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MATERIAL TESTING AND PHYSICAL SIMULATION IN MODELLING PROCESS CHAINS BASED ON FORGING OPERATIONS

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Abstract

The paper deals with the numerical and experimental modelling of the different steps that can involve a manufacturing process chain, based on forging operations. The focus is on near-net-shape manufacture of metal parts where hot deformation operations are followed by controlled cooling from forming to room temperature. The roles that material testing and physical simulation play today in simulation systems are presented and discussed.

Key words: material testing, physical simulation, forging operations

1. INTRODUCTION

One of the major developments expected in the next future for the simulation systems applied to manufacturing technologies is that to integrate all the aspects of the process and all the steps of the life cycle from the rough product manufacturer to the end user (Doege & Dittman 2003; Grass et al., 2004). According to these prospects, the numerical simulation tools are expected:

- to extend their predictive ability to all technological and auxiliary operations and the relevant physical components as well, with the aim of creating a *virtual manufacturing* model where all product- and process-design tasks are carried out and process setting-up is virtually tested before implementation in the real plant;
- to couple the material-, process- and product-oriented modelling domains in order to provide designers with models capable of predicting material behaviour and performance during manufacturing and during the product service life.

Nowadays, many CAE tools provide effective simulations of manufacturing processes in the different technological domains such as casting, forming, machining and welding. Most of them are based on the Finite Element Analysis (FEA) and are commercially available. These codes are process-specific simulation tools that prove to be reliable and powerful in analyzing specific manufacturing operations but suffer from a lack of interoperability with each other. This makes the numerical simulation of the whole process chain or of part of it still a challenging task for most of practical applications. Major restrictions on interoperability are due to the insufficient predictive capability of the numerical simulation tools in calculating properties or features of the product at different stages of the process chain. To fill this gap between numerical tools, information can be provided by physical experiments where the operating conditions of the actual process are repro-

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duced. These experiments are carried out on industrial sites or, more conveniently, in the laboratory on real-material samples and in this latter case they are also known as *physical simulation* experiments (Bariani et al., 2004). A further cause of the above restrictions is the lack of interfaces that effectively couple the different process simulation codes by managing and transferring the data on workpiece properties in such a way to realize an integrated process-chain simulation-system which at the same time has the advantages of the process-specific simulation approach (Roeren et al., 2006). This paper deals with the coupling of the simulations of different steps in manufacturing process chains. The paper focuses on process chains that are typically used in near-net-shape manufacture of metal parts where hot-deformation operations are followed by a controlled cooling from forming temperatures to room temperature. Within this scope, the aim of the paper is to illustrate the role that material testing and physical simulation experiments play today in simulations of process chains and, in particular, in enhancing the predictive capabilities of the models that are currently implemented in FEA and in filling the gaps between the numerical simulation tools. With this aim in mind, the paper has been organized in three parts.

Three applications of the joint use of FEA, advanced material testing and physical simulation experiments in process chain simulations are presented. Correlations between process parameters, microstructure evolution and properties of the final product are established.

2 MICROSTRUCTURE EVOLUTION IN PROCESS CHAINS

In the process chains based on hot deformation operations, the physical and mechanical properties of the final part depend on the final microstructure which is the result of phenomena occurring in each step of the process chain. Depending on the operating conditions, these phenomena may include strain and strain-rate hardening, crystallographic anisotropy and mechanical fibering, recovery and recrystallization, phase transformation, grain growth, strain-induced ageing, failure and fracture, all of them causing significant changes in the properties of the workpiece material (Pietrzyk, 2002; Hu et al., 1999). Since most of the above micro-structural phenomena are affected by the thermal and mechanical history generated in the previous steps, the analyses of the micro-structure evolution and the material response in the different steps of the process chain must be closely interconnected. Figure 1 illustrates the connectivity at a "macro" level between the thermo-mechanical-metallurgical FE analyses of the hot-deformation phase and the post-deformation cooling phase in a process chain. Figure 1 refers to commercial FE codes with standard predictive capabilities of the models for micro-structure analysis.

