Computer simulation of the heat treatment process applied to a forged shaft

G.M. La Vecchia, A. Pola, F. Zola

Process modelling using finite elements analysis is very effective to design an optimized process in order to obtain high quality forging parts. For instance, the application of computational analysis on heavy forgings allows the definition of an adequate forging process in terms of temperature, pressure and ramp speed as well as the heat treatment procedure. Quenching and tempering represent a critical phase in the production of heavy forged steel parts. In fact, improper cooling can cause the obtainment of undesired microstructure (i.e. bainite instead of martensite at the component surface as a consequence of a soft cooling) or unexpected residual stress distribution, related to severe heat treatment steps causing cracks. The aim of the present study was to evaluate the adequacy of an industrial heat treatment procedure applied to a heavy 4140 steel forged shaft by means of finite elements simulation, a technique able to predict the temperature/time distribution along the thickness of the forged part in various heating or cooling conditions. A comparative study of experimental and numerical superficial temperature distribution was also proposed, allowing the validation of the numerical model used and, subsequently, of the internal temperatures and stresses distribution.

PAROLE CHIAVE:
forging, quenching and tempering, numerical simulation

INTRODUCTION

Forging technology enables the production of components of the desired shape, characterized by improved microstructure, with respect to the starting ingot, because of the reduction in porosity level and of the grain refinement, both associated to the plastic deformation process. Therefore, a better quality is expected and, in consequence, higher mechanical properties.

During the definition of a complete forging production cycle, attention must be also paid to the heat treatments which supply to the part the final microstructure and, therefore, the performance. Thermal treatments, in fact, are responsible of microstructural evolution but also of internal stresses and subsequent deformation due to temperature gradients and local microstructural changes; they must be taken under control in order to avoid any damage during production and/or service.

This kind of control becomes much more important in heavy forgings, because of the unavoidable microstructural inhomogeneity of the starting ingot and of the thermal-inertia during heat treatments, which causes irregularity in temperature and stress distribution. A further reason is the difficulty in managing the different process steps, as a consequence of the large size of the components. Moreover, properties control and prediction of heavy forged parts are still complex since the internal stress, strain rate and temperature distribution are very difficult to measure because of the shape and size of the components and

the several manual work phases also present in a forging plant. In order to solve or, at least, reduce these problems the numerical simulation represents a valid tool to support process design and development [1], assisting in the obtainment of sounds part having suitable mechanical properties and no defects, such as cracks related to improper applied loads, press speed during forging or strain due to wrong heat treatment procedure [2-3]. In fact, the prediction of the material behaviour, as a function of its manufacturing and thermal history, helps the users in defining the correct forging shape and the proper process parameters.

While many features of the forging process have been covered (flow-type formulation, process modeling etc.. [4]) there are still others, such as inter-stage heat treatment and post-process thermal behaviour, which have received little attention. In that contest the numerical approach of the heat treatments is an advantageous instrument that allows the rapid prediction of the effective time-dependent temperature and stress distribution along the thickness, avoiding expensive tests on sacrificial forgings.

In the present paper the heat treatment of an wind shaft in 4140 steel was studied. The choice of this specific component is related partly to the increasing interest and demand in this kind of alternative power resource and partly to the request of very restricted mechanical properties (fatigue resistance) on these large size forgings, with the subsequent problems in their production. In order to better understand the critical aspects of the current industrial heat treatment practice, a water quenching and tempering cycle was deeply analyzed by means of numerical simulation, evaluating the time-dependent temperature, stress and microstructure profile along the thickness. The results obtained were compared to the measurements on an instrumented shaft to validate the simulation.

G. M. La Vecchia, A. Pola
Università degli Studi di Brescia,
Dipartimento di Ingegneria Meccanica e Industriale, Italy

F. Zola
Ofar Spa, Visano (Bs), Italy

C	Mn	Si	Cr	Ni	Mo	P	S
0.38	0.76	0,40	1.2	0.27	0.24	0.035	0.035

TAB. 1 *Chemical composition (wt.%) of the 4140 forged shaft steel.* *Composizione chimica (%peso)dell'albero forgiato in acciaio 4140.*

EXPERIMENTAL PROCEDURE

The investigated component is a heavy forged shaft having a flange diameter of 1520 mm and a total length of 2920 mm. The shaft is made of 4140 steel grade, whose chemical composition (wt.%) is given in Table 1. Therefore, the used material is a low alloyed steel commonly employed in mechanical applications because of the good compromise between costs (quite low considering the limited percentage of alloying elements) and mechanical behaviour (improvable by means of a heat treatment, like quenching and tempering).

