comprehension of the mechanisms that control void closure and bonding. However, most of the studies refer to void closure, without paying much attention to the problem of bonding.

The first studies on void closure recognised equivalent strain and hydrostatic pressure as critical parameters for the closure behaviour. More recently, in [1-2] experimental studies are proposed where voids closure is evaluated by considering the effects of process parameters on the closure of artificially made holes.

In [3] the hydrostatic pressure integration parameter is considered as an indicator of the void closure. A closure criterion based on the analysis of a cell model that considers triaxiality was proposed in [4]. In [5] the integration of triaxiality is the parameter implemented in Forge^{TM} for the void closure evaluation and a threshold value is given. A DOE analysis is carried out to determine a function for estimating the correct process parameters to reach the threshold for closing voids. Differently from the previous cited works, in [6,7] the focus is on the bonding stage, by considering the interaction between an 'anti-bonding film' and process parameters, such as normal pressure and equivalent strain; compression tests were carried out on specimens

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with artificially made axial holes and afterwards tested to evaluate the bonding strength through tensile tests. As a consequence of this work, in [8] a 'crushing' efficiency, i.e. the efficiency of closing and bonding, is proposed.

Literature analysis has revealed a lack in the modelling of the mechanisms involved in the bonding stage, which could be analysed from a new point of view. A relation can be established between the goodness of bonding and material recrystallization. Thus, the void closure can be considered effective only when complete recrystallization occurs in the portion of material where the initial void was present. Therefore, a model capable to predict the closure and bonding of internal voids must be utilized in connection with a microstructural model stating the completion of recrystallization phenomena. In order to reach this final result, an accurate FE model of the hot forging process must be set up and suitably calibrated through data relevant to material rheology, microstructural evolution and void closure mechanisms.

With the above mentioned general objective in mind, this paper presents a preliminary work focussed on the modelling of a hot cogging process carried out on large duplex steel ingots. The base elements that will contribute to the development of a model for predicting void closure and bonding are reported. Among them, to be cited material characterization in terms of rheology and microstructural evolution, which mostly contribute to the calibration of the process FE model. In particular, the procedure for the evaluation of recrystallization in duplex steels is reported and discussed.

2 APPLICATION CASE

This work refers to an industrial case concerning large ingots cogging for the power industry. The forging material is the super-duplex X2CrNiMoCuWN15-7-4 steel, commercially known as the 329s steel. Its chemical composition is reported in Table 1.

C	Cr	Ni	Mo	Mn	Cu
0.02	25	7	3.6	0.6	0.6
W	Si	N	P	S	
0.6	0.5	0.25	0.025	<0.005	

***Table 1:** 329s chemical composition.*

The ingots, obtained from casting, present at room temperature a duplex structure, made of austenite and ferrite distributed almost in the same percentage. During a cogging cycle, the ingots are subjected to several deformations until a homogenous diameter reduction is reached. Each cycle is preceded by a furnace heating up to 1150-1200 °C in order to assure homogeneous temperature conditions. At any deformation cycle, the ingot handling is performed by means of a manipulator, able to translate and rotate the workpiece.

3 MODEL ARCHITECTURE

Considering the final aim of having a numerical model able to predict the effective closure and bonding of shrinkage voids in the ingot subjected to cogging, several experimental-numerical activities must be accomplished. Among them, (i) development of the FEM model of the reference industrial case; (ii) calibration of the FEM model in terms of material rheology, (iii) development and implementation of a calibrated recrystallization model devoted to duplex steels; (iv) development and implementation of a void closure criterion, (v) validation of the closure criterion through experimental evaluation of the bonding strength. This paper presents preliminary results with respect to the steps from (i) to (iii).

3.1 RHEOLOGICAL DATA

The material rheological behaviour was obtained performing hot compression tests on a *Gleeble*^{TM} 3800 thermo-mechanical simulator. The testing parameters were chosen accordingly with the deformation conditions of the industrial process. As example, results concerning the temperature influence on material flow strength at constant strain rate are presented in Figure 1.

