Numerical analysis applied to thermal and fluid-dynamic quenching simulation of large high quality forgings.

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Heat treatments of steels consist in a modification, in hot conditions, of the initial crystal lattice of such alloys and represent one of the most delicate step in the industrial production of forgings. In this frame, one of the most critical stages is quenching, which consists in rapid cooling of steel pieces at high temperature, in water or oil or in a polymer water solution (aquaquench). It is a process which is intrinsically unstable, complex from a physical point of view, which can be hardly predicted without using suitable simulation software. If not carefully carried out, this heat treatment can be inefficient or even harmful, causing fracture triggering, or, worse, directly the breakage of the piece. Of course, the bigger the forging, the greater the importance of estimating the process dynamics and, consequently, designing the plant configuration to obtain the expected final results, in order to avoid heavy economical losses deriving from a bad treatment.
In this work a study of the water quenching process of large industrial forgings, made of SA 508 steel and intended for nuclear applications is presented. This is carried out by means of transient thermo-fluid-simulations in CFD environment (Computational Fluid Dynamics).
The models have been validated by comparing the numerical results with the ones obtained by experimental trials carried out on steel test samples, having suitable dimension and properly instrumented: the results have shown that the average error is below 3%, while the maximum error is below 10%. These results confirm that the chosen method suitably simulates the physical phenomenon and so it can be extended to study a wide range of cases, in order to provide a valid and reliable support for large forgings Manufacturers.

Keywords:
forging, quencing and tempering, numerical simulation

INTRODUCTION

Production of industrial forgings is devoted to the production of finished pieces having geometrical and mechanical characteristics required by the customer's technical specifications.
The process of forging consists in the plastic deformation of steel ingots at a temperature above the austenitizing temperature, using localized compressive forces in order to plasticize, re-crystallize and refine the austenitic crystal grain .
This process improves the mechanical characteristics of the material in comparison with the initial ones; they are further increased by the following heat treatments, which fix the final results in terms of quality and performance.
The aim of this work is to define the best thermal and fluid-dynamic conditions to be achieved on forging boundaries during quenching, in order to obtain cooling at the desired temperatures and times, thus avoiding the critical phases of the mechanical and metallurgic process.
First of all, the whole set of input data was acquired and the physical model and the geometries were entered into the CFD environment. Particular attention was paid to the fluid physics description; it was decided to use a multiphase physical model in order to simulate the process of creation and spreading of the steam on the forging boundaries. Although this approach needs powerful calculators and long CPU times compared to the simplified models of heat exchange by boiling, it was preferred to use the more realistic available model to analyze the process of cooling and the effect of vaporization.
In fact steam plays a critical role in heat exchange by quenching process because, even if it removes a lot of heat during evaporation, it also causes a sudden decrease of the heat transfer coefficient due to the occurrence of the "film boiling" effect and the stagnation phenomenon.
Firstly the steam in contact with the surface of the piece spreads itself into an insulating thin layer that reduces heat exchange, slowing down the overall quenching speed.
Secondly, the external steam of the boiling layer moves away and towards the free surface of the quenching tank, and may accumulate in flat areas or by concave regions, producing sudden and localized lowering of heat exchange.
To solve these two problems it is a standard procedure to equip the quenching tanks with air or water pumps and stirrers, in order to mix the stagnant steam with the adjacent water. However these devices must be correctly dimensioned and positioned, since the case is very complex and specific for every single piece; solutions that at first sight could seem to be effective could instead be counterproductive.

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So a preventive approach through numerical simulations is important.
Otherwise theoretical assumptions [1] have to be made about the interface temperatures, based on data available in literature, which, the more the pieces exhibit a complex shape, the less reliable they could be.
The simulations that were carried out investigate the evolution of cooling of two wide forgings in water, first in conditions of natural convection, then with forced convection modelling the behaviour of devices which cause water movement - as previously said, natural convection cannot assure the cooling rates needed for the SA 508 metallurgic transformation.
The results of such simulations show the variation of temperature, steam concentration and convective motions existing in the tank with over in a 3D space.
Furthermore, analysing the CCT (Continuous Cooling Transformation) Bain's diagrams together with the above-mentioned results, it was possible to investigate the transformation of steel structure during quenching.
The space-time correlation of quenching made the realization of an accurate map of the thermal gradients and metallurgic structure in the main sections of the forging, an evaluation of speed, evolution and homogeneity of the process and the detection of the critical zones with a slower cooling possible.
For the validation of the model, the results were compared to data obtained in an experimental way: cooling in natural convection, in water, of three steel cylindrical test pieces of different dimensions (diameters 1000 mm, 500 mm and 250 mm) finding that the mean error is below 3% and the maximum below 10%.

METHODOLOGY

The forgings examined are a "reactor vessel closure head" as shown in fig. 1, whose dimensions are around 5000 mm of flange external diameter and 4000 mm of internal diameter, bend radius of the convexity around 2000 mm, membrane thickness 160mm and a weight approx. 57 tons, and a "steam generator tube sheet" as shown in fig. 2, with diameter around 4500 mm, height around 1000 mm and a weight of approx. 115 tons.
The pieces are in SA 508 steel, whose chemical composition can be found in table n° 1. After having imported the 3D geometry in the CFD code the mesh of solid was generated and the physics of problem was defined.

FIG. 1 ***Reactor vessel closure head.***
Fondo bombato di chiusura reattore.

FIG. 2 ***Steam generator tubesheet.***
Piastra tubiera del generatore di vapore.