The shaft was instrumented by means of K-type thermocouples, with a recording rate of 1 per min, placed 3 mm under the surface in three specific points, as shown in Fig. 1:

• thermocouple 1 (T_R1) in the bottom part of the shaft (corresponding to the bottom of the ingot);
• thermocouple 2 (T_R2) in the thicker diameter of the central part of the shaft;
• thermocouple 3 (T_R3) 200 mm from the top of the shaft (corresponding to the top of the ingot).

The industrial thermal treatment analyzed in the present paper (quenching + tempering) consists in the following steps:

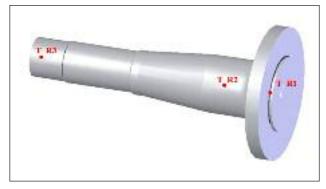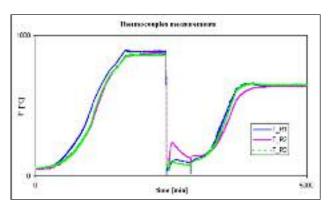S.1) Maintenance in furnace from room temperature up to austenitizing temperature. During the very first hours of this step it can be observed a delay in the shaft heating respect to the imposed ramp; this is due to the thermal-inertia of the furnace, because of the high volume of the part placed in the furnace at room temperature.

S.2) Exit in air for few minutes, in order to allow the handling of the shaft towards the quenching bath.

S.3) First quenching in water for 35min; the quenching bath is wide and stirred in order to guarantee a continuous cooling of the components at almost constant temperature (as demonstrated by measurements inside the water bath), reducing also Leidenfrost effect.

S.4) Exit in air for few seconds, in order to interrupt the quench phase and reduce the temperature gradient between the skin and the bulk.

S.5) Second quenching in stirred water for 30 minutes, dipping again the shaft in the same cooling bath.

S.6) Exit and maintenance in air for some hours, in order to encourage the auto-relaxation of the part due to the heat exchange between the hot core and the cold surface.

S.7) Tempering up to 650°C, to improve toughness of the shaft martensitic portions.

In Fig. 2 the measured temperatures are shown.

NUMERICAL MODEL

In order to improve the efficiency of the solution, only a half of the shaft was modeled using the symmetry and imposing the corresponding boundary conditions on the nodes lying on the symmetry surface. Two different finite elements (FE) commercial software where used: Procast® 2009 and Comsol® 3.5a. A FE mesh was created using tetrahedral elements; in Fig.3 shape and mesh of the component are shown.

Temperature dependent thermal properties of the 4140 steel (conductivity, density, specific heat or enthalpy) used in the analyses were calculated by means of Computherm Database®, available in Procast. The temperature dependent mechanical properties (Elastic modulus, Poisson coefficient, yield stress, ther-
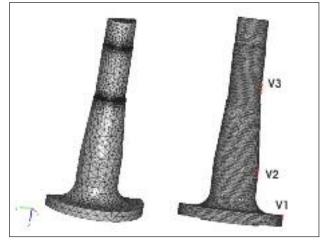

FIG. 1 *Thermocouples position.*

Posizione delle termocoppie.

FIG. 2 *Heat treatment procedure monitored by thermocouples.*

Procedura del trattamento termico monitorata attraverso le termocoppie.

FIG. 3 *Mesh of the wind shaft by Comsol® (left) and Meshcast® (right); V1, V2 and V3: constrain positions.*

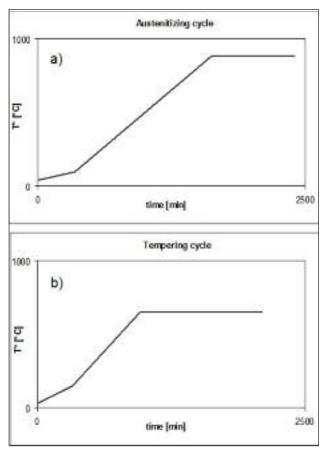*Mesh dell'albero eolico mediante i software Comsol® and Meshcast®; V1, V2 and V3: posizioni dei vincoli.*

mal expansion coefficient and plastic modulus) were obtained from calculation and from literature [5].