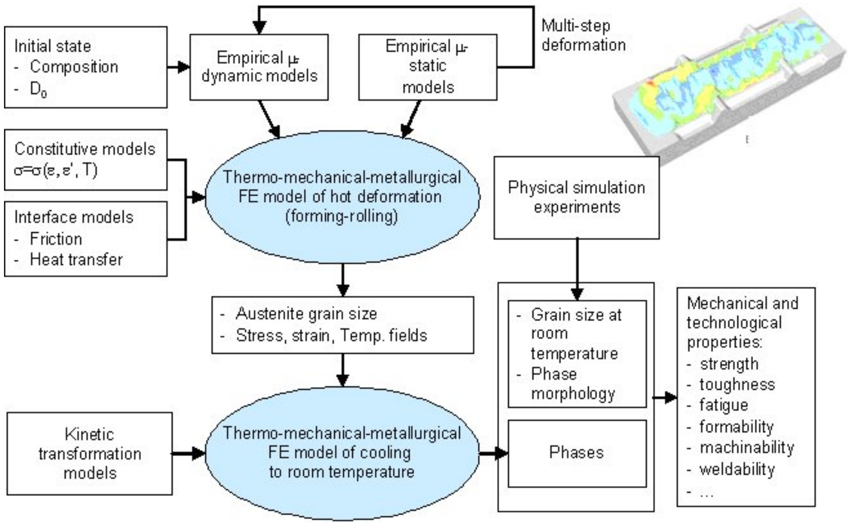

Fig. 1. *Sub-modules and connectivity at a "macro" level between the thermo-mechanical-metallurgical FE analysis of the deformation and cooling phases.*

3 APPLICATION CASES

3.1. Fracture-split connecting rods

The process chain to manufacture CK70 fracture-split connecting rods consists of three main phases (Park et al., 2003): hot forging, controlled cooling to room temperature (figure 2) and separation of the rod from the cap (besides final machining). The industrial requirement is to guarantee the right crackability in the conrod fracture zone and, at the same time, suitable mechanical properties during the conrod service life. A specific microstructure is needed to meet this requirement. And this microstructure has to be obtained through a controlled cooling after forming. Therefore the numerical simulation of the forming and post-forming phases must be capable of predicting the material microstructure at the end of the cooling both in terms of both grain size and microstructural constituents proportion.

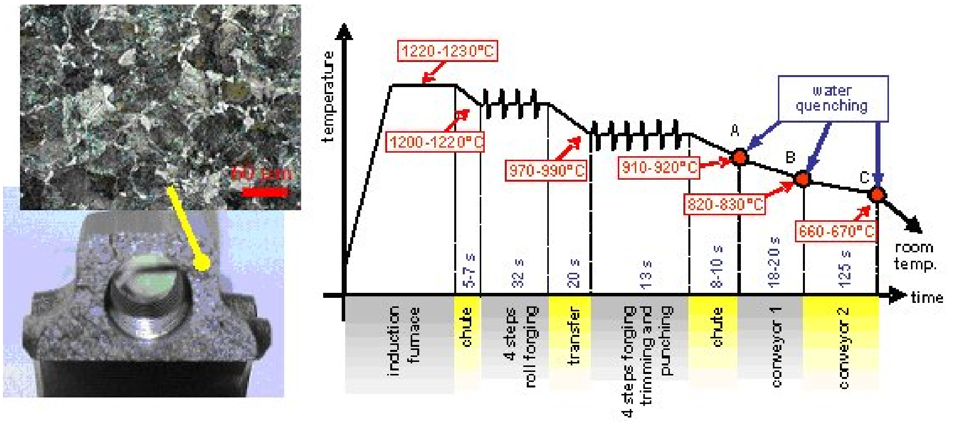

Fig. 2. Conrod fracture zone microstructure (left) and temperature vs. time diagram of the industrial hot forging process with indication of temperature measurements and quenches (right).

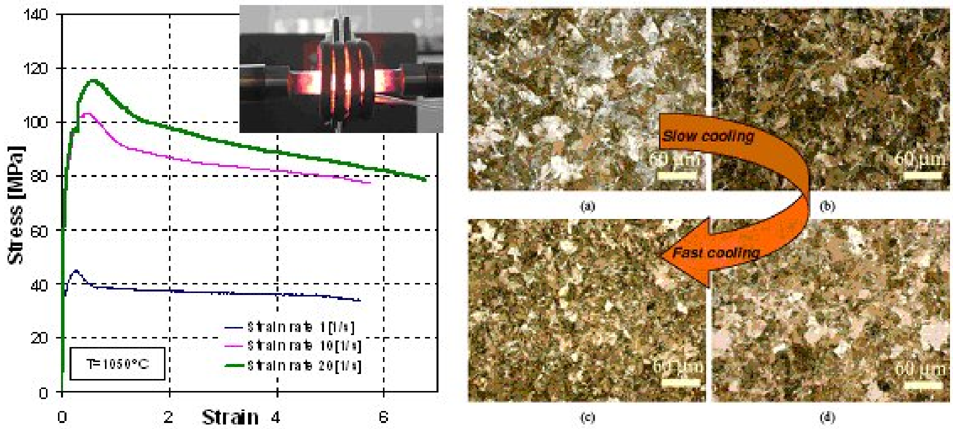

Fig. 3. Sensitivity of CK70 steel to strain rate (left) and microstructures at room temperature obtained at different cooling rates through physical simulation experiments (right).