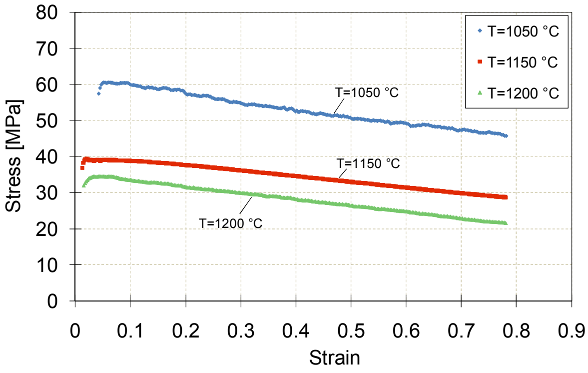

***Figure 1:** 329s sensitivity to temperature at constant strain rate equal to 0.01 s^{-1}.*

Three different strain rate conditions of 0.01, 0.05 and 0.1 s^{-1} were applied . Material behaviour was modelled through Hansel-Spittel equation whose material constants were determined through non linear regression analysis and implemented into the FE model.

3.2 FE MODEL

The reference industrial process described above was modeled in the *Forge2008*^{TM} environment.

The actual manipulator movements were simulated in order to prevent the axial movement of the ingot on its side held by the manipulator. Due to the geometry of the process, two symmetry planes were adopted to lower the computation time. In order to have the real temperature field of the ingot, the ingot transfer from the heating furnace to the press was simulated as well. Figure 2 shows the results of this simulation step: it can be noticed that temperature significantly decreases only on the ingot surface, while most of the inner portion remains at the heating temperature. The resulting temperature distribution on the surface was validated by means of on-field thermocamera measurements.

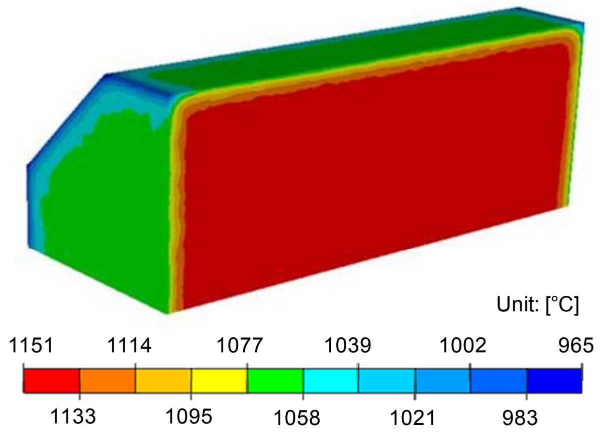

Figure 2: Temperature distribution in the ingot at the beginning of the deformation phase.

The cumulate strain distribution is shown in Figure 3, after three deformation steps along one direction and three more steps along its perpendicular one. This deformation sequence has been assumed as representative of the real cogging cycle. Quite high strain values can be noticed in the zone of the first deformation step, being the deformation influenced by the axial translation pitch. However, in the central region of the ingot, which is the one characterized by the majority of shrinkage, the maximum strain reaches values of about 0,25. Furthermore, the strain rate profile presents low values, everywhere in the central region lower than 0,1 s^{-1}.

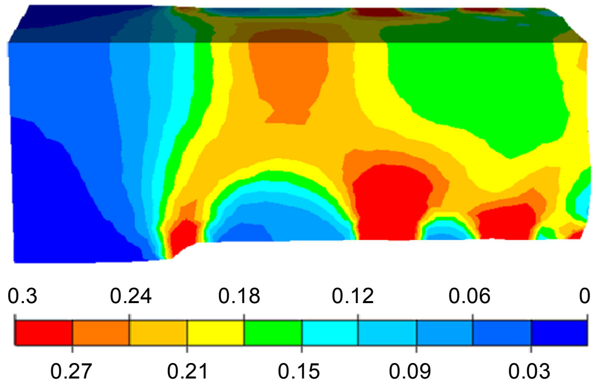

Figure 3: Strain distribution after 6 deformation steps.