Elements	C	Si	Mn	P	S	Ni	Cr	Mo
wt. %	0.18	0.05	1.39	0.008	0.003	0.86	0.16	0.51

Tab. 1

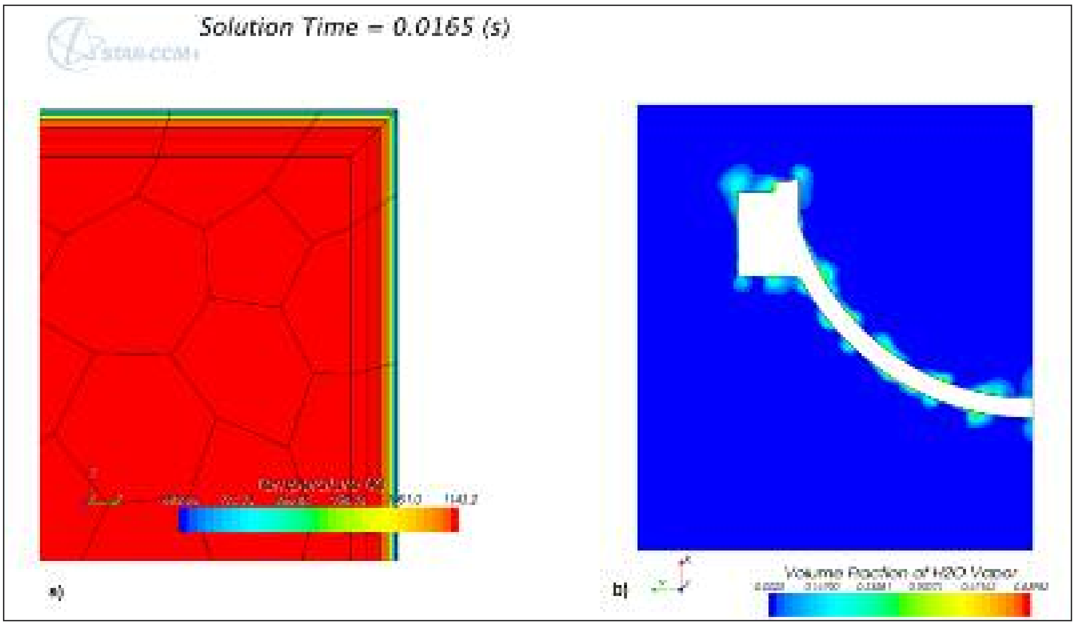

FIG. 3
a) Example of prism layer mesh b) Example of 2d modelling for natural convection boiling.
a) Esempio di una prism layer mesh b) Esempio di una modellazione 2d per l'ebollizione in convezione naturale

Numerical Mesh

In order to optimize the boiling model, particular attention was paid to the mesh characterization.

The meshes were built using polyhedral cells far away from the wall, and layers of prismatic-cell for interface between solid and liquid.

As shown in fig. 3a, a prism layer mesh, composed of orthogonal prismatic cells, has been selected to model the volume next to wall boundaries. This type of mesh is usually adopted to simulate the turbulence and heat transfer with the necessary accuracy. The thickness, number of layers and distribution of the prism layer mesh is determined primarily by the model used.

Physical Models

In order to model the quenching phenomena occurring near the surface of the plate (fig. 3b), a finite volume, multiphase CFD simulation was carried out with the code STAR-CCM™ by CD-adapco [2]. In a first step of the study a 2D axially-symmetric model, with no forced convection in the water was analyzed.

In the second step, a full 3D model was used to investigate the effect of forced convection generated by stirring fans and pipes for water pumped at high pressure (fig. 4, 5).

In both cases, a transient simulation of the solid body and the fluid phases (water and vapour) was carried out simultaneously (conjugate heat transfer simulation).

The presence of multiple phases (water vapour and liquid water) was modelled with the VOF approach (Volume of Fluid), using the standard formulation implemented in the HRIC code [3]. The VOF assumes a single common velocity, pressure and temperature field for all phases in each computational cell, and no extra modelling is needed when no phase change occurs.

The phase exchange phenomenon is modelled through the application of boiling and condensation models. The boiling models can address a range of boiling stages, namely nucleate transition and film. The latter is the most relevant for the current study as it occurs when the critical heat flux is exceeded and the heated surface is blanketed by a continuous vapour film.

In this case the vapour film acts as an insulator between the liquid and the metal. The boiling then occurs at the liquid vapour interface, and is modelled as

$$\dot{m}_{ec} = \frac{C_{HTCxArea}(T - T_{sat})}{h_{lat}}$$

where m_{ec} is the rate of evaporation, T_{sat} the saturation temperature of the liquid, T is temperature of the liquid, $C_{HTCxArea}$ is the heat transfer coefficient between the vapour bubbles and the surrounding liquid multiplied with the specific contact area (contact area per unit volume) between the two.

With the above approach, no hypothesis is done on heat exchange coefficient at the wall, which is a result of the analysis. The only data provided as input of the calculation is the initial temperature of solid and liquid, as well as the physical properties of all phases (in this case water, at liquid and vapour state, and the studied steel SA 508). Heat is transferred inside the metal and exchanged at the wall-fluid interface, partly as convection and partly as latent heat of water vapour produced. As vapour it is transported due to buoyancy forces, and can condensate as it meets lower temperatures.