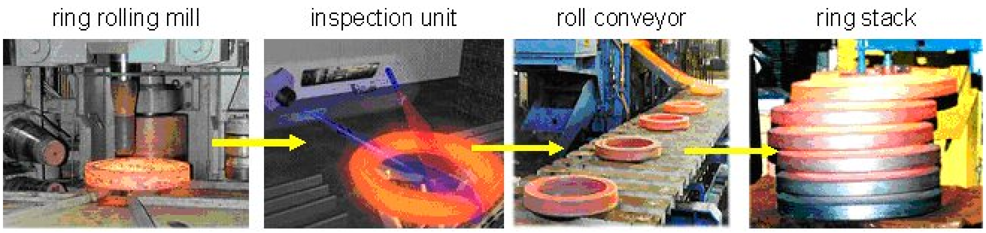

Fig. 4. The industrial process for rings production.

To predict the material microstructure, a calibrated thermo-mechanical-metallurgical model of both forging and cooling phases is needed. Material testing is utilised to determine the material behaviour during the deformation phase and the cooling as well. Single-step hot torsion tests were carried out in the range of temperatures and strain rates typical of the process. Figure 3 shows the important material sensitivity to strain rate. Dilatometric tests were conducted to identify CCT curves and tensile tests to determine elastic-plastic behaviour of the phases in which austenite transforms during cooling. The final proportion of steel phases at room temperature were identified thanks to simulations performed with these material data. However, FEA does not provide the material grain size at room temperature and physical simulation experiments were necessary (see diagram of figure 1). In these experiments, the deformation phase and the following cooling were accurately reproduced through hot compression and controlled cooling of real-material samples carried out on the thermo-mechanical simulator Gleeble 3800®. Particular attention in designing these experiments was paid replicating the same austenite grain size at the beginning of the cooling phase, since it influences the phase transformation kinetics (Bariani & Bruschi, 2005). The sensitivity to different cooling rates in terms of grain size is shown in the micrographs of figure 3.

3.2. Hot rolled rings

Hot rolling of large-diameter 42CrMo4 steel rings is carried out on an automatic axial-radial ring rolling mill followed by cooling of the rings on a roll conveyor till room temperature (figure 4). Such rings have usually been produced with material allowances up to 50% while today's industrial requirement is to have a near-net shape manufacturing. Apart from distortions that may arise during the rolling stage due to inadequate control of rolls, significant deviations from planarity of the rings at room temperature are caused by non-uniform cooling conditions that can lead to thermal gradients inside the ring and non-homogeneous change of phase. The objective of the simulation is to determine the geometry of the rings at room temperature, starting from the description of their geometry and surface temperature at the mill exit (Bruschi et al., 2005; Chen et al., 1997).

The correct prediction of geometrical distortions depends on the accuracy of the data which are used in the thermo-mechanical-metallurgical FEA of the cooling phase. The calibration of the FE model requires a large amount of data that are generated through a variety of material testing experiments. However, parameters such as transformation plasticity, that arises when a phase transformation takes place, needs to be determined with a level of accuracy that goes beyond the traditional material testing (figure 5). Complex physical simulation experiments are required where the austenite grain size at the beginning of cooling has to be controlled through a thermal or a coupled thermo-mechanical cycle (Taleb et al., 2001; Casotto et al., 2005). The same approach is followed to determine the dependency of phase change (parameters of the transformation kinetics and martensite transformation temperature) on initial austenite grain size and stress state.

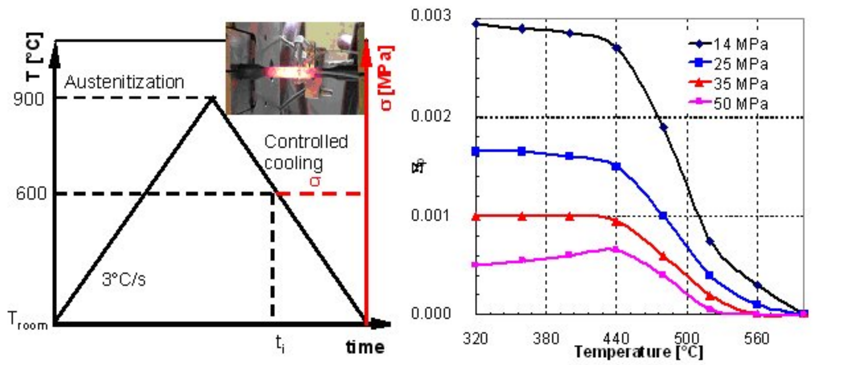

Fig. 5. Thermo-mechanical cycle to determine transformation plasticity parameters (left) and transformation plasticity strain as function of temperature and applied stress (right).