Initially the temperature was set to 40°C for all nodes, according to the temperatures measured by the thermocouples at the beginning of the heat treatment.

The boundary conditions for the thermal calculations were set as follows:

S.1) The heat transfer coefficient h was fixed equal to 20 W/m²K, because of the very low ventilation inside the furnace chamber; the ambient temperature was imposed as a function of time, considering the initial thermal-inertia of the furnace, as shown in Fig. 4a. The emissivity was set as temperature-dependent, in order to consider the variation related to the oxide scale formation. On the symmetry surface an adiabatic condition was considered.

S.2) The heat exchange coefficient h was maintained equal to 20 W/m²K; in fact, because of the movement of the shaft (from the furnace to the quenching bath) a boundary condition of low ventilation can be considered. The external temperature was fixed at 90°C; this value is due to the close position of the extracted shaft to the open furnace door. The emissivity was considered taking into account the oxide scale presence.

S.3) A temperature-dependent film coefficient was imposed, according to the data available in literature [6]; in this way the effect of the water quenching is related to the superficial temperature of the shaft. The water temperature was considered constant at 20°C.

S.4) For the second exit in air, the same h value used in the S.2) step was used, while the external temperature was fixed equal to the room temperature; no oxide scale was considered (removed during quenching).

S.5) Same condition as the S.3) phase.

S.6) Same condition as the S.4) step but for longer time.

S.7) The heat exchange coefficient was imposed at 20 W/m²K and the furnace temperature was set time dependent, as shown in Fig. 4b.

The needed boundary conditions for the stress calculation consist in the definition of the symmetry plane and structural boundaries; particularly:

S.1) Because of the position of the shaft inside the furnace, a constrained displacement in point V1 along y and z directions and in point V3 along gravity direction y was imposed (Fig. 3).

S.2) To S.6) during the cooling steps the shaft is moved by a proper equipment able to block the part only in the gravity direction; therefore, during the steps subsequent to the austenitizing one, a constrained displacement along y was fixed in positions V2 and V3 (Fig. 3).

S.7) The same as S.1) step.

RESULTS AND DISCUSSION

Thermal results

In order to validate the simulation parameters a comparison between the temperatures measured by the thermocouples and the calculated ones (3 mm under the skin) was done. In Fig. 5 the comparison between the temperature profile during austenitizing (step S.1) recorded by the thermocouple T_R2 in the thicker central section and calculated by the two software is shown as an example. It can be noticed the good correspondence of the results, index of the correct choice of the material thermodynamic data and of the parameters used to describe the boundary conditions.

Similar trends were obtained for each subsequent step of the heat treatment. In Fig. 6 the experimental and calculated temperature at the end of S.3, S.4, S.5 and S.6 step are reported; it can be seen a very limited spread independently from the considered position along the longitudinal axis of the shaft.

Because of the good convergence of results on the forging surface, particularly during the very long maintenance in air in the S.6 step (a difference of 20°C after 6 hours in the thicker section), also the temperature profile along the shaft thickness can be considered reliable.

FIG. 4   *Time-dependent austenitizing (a) and tempering (b) furnace temperatures.*

Andamento della temperature nel tempo durante la fase di austenitizzazione (a) e di rinvenimento (b).
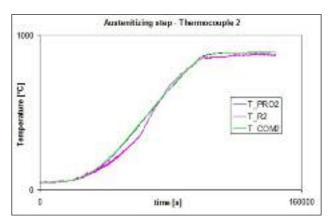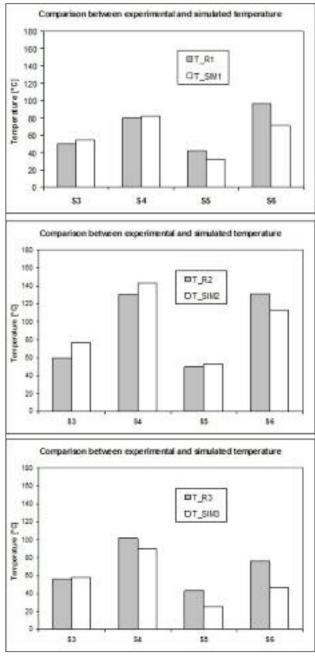

FIG. 5   *Comparison between experimental and calculated temperatures during the S.1 step.*

Confronto fra le temperature misurate sperimentalmente e calcolate durante lo step S.1.