Analysis steps

The first analysis in conditions of natural convection was carried out by supposing the bodies were at the initial temperature of 870°C and suddenly immersed into the quenching tank (stepped load), containing water in state of rest at 15°C. The immersion phase was simulated with a descending velocity equal to 6 m/min, typical of overhead travelling crane devices, but the results have clearly demonstrated that there is no significant difference in temperature distribution considering it an instantaneous heat transfer at the interface. As a first approach, two-dimension models were studied, taking advantage of the axial symmetry and specularity of the geometries to speed up the calculation times.

The following simulations were aimed at investigating, in quality and amount, the effectiveness of water forced movement on heat

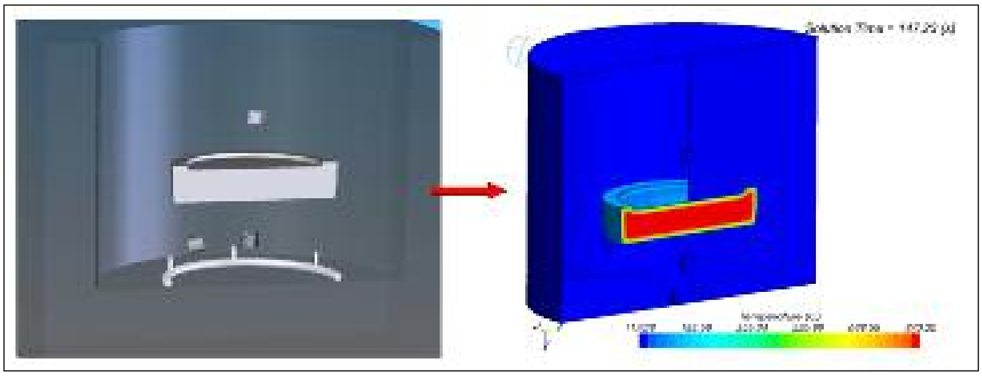

FIG. 4

Steam generator tubesheet – Quenching tank and mixers CFD modelling in forced convection.

Piastra tubiera del generatore di vapore – Modellazione CFD della vasca di tempra e del sistema di agitazione in convezione forzata

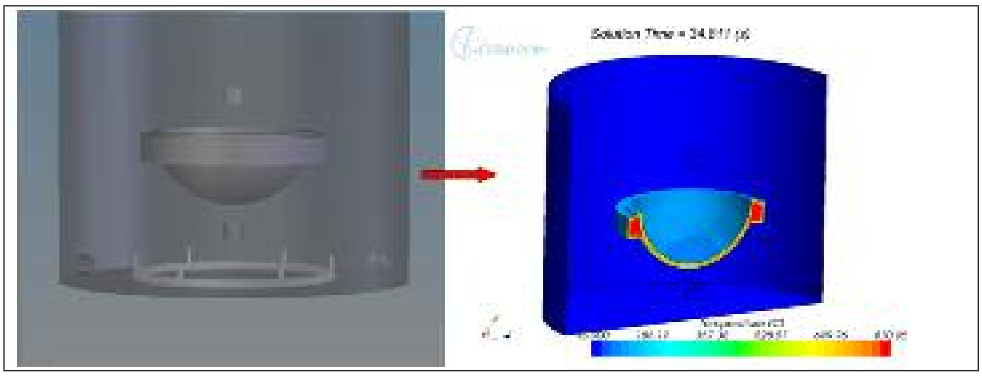

FIG. 5

Reactor vessel closure head – Quenching tank and mixers CFD modelling in forced convection.

Fondo bombato di chiusura reattore – Modellazione CFD della vasca di tempra e del sistema di agitazione in convezione forzata

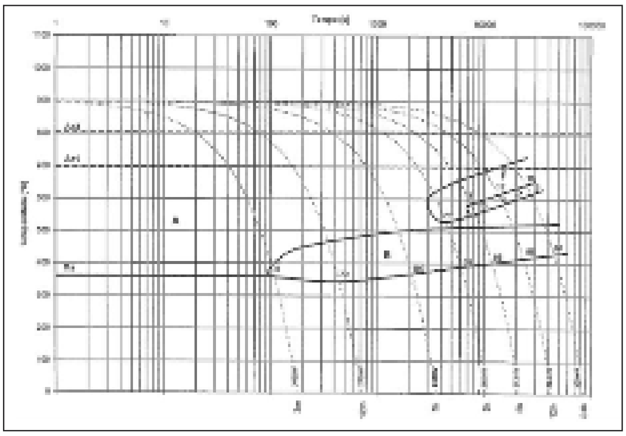

FIG. 6 ***SA 508 Bain CCT diagram.***

SA 508: diagramma caratteristico CCT di Bain.

exchange. To simulate the effect of stirrers in the quenching tank the software uses the "Fan Momentum Source" node, which allows the introduction of the fan performance curve in the model. Further actions are determined by nozzles which introduce the necessary water to maintain the liquid level in the tank.