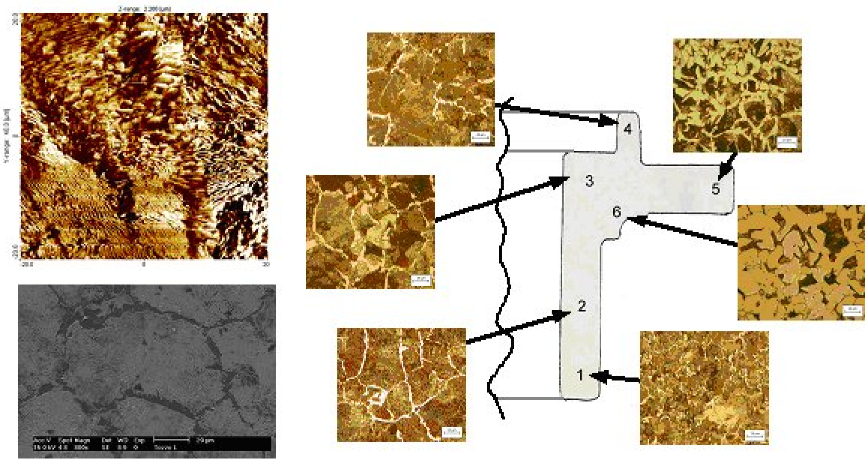

Fig 6. SEM (dark figure at the bottom) and AFM (bright figures) analysis of perlite morphology distribution in wheel hubs after cooling.

3.3. Wheel hubs

The main steps in the process chain to manufacture steel wheel hubs include hot forging on a multistage hot former, cooling from forging temperature to room temperature on a roll conveyor and, finally, turning, drilling and reaming. Due to a rough control of the parameters of the cooling phase, forged rings display an unacceptable scattering of machinability properties. It is well-known that microstructure strongly influences machinability, even if precise and quantitative correlations between specific microstructure features and machinability have not been proposed yet. In particular, micro-structural parameters, such as pearlite lamellar shape and interlamellar distance, play a fundamental role in assuring high levels of machinability. The industrial need is then to have reliable correlations between machinability characteristics and those microstructural parameters obtained after hot forging and cooling (Modi et al., 2001).

Empirical and/or physically-based models describing the evolution of advanced microstructural parameters have not been implemented yet in numerical models. Therefore, real experiments are required to prepare samples which can be used in machinability tests. Numerical simulations are performed to determine the thermo-mechanical cycles and cooling routes which the material experiences in different zones of the ring. Then advanced microstructural analysis, exploiting the capabilities of scanning electron (SEM) and atomic force microscopes (AFM), was carried out, evaluating the pearlite morphology and quantifying its features (figure 6). Results from machinability experiments conducted on the same samples were finally correlated with the interlamellar pearlite distance and total amount of ferrite.

4. CONCLUSIONS

Three different industrial cases have been presented in order to illustrate appropriate modelling strategies of the manufacturing process chain based on forging operations. Emphasis is placed on the use of experimental techniques involving both material testing and physical simulation. In particular, when the in-use properties of forged components as well as technological characteristics after forming operations, like machinability, have to be determined, the need of taking into account the microstructural evolution since the very beginning of the manufacturing route has been clearly shown. It is underlined that the typology of requested experiments ranges from almost standardised material testing to complex microstructural analysis which allows to evaluate morphology of microstructural constituents.

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BADANIA MATERIAŁÓW I FIZYCZNA SYMULACJA W MODELOWANIU CYKLI PRODUKCYJNYCH OPARTYCH NA PROCESACH KUCIA

Streszczenie

W artykule przedstawiono numeryczne i fizyczne modelowanie różnych etapów cykli produkcyjnych opartych na procesach kucia. Szczególny nacisk położono na dokładne kształtowanie części metalowych w procesach, w których kontrolowane chłodzenie wyrobów do temperatury otoczenia jest stosowane po przeróbce plastycznej na gorąco poprzedzała. Zadania jakie badania materiałów i fizyczna symulacja spełniają w symulacji numerycznej są przedstawione i omówione w artykule.

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