FIG. 6 *Comparison between measured and calculated temperatures at the end of S.3, S.4, S.5 and S.6 steps.*

Confronto fra le temperature misurate sperimentalmente e calcolate alla fine degli step S.3, S.4, S.5 e S.6.

In Figs. 7 and 8 the thermal gradient along the symmetry and external surface at the end of the quenching steps (S.3 e S.6) are shown. It can be observed that in the core of the shaft, at the end of the first quenching, the temperature is still very high (Ms = 370°C for the examined 4140 steel grade) and, therefore, this area did not undergo to martensitic transformation.

In order to deeply investigate the microstructure evolution during quenching, the cooling curves of five points at increasing depth from the surface to the shaft centre were extrapolated from the numerical simulations results, analysing the sections corresponding to the position of thermocouple 2 and 3. The se-

lected distances are:
1) 3mm from the surface,
2) 12.5 mm from the surface,
3) ¼ of the radius from the surface,
4) ½ of the radius,
5) centre.

The positions at 12.5mm and ¼ of the radius from the surface are those suggested during forgings production for the extraction of samples subsequently used for mechanical and metallurgical investigation [7].

The so obtained cooling curve were superimposed to the CCT curve of the 4140 steel [8] as shown in Fig. 9.

As can be noticed, only the surface of the shaft, both in the thicker (T_R2) and in the thinner (T_R3) section, undergoes to hardening. Since the 12.5 mm depth, the formation of bainite can be observed, in lower percentage for the thicker section because of the higher thermal-inertia associated to the high thickness. Going towards the centre of the shaft, only ferrite and fine perlite can be obtained, while the central part of the shaft (T_R2 section) is transforming in ferrite and coarse perlite.

Therefore, the subsequent quenching (step S.6) has only a cooling effect, according to the thermal gradient strongly influenced by the still high temperature of the component core, and does not induce neither bainitic or martensitic transformation.

Stress results

Numerical simulation allows to obtain the internal stress in every point of the forging shaft during the complete heat treatment cycle at which the forged part undergoes. Both the commercial software used can consider the stress associated to thermal expansion and contraction but can not take into account the effect of microstructural transformation.

From the austenitizing simulation (S.1) it was observed a total displacement of the shaft of about 35 mm in the longitudinal direction and of about 18 mm in the radial direction on the flange. During this first step of the heat treatment, because of the prolonged maintenance at high temperature, sufficiently to homogenise the temperature along the thickness, no particular stress conditions can be noticed.

This condition strongly changes at the end of S.3 and S.5 step, because of the drastic cooling by water immersion.

In Fig. 10 the Von Mises stress profile at the end of the first quenching is shown. It can be noted, in fact, that in the external area close to the connection flange-shank there is a very high stress, potentially dangerous for the shaft. In the same region of the shaft, a high level of tensile stress was also detected just below the surface.

At the end of the second quenching a high level of tensile stress still affecting the connection flange-shank can be deduced by FEM analysis (Fig. 11). Such a result can be used to improve the industrial quenching step.

Finally, the tempering procedure assures a sufficient reduction of stresses; in fact, a low level of tensile stress (always lower than 150MPa) was detected everywhere in the part, as shown in Fig. 12.

CONCLUSIONS

In the present paper the complete heat treatment of a heavy forged shaft in 4140 steel was investigated by means of numerical simulation, using two commercial software Procast® 2009 and Comsol® 3.5a, as well as by experimental investigations.

The results obtained by the numerical modelling allowed to:
• predict the temperature profile in every point of the considered geometry, during quenching and tempering;
• validate the numerical model by the comparison between the

FIG. 7
Temperature profile at the end of the step S.3 (first quenching) by Procast® (left) and Comsol® (right).