To evaluate the effectiveness of the cooling caused by the quenching, it is necessary to compare the calculated temperature vs. time results along the forging thickness with the CCT diagrams for SA 508 (fig. 6). In fact, to perform quenching, the metal must be heated up to the austenitic crystal phase (generally 50°C above the Ac3 point) and then quickly cooled (below Ms Martensite start). Upon being rapidly cooled, a portion of austenite (dependent on alloy composition) will transform to martensite, a hard, brittle crystalline structure. In order to realize the desired depth of quenching, it is necessary that cooling speed is higher than the critical one, typical for every steel, to obtain a martensitic external layer along the entire surface and avoid the formation of ferrite and perlite in the core. In fact, to achieve an ideal hardening, i.e. with a complete martensitic structure, it is necessary that the cooling rate is higher than the critical one, characteristic for each kind of steel. Therefore, referring to the diagram in fig. 6, the cooling curve of the piece must not intersect either the perlitic (P) or the ferritic (F) transformation zones. If intersection occurs, the development of perlite and/or ferrite takes place and there is a partial hardening: the martensite content goes down, and there is mixed perlite/ferrite/bainite crystal growth [4]. However, in the industrial practice an incomplete hardening to the core of the piece could be allowed, depending on the end use of the forging and therefore, on the Customer's technical specifications.

From the CCT diagram for the SA 508 steel (fig. 6), for the abovementioned purpose temperature should be lowered to 360°C within 90 seconds from the beginning of cooling, ferrite is avoided if the temperature reaches below 600°C within 50 minutes, perlite is avoided if temperature reaches below 560°C within 2 hours.

Model validation

The experimental curves were obtained recording temperature variations coming from thermocouples placed on three cylindrical test pieces, in four points at different depths along the radius, thus obtaining n. 12 temperature curves.

These cylindrical test pieces have three different diameters , i.e. 1000 mm, 500 mm and 250 mm, which are comparable with the thickness of the real forgings. A CFD simulation was carried out with analogous geometries, detecting temperature on points placed in the same position as thermocouples (fig. 7). All the n. 12 experimental curves were compared with resulting simulation curves [5, 6].

Fig. 8 shows the cooling curves of one of the test pieces (experimental-continuous lines) superimposed on those from the CFD simulation. These curves are referred to the 250 mm test sample. It is possible to observe that the mean error of the model is below 3%, while the maximum is never above 10%.

In all the other cases – i.e. for the test samples having 500 mm and 1000 mm - the agreement between all the experimental and calculated curves are much better.

CFD ANALYSIS RESULTS

Natural convection of a reactor vessel closure head

The head was placed with the flange and concavity upwards.

The total duration of the simulation was 2.830 sec (47 min); as shown in fig. 9, the hottest point temperature was 319°C (flange core); this means that in natural convection ferrite and/or perlite is avoided in all forging sections, and metal is a mix of martensite and bainite, depending on the local temperature.

Fig. 10 shows which zones of the forgings were below 360°C

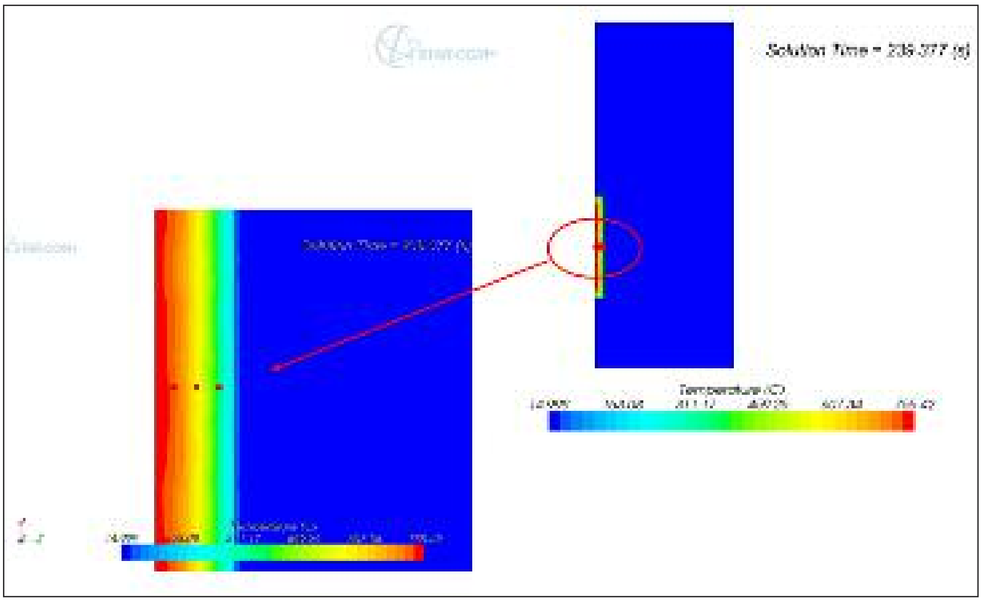

FIG. 7
Sample quenching simulation model.

Modello di simulazione della tempra su provino.

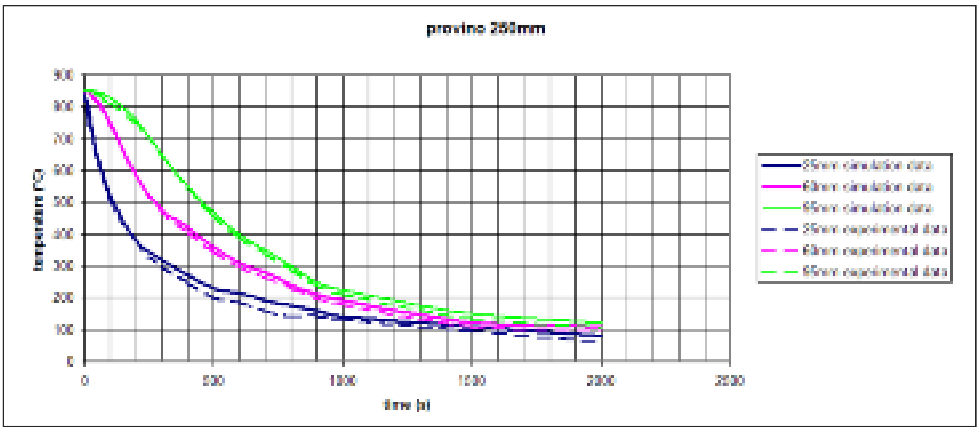

FIG. 8
Sample cooling graphs.