3.3 MICROSTRUCTURAL EVOLUTION

Microstructural evolution in terms of dynamic, static or metadynamic recrystallization is strongly influenced by the strain accumulated during the forging steps. Therefore, microstructural models must be chosen according to the level of strain reached in the inner portion of ingot. Due to the low strain values detected at the ingot core and by comparing them with the peaks of the flow curves indicative of the onset of dynamic recrystallization, the conditions for static recrystallization to occur were identified. Scientific literature reports two different approaches to determine material constants of the static recrystallization model: their procedures are reported in the following and applied to the specific case of duplex steels.

3.3.1 Double-Compression tests

This procedure is the fastest and consists of the analysis of flow stress values from a double compression test. The calculation of the recrystallized fraction is fulfilled according to various and alternative formulations, based on the yield strength, the maximum stress or the integration of the flow curves. As example, the ‘offset method’ [9], based on the change in the yielding point after the holding time, is expressed by equation (1), where σ_m is the maximum flow stress, σ_1 and σ_2 are the yielding stresses of the two flow curves.

$$X_{off} = \frac{\sigma_m - \sigma_2}{\sigma_m - \sigma_1} \tag{1}$$

A certain amount of offset strain must be assumed to determine the yield stresses and consider material recovery. Both deformation steps are performed with the same configuration of temperature, strain and strain rate while a certain time interval separates the two steps. By varying the time interval different recrystallized fractions can be obtained, corresponding to different shapes for the second flow curve. Since this method is based on an indirect measure of the recrystallized fraction, it is not able to separately analyze the behaviors of two different phases, which is the case of the duplex steel considered in this work made of a mixture of ferrite and austenite phases; in fact, only the former recovers, while the latter is subjected to recrystallization. Due to that, the double compression procedure can not be efficiently utilized for the 329s micro-structural characterization.

3.3.2 Microstructural analysis

This approach is more time-consuming but, differently from the previous one, allows to directly measure the material fraction that actually recrystallizes. Specimens are subjected to a single deformation step and quenched after a predetermined time interval. Afterwards they are sectioned, etched with a material dependent etchant and the recrystallized fraction evaluated.

3.3.3 Proposed procedure

The proposed procedure to evaluate static recrystallization in duplex steels is a hybrid one between the two above presented. This procedure comprises the following steps: (i) microstructural analyses according to § 3.3.2 on a minimum number of samples subjected to single compression and subsequent soaking time; (ii) double compression tests according to § 3.3.1 reproducing the operating conditions not covered in (i); (iii) determination of a corrective factor that allows to determine the amount of recrystallization of the only austenite from the results of double compression tests.

Beraha etchant was utilized to reveal the microstructure of the duplex steel after the single compression tests. Figure 4 shows microstructures of single-hit deformed samples obtained after 1 s and 100 s of soaking time, being the testing conditions in terms of deformation step parameters the same. Even if in this work the influence of the material grain size before deformation is neglected, a homogeneous initial microstructure was assured for any test through a correct thermal cycle. Specimens are heated up to 1250 °C, held in temperature for homogenization and finally cooled slowly to the testing temperature.