Profilo di temperature alla fine dello step S.3 (prima tempra) ottenuto mediante Procast® (sinistra) e Comsol® (destra).
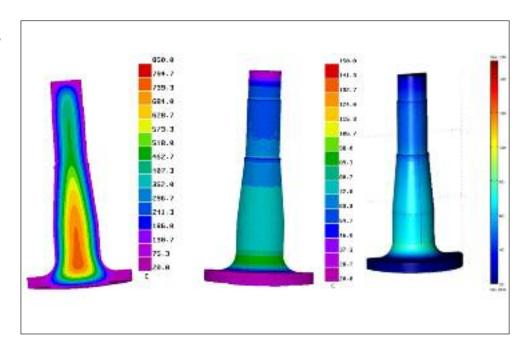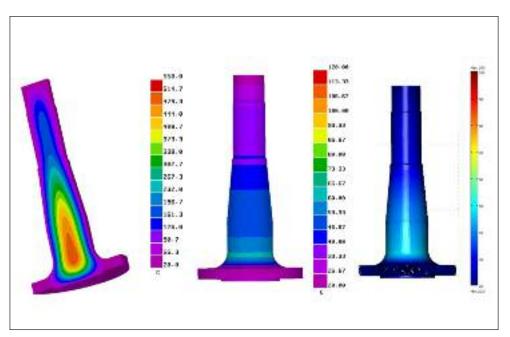

FIG. 8
Temperature profile at the end of the step S.5 (second quenching) by Procast® (left) and Comsol® (right).

Profilo di temperature alla fine dello step S.5 (seconda tempra) ottenuto mediante Procast® (sinistra) e Comsol® (destra).
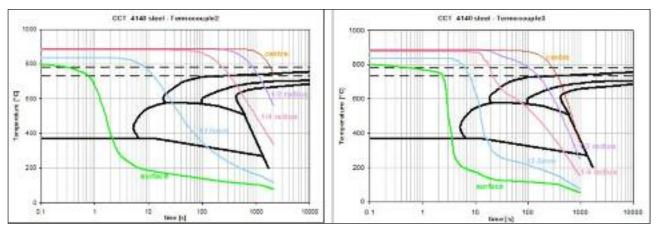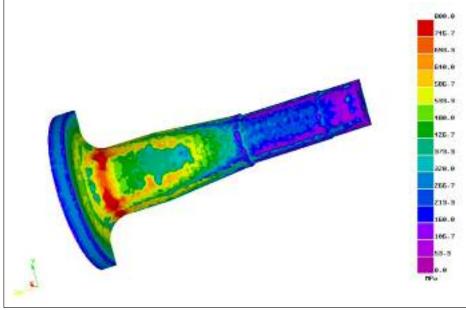

FIG. 9   **CCT curves of the 4140 forged shaft during the first quenching (S3), TR2 on the left and TR3 on the right.**

Curve CCT dell'acciaio 4140 durante la prima tempra (S.3), TR2 a sinistra e TR3 a destra.

FIG. 10
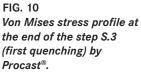*Von Mises stress profile at the end of the step S.3 (first quenching) by Procast®.*

Andamento delle tensioni di Von Mises alla fine dello step S.3 (prima tempra) ottenuto mediante Procast®.

FIG. 11
Principal stress I profile at the end of the step S.5 (second quenching) by Procast® (left) and Comsol® (right).

Andamento delle tensioni principali I alla fine dello step S.5 (seconda tempra) ottenuto mediante Procast® (sinistra) e Comsol® (destra).
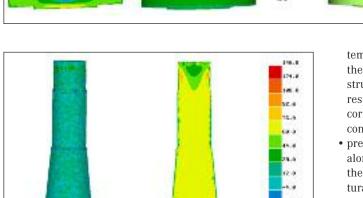

FIG. 12 *Principal stress I profile at the end of the tempering step (S.7) by Procast®.*

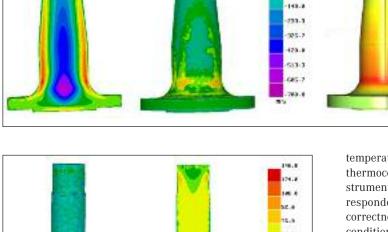Andamento delle tensioni principali I alla fine del rinvenimento (S.7) ottenuto mediante Procast®.