Curve di raffreddamento del provino.

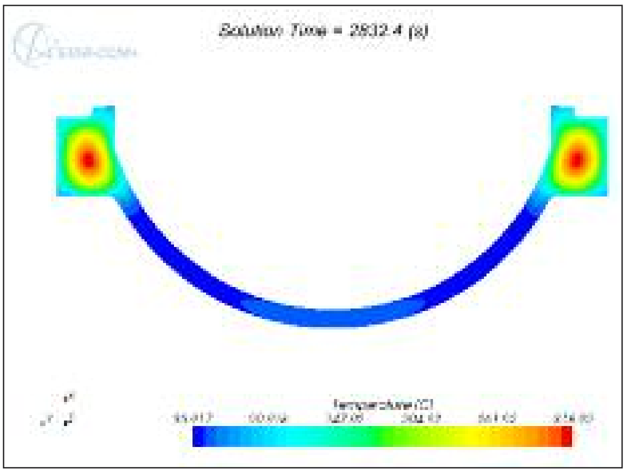

Fig. 9 Reactor vessel closure head: thermal field at end simulation.

Fondo bombato di chiusura reattore: campo termico a fine simulazione.

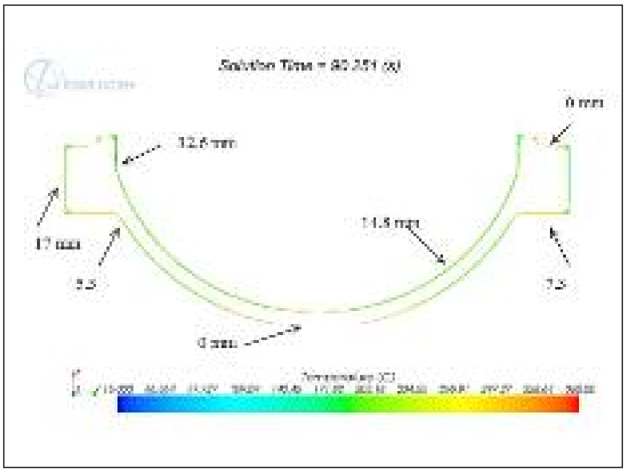

FIG. 10 ***Reactor vessel closure head: thermal field at 90 s in natural convection.***

Fondo bombato di chiusura reattore: campo termico in convezione naturale dopo 90 s di simulazione.

after 90 seconds from the beginning of cooling. This representation highlights the zones with martensite formation in the section; what can be noticed is that the martensitic layer thickness is neither continuous not uniform.
The main reason for this result can be found in the above explained effect of stagnation of steam along the flat downward oriented surfaces, whereas on the vertical or angled surfaces steam moves towards the free surface of the liquid increasing heat exchange.
It's worth noting that this effect may be particularly harmful next to geometrical discontinuities, where the associated effect of reduced mechanical strength (bainite instead of martensite) and high stress intensity factors can lead to fractures even during cooling.

Natural convection of a steam generator tube sheet
The tube sheet was placed horizontally. The total duration of the simulation was 3.910 sec (65 min); as shown in fig. 11, the hot-test point temperature was 650 °C (core).
The small value of surface-to-volume ratio caused a very slow cooling of the sheet core.
The wide horizontal surface is locally critical towards heat exchange; steam tends to stagnate, slowing down the flow and the cooling.
In these conditions, at the core of the piece, there are high percentages of perlite and ferrite. Analysing fig. 12, martensite tran-

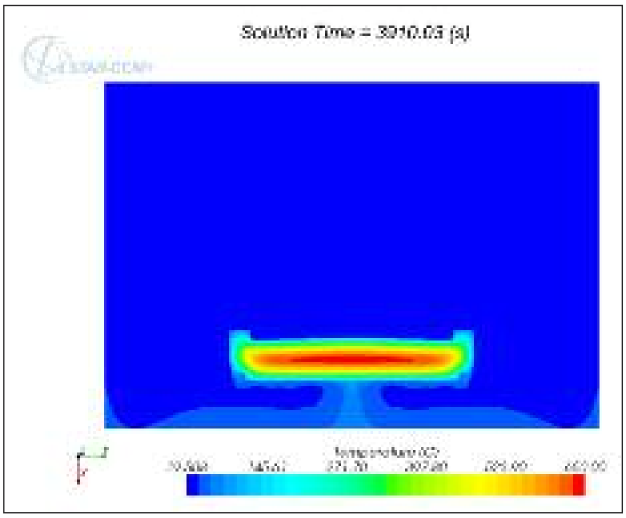

FIG. 11 ***Steam generator tubesheet: thermal field at end simulation.***

Piastra tubiera del generatore di vapore: campo termico a fine simulazione.