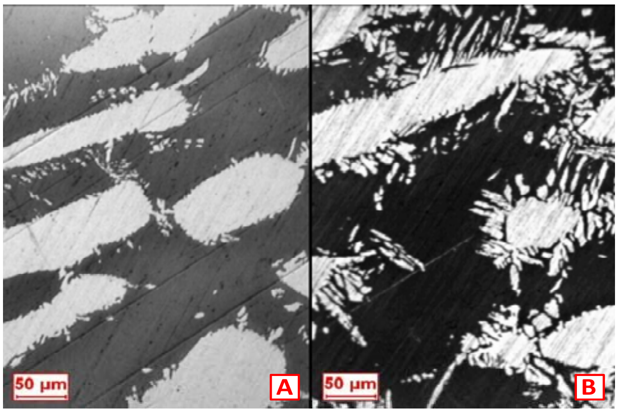

Figure 4: *329s microstructures after: 1 s (A) and 100 s (B) of soaking time.*

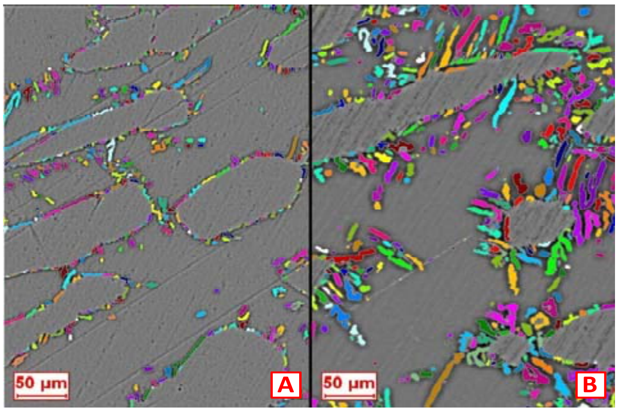

Figure 5: *329s graphical elaboration through Spip^{TM} (microstructures refer to the ones in figure 4).*

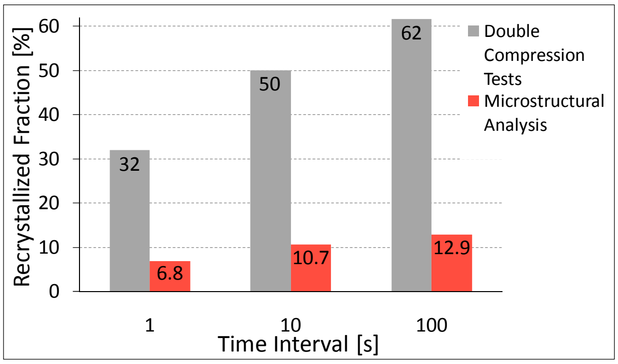

Figure 6: *Results comparison.*

Finally, the micrographic observations were analyzed by means of the software *Spip*^{TM}, for an accurate calculation of the recrystallized fractions. Figure 5 is an example of the graphical elaboration performed by Spip.

Comparing the results obtained from both procedures it can be seen from Figure 6 that the double compression approach greatly overestimates the real recrystallization fractions, as underlined above.

4 CONCLUSIONS AND OUTLOOK

In this paper the numerical modeling of an industrial cogging operation performed on a duplex steel was presented. Accurate rheological characterization allowed to investigate the range of the process parameters in order to establish a proper microstructural model, which is static recrystallization. The determination of the static recrystallization kinetics was the following step, accomplished by means of a hybrid experimental procedure, applied to duplex steels.

The work presented in the paper represents the basis for the development of a comprehensive voids closure and bonding criterion, capable to predict the defect in forging operations of large size ingots in FE simulations.

REFERENCES

[1] A. Wang, P. F. Thomson, P. D. Hodgson: A study of pore closure and welding in hot rolling processes. Journal of Materials Processing Technology, 60:95-102, 1996.

[2] G. Banaszek, A. Stefanik: Theoretical and laboratory modelling of the closure of metallurgical defects during forming of a forging. Journal of Materials Processing Technology, 177:238-242, 2006.

[3] M. Nakasaki, I. Takasu, H. Utsunomiya: Application of hydrostatic integration parameter for free-forging and rolling. Journal of Materials Processing Technology, 177:521-524, 2006.

[4] X. X. Zhang, Z. S. Cui, W. Chen, Y. Li: A criterion for void closure in large ingots during hot forging. Journal of Materials Processing Technology, 209:1950-1959, 2009.

[5] H. Kakimoto, T. Arikawa, Y. Takahashi, T. Tanaka, Y. Imaida: Development of forging process design to close internal voids. Journal of Materials Processing Technology, in press, 2009.

[6] C. Y. Park, D. Y. Yang: A study of void crushing in large forgings I: Bonding mechanism and estimation model for bonding efficiency. Journal of Materials Processing Technology, 57:129-140, 1996.

[7] C. Y. Park, D. Y. Yang: A study of void crushing in large forgings II. Estimation of bonding efficiency by finite-element analysis. Journal of Materials Processing Technology, 72:32-41, 1997.

[8] C. Y. Park, D. Y. Yang: Modelling of void crushing for large-ingot hot forging. Journal of Materials Processing Technology, 67:195-200, 1997.

[9] A. Yanagida, J. Yanagimoto: Formularization of softening fractions and related kinetics for static recrystallization using inverse analysis of double compression test. Materials Science and Engineering A, 487:510-517, 2008.