temperature calculated and measured experimentally by 3 thermocouples positioned 3 mm under the surface of an instrumented shaft during industrial production. The good correspondence between the results demonstrated the correctness of the imposed material properties and boundary conditions;
• predict the microstructure obtained at the end of quenching along the thickness in different sections of the component; these results are under verification by means of microstructural analyses of various samples machined from the instrumented shaft;
• predict the stress and strain conditions of the forged component, allowing to detect the critical step of the present industrial heat treatment and to suggest possible adjustments.
The obtained results show a limited hardenability of the analyzed steel, even though it is water quenched, because of the high thicknesses which cannot ensure a complete martensitic transformation, not even at 12.5 mm from the surface. Therefore, considering shafts having very thick sections and high mechanical properties requested, particularly toughness and fatigue resistance, different chemical compositions of steel must be eva-

luated. No variation of the quenching media can be suggested, because the one currently used in the industrial process induces high level of stresses, particularly severe in the connection flange-shank zone.

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Abstract
Simulazione numerica del trattamento termico di bonifica di un albero forgiato

Parole chiave: forgiatura, trattamenti termici, simulazione numerica

La tecnologia di forgiatura consente la produzione di componenti di ben definite geometrie, caratterizzati da una microstruttura migliore di quella del lingotto di partenza grazie alla riduzione del livello di porosità ed all'affinamento del grano indotti dal processo di deformazione plastica, con conseguente aumento delle proprietà meccaniche del prodotto. Tali proprietà vengono ulteriormente incrementate attraverso l'esecuzione di opportuni trattamenti termici, la cui corretta definizione, nell'ambito di un ciclo completo di forgiatura, assume un ruolo di primaria importanza.

I trattamenti termici sono infatti responsabili dell'evoluzione della microstruttura ed anche dello stato tensionale interno, con eventuali deformazioni, del pezzo dovuto a gradienti di temperatura ed a variazioni microstrutturali locali. Tempra e rinvenimento necessitano, pertanto, di adeguati controlli al fine di evitare danneggiamenti del pezzo in esercizio. Tali controlli assumono maggiore importanza nel caso di grossi forgiati, in parte a causa delle disomogeneità microstrutturali presenti nel lingotto di partenza e dell'inerzia termica durante i trattamenti, che comportano irregolarità nella distribuzione delle temperature e delle tensioni, in parte a causa delle difficoltà operative che si incontrano nel movimentare componenti di elevate dimensioni nelle diverse fasi del ciclo termico. In aggiunta, il controllo e la predizione delle proprietà finali di un grosso forgiato appaiono complessi poiché, a seguito delle dimensioni del pezzo, tensioni interne, deformazioni e distribuzioni di temperatura sono difficili da misurare.

La simulazione numerica rappresenta un valido strumento per supportare la progettazione e lo sviluppo di un ciclo di forgiatura, risolvendo alcuni dei citati problemi di misura sperimentale. Infatti, la predizione del comportamento del materiale, in funzione del ciclo produttivo e della storia termica, facilita la determinazione della corretta geometria del pezzo e l'individuazione dei parametri di processo ottimali.

Numerosi studi sono stati condotti al fine di valutare le diverse fasi del processo di forgiatura ma lo stadio di trattamento termico sembra aver ricevuto minor attenzione. In quest'ambito la simulazione numerica risulta un utile strumento per la rapida predizione della distribuzione di temperatura e delle tensioni interne nel tempo lungo lo spessore del pezzo.

Il presente lavoro ha come obiettivo lo studio della procedura di trattamento termico industriale di un albero eolico in acciaio 4140 mediante l'analisi ad elementi finiti, affiancando al calcolo numerico un'indagine sperimentale volta alla validazione del modello utilizzato ed alla predizione dello stato tensionale del componente.

In particolare, un albero strumentato con termocoppie posizionate in diversi punti è stato sottoposto ad un trattamento di tempra in acqua agitata seguita da rinvenimento ed i dati monitorati sono stati confrontati con gli andamenti delle temperature calcolate. La simulazione è stata condotta mediante i software ad elementi finiti Procast® e Comsol®, al fine anche di valutare l'affidabilità di entrambi i pacchetti a pari condizioni al contorno.