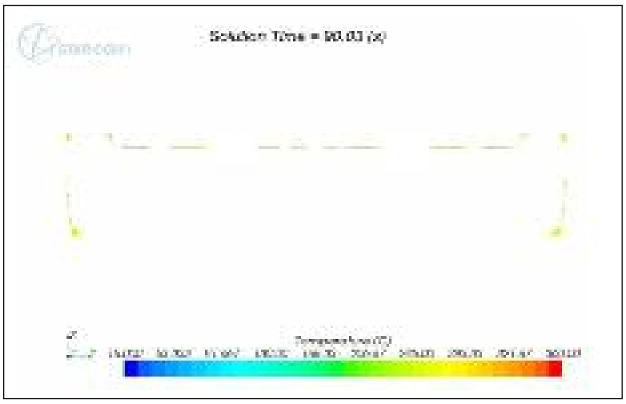

Fig. 12 ***Steam generator tubesheet: thermal field at 90 s in natural convection.***

Piastra tubiera del generatore di vapore: campo termico in convezione naturale dopo 90 s di simulazione

sformation is extremely reduced, especially in the bottom, where, as was said, heat exchange factor has poor values.

Forced convection

The analysis results show that water motion is to be matched with the geometry of the piece to be processed, in order to avoid cold spots or a contrast of the motions reducing the exchange efficiency [7, 8]. In this context a primary role is played by two key parameters: the relationship between vertical and horizontal surfaces of the forging (V/H) and the relationship between the surface and the volume of the forging (S/V).

Forced convection has been introduced by means of two imposed motions in the tank:

- Upwards spiral motion: obtained with two stirrers placed on the double end of a diameter, the axis angled both respect to the horizontal and to the tangential direction;
- Axial motion from top to bottom and vice versa: obtained with two stirrers above and below the forging or (with less effective results) with a nozzle immersed by the top and facing the bottom of the tank,

Such a layout was developed with the following aims:

- Spiral motion: to mix cold and hot water homogenizing the quenching tank temperature; it also contributes to eliminating the steam from the forging vertical surfaces.
- Axial motion: to carry away the steam from the forging non-vertical surfaces; this action is of primary importance in the bottom surface of the forging where the movement of steam by buoyancy is slowed down by horizontal surfaces.

Fig. 13 compares water vector fields of the reactor vessel closure head, in natural convection (right) and forced convection (left).

Reactor vessel closure head forced convection

The convex bottom has a S/V relation of about 17, assuring significant heat exchange even while the tank is in state of rest. Nevertheless the simulations show that natural convection is not sufficient for a complete quenching (as explained above).

Hence the introduction of spiral and axial motion was investigated.

In fig. 14 it is possible to see the martensite layer formation for this configuration.

The temperature progress after 90 seconds attests to a martensite continuous layer formation, with a minimum thickness of 10 mm also in the zones with high geometrical discontinuity (notch zone).

Steam generator tube sheet forced convection

The tube sheet has a S/V ratio below 3 and a V/O ratio < 0,5.

In these conditions it is necessary to use 4 stirrers.

The axial ones carry away steam from the horizontal surfaces, while the tangential ones act on vertical surfaces and improve temperature uniformity of water.

Even if forced convection allows surface exchange coefficient to increase, transport of heat inside the forgings is governed by conduction, which thus represent a physical limit for the quenching process.

As shown in fig. 15, forging skin cooling is accelerated by the stirrers and there is the formation of a continuous layer of martensite, uniform on the external piece surface, but the poor thermal conductivity of steel (about 20 W/m^2 °C) represents the "bottleneck" of the process.

In fig. 16 it is possible to observe that after 3.000 seconds there is still a region in the core of the forging where the temperature

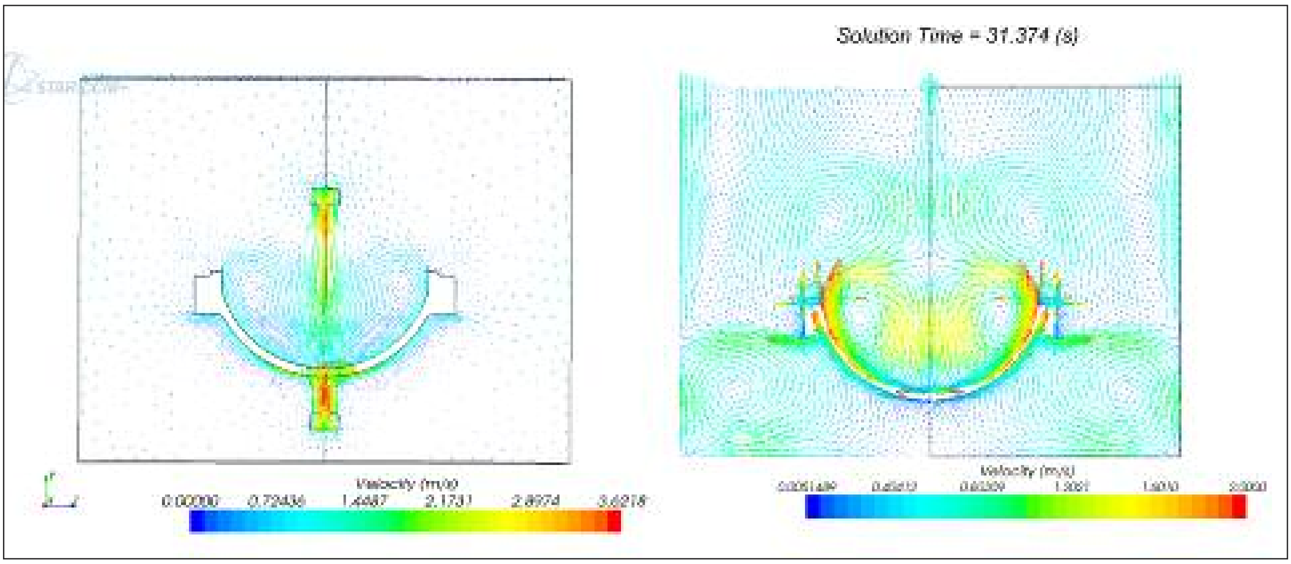

FIG. 13 ***Comparison between water vector fields in natural convection (right) and forced convection (left).***

Confronto fra i campi vettoriali dell'acqua in convezione naturale (destra) e forzata (sinistra).

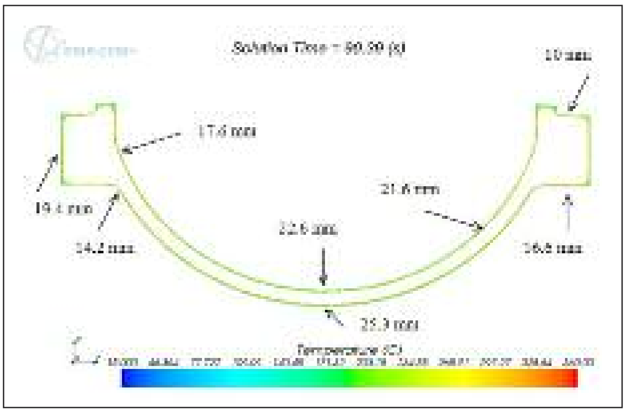

FIG. 14 ***Reactor vessel closure head thermal field at 90 s in forced convection.***

Fondo bombato di chiusura reattore: Campo termico in convezione forzata dopo 90 s di simulazione.

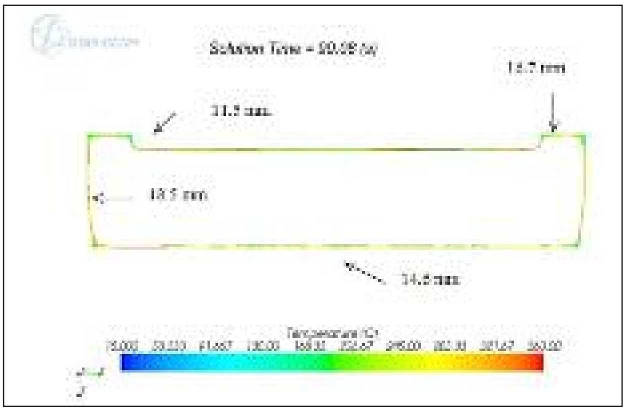

FIG. 15 ***Steam generator tubesheet thermal field at 90 s in forced convection.***

Piastra tubiera del generatore di vapore: Campo termico in convezione forzata dopo 90 s di simulazione.

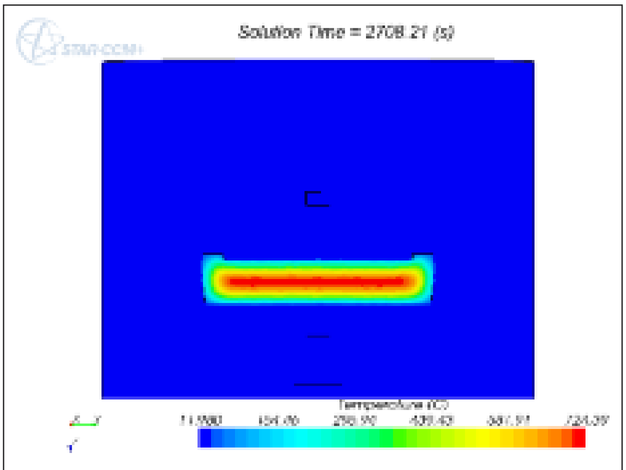

FIG. 16 ***Steam generator tubesheet thermal field at 3000 s in forced convection.***

Piastra tubiera del generatore di vapore: Campo termico in convezione forzata dopo 3000 s di simulazione.

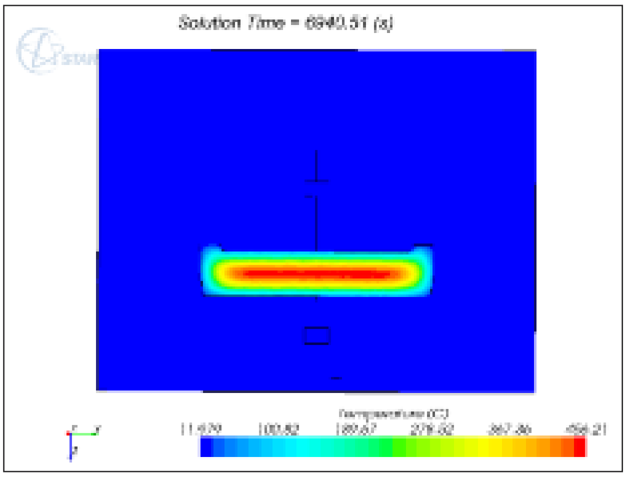

Fig. 17 ***Steam generator tubesheet thermal field at 7000 s in forced convection.***

Piastra tubiera del generatore di vapore: Campo termico in convezione forzata dopo 7000 s di simulazione.

is above 600°C.
In the zone where cooling is lower, there's a chance to obtain perlite or ferrite; the border point is in fact represented by the couple 7000s/540°C.
As show in fig. 17, the forging temperature at 6700s, hence before the beginning of ferrite formation, is amply below the critical temperature of the beginning of transformation.

FUTURE DEVELOPMENTS

The possibility to monitor the temperature variations across the thickness of simulated pieces during hardening, could be a starting point for a future computational study, to calculate the stress and strain in each point of the forging, associated to the thermal gradients.
Although Star-CCM + contains a solid-stress code, it can be applied only to study stress and strain states at uniform and constant temperatures without modification of the chemical and physical proprieties of the pieces.
At the moment, a Java® macro has been realized to convert, step by step, the thermal gradients of the forging's finished volumes in to a matrix form, so they can be used as input data by a Software dedicated to the piece's tension-stress study during cooling. It would be interesting to obtain the piece's mechanical analysis referred to the thermal one, in order to check the beginning and the progress of high tensions caused by sudden cooling of the piece. The variation of the steel's mechanical and thermodynamic characteristics during quenching, due to the continuous structural alterations of the crystal lattice, makes the tension-stress study very delicate and specific. So this study must be carried out using a Software capable of identifying the steel's mechanical characteristics at the temperature change, in order to fix the deformations and the tensions, in the forging sections, which are generated during the piece cooling [1, 9].

CONCLUSION

In this work the process of hardening of two large industrial forgings, having different geometries, has been simulated. The first forging is a reactor vessel closure head and the other one is a steam generator tube sheet. Two analysis conditions have been taken into consideration: hardening by natural convection and hardening in the same geometrical configuration by forced convection.

Thanks to the cooling timing analysis for every section of the pieces, compared with the typical curves of the Bain CCT diagrams for SA 508 3rd grade steel, it has been possible to monitor how the crystal microstructure evolves inside the forging during quenching in order to determine the quality and uniformity of the evolution of the process.
Results show that in natural convection, in the reactor vessel closure head, ferrite and perlite is avoided in all the forging sections, and the metal is a mix of martensite and bainite (depending on the local temperature) in the core, while on the surface, the martensitic layer thickness is neither continuous nor uniform.
In the steam generator tube sheet, results show that martensite transformation is extremely reduced and at the core of the piece, there are high percentages of perlite and ferrite while at the surface the martensitic layer is virtually absent .
These results thus show that the hardening process in natural convection is ineffective in both case studies. Looking at the results obtained in the case of hardening in forced convection, the situation is much better.
In fact in the reactor vessel closure head a continuous layer of martensite has been formed over the surface of the whole section, with double the average thickness of martensite compared to the case of natural convection. Even in the steam generator tube sheet, the situation is much improved, with a continuous surface layer of martensite and a threefold increase in thickness compared to the case of natural convection. It should be noted that, due to forced convection introduced into the quenching tank of the steam generator tube sheet, the formation of perlite and / or ferrite in the core is avoided, an important condition for the quality of heat treatment.
The results thus show that by using CFD software a system of forced movement of the water can be studied that enables to the hardening process to be effective over the entire section of the forgings, both on the surface and in the core of the forging. It should be stressed that the number, location, performance and orientation, of the movement apparatus can only be determined through a CFD software in order to create the convective forced motion necessary to achieve the required performances.

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Abstract

Analisi numerica applicata alla simulazione termica e fluido-dinamica della tempra di grossi forgiati di alta qualità

Parole chiave: forgiatura, tempra e rinvenimento, simulazione numerica

I trattamenti termici degli acciai consistono in una modifica, a caldo, del reticolo cristallino iniziale di tali leghe e rappresentano uno dei passaggi più delicati per la produzione industriale di pezzi fucinati. Nell'ambito della forgiatura, una delle fasi più critiche e delicate è il processo di tempra, che consiste nel raffreddamento rapido dei pezzi in acciaio che si trovano ad alta temperatura, in acqua, in olio o in una soluzione acquosa con polimero (aquaquench). Tale processo è intrinsecamente instabile, complesso dal punto di vista fisico, e soprattutto i suoi esiti sono difficilmente prevedibili senza l'utilizzo di softwares di simulazione termo-fluidodinamico specializzati. Infatti, se non opportunamente eseguito, questo trattamento può essere inefficace o addirittura dannoso, causando cricche, o, peggio, direttamente la rottura del pezzo.
Naturalmente, più grande è il forgiato, maggiore è l'importanza di stimare la dinamica del processo e, di conseguenza, la progettazione della configurazione dell'impianto per ottenere i risultati attesi, al fine di evitare pesanti perdite economiche derivanti da un cattivo trattamento.
In questo lavoro è stato condotto uno studio del processo di tempra in acqua di grossi pezzi industriali fucinati, realizzati in acciaio SA 508 e destinati ad applicazioni nucleari, attraverso simulazioni termo-fluidodinamiche dei transitori termici in ambiente CFD (Computational Fluid Dynamics).
I modelli sono stati validati comparando i risultati numerici con quelli ottenuti da prove sperimentali effettuate su campioni di acciaio, di adeguate dimensioni ed opportunamente strumentati: i risultati hanno dimostrato che l'errore medio è inferiore al 3%, mentre l'errore massimo stimato è inferiore al 10%. Questi risultati confermano che il metodo scelto simula egregiamente il fenomeno fisico e quindi può essere esteso per studiare una vasta gamma di casi, determinando numero, posizione, orientamento e specifiche funzionali di eventuali promotori di turbolenza, al fine di fornire un supporto valido e affidabile ai costruttori di grandi pezzi fucinati.