HYDROGEN TRACKING IN PRODUCTION OF A SPECIAL FORGING:
FROM INGOT CASTING TO HEAT TREATMENT USING SIMULATION

Authors:
A. Ghidini - Lucchini RS - Lovere - Italy
C. Viscardi - Ecotre Valente srl - Brescia - Italy

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ABSTRACT

Hydrogen has been and always will be a source of various problems within steel production because of its generally detrimental effects on processing characteristics and service performance of steel products.
Generally a small quantity of hydrogen is sufficient to cause failures because it has the ability to magnify its effect by migrating to regions of high triaxial stress.
Unfortunately, simply determining that a failure is due to hydrogen embrittlement or some other form of hydrogen induced damage is of no particular help to the customer unless that determination is coupled with recommendations that provide pathways to avoid such damage in future applications.
The solubility of hydrogen in liquid steel is greater than that in solid steel at the melting point.
During production cycle of a component hydrogen migrates from original sites across steel, thus affecting final performance of the part.
In this paper hydrogen effect in a special forging is studied through the use of simulation.
Hydrogen is tracked from ingot casting simulation along the complete production progress, including forging and heat treatment.
Size and location of hydrogen are detailed in every phase and compared to experimental data.
Process parameters affecting hydrogen removal are here studied and developed in order to achieve a component with sound microstructure.
INTRODUCTION

Manufacturing process of special forging is fundamental to achieve performances requested by International Standard for Safety, in particular to control fracture mechanics phenomena. The final quality in terms of service behavior depends mainly on: chemical composition of the steel; melting technology, forging technology and heat treatment cycle [1,2].

A peculiarity of special steel grades for forgings is the need for high fracture toughness and fatigue resistance. This requires a very dedicated steel-making process, able to reach a low content of non-metallic inclusions coupled with a low percentage of gasses, sulphur, phosphorous and other impurities. Secondary metallurgy, which takes place in LF, refines the chemical composition by the use of wire-feeding machines for the addition of specific elements, regulates the temperature and improves cleanliness with decantation of inclusions thanks to Argon flushing. The use of a further tank-degassing (Vacuum Degassing) station leads to a drastic reduction in gases such as hydrogen (less than 2 ppm in liquid steel), nitrogen, oxygen and allows “fine tuning” of chemical analysis by adding specific elements to create an inert atmosphere at the vacuum stage.

After refining, addition of alloy agents and degassing operations the molten steel for forgings is teemed from ladle into a bottom-poured ingot.

Ingot casting stage is fundamental to achieve homogeneity in the mechanical properties of the special forging: during solidification the steel may lose its uniformity and become an heterogeneous mass: it is widely known that the last stage of ingot is usually the most chemically segregated.

Shrinkage porosities and inclusions can be eliminated with a proper casting practice while segregation and gas entrapment can only be controlled and reduced for the nature itself of solidification pattern.

After pouring and any intermediate heat treatment ingots are cut into blocks prior to the forging process; the blocks are then heated to the forging temperature in a dedicated device.
Shaping of the special forging is obtained by hydraulic press forging; force is applied in a continuous way for some seconds through steel molds in order to impose desired deformation and increase mechanical performances of the part by recrystallization.

With some products, intermediate rough-machining can be performed before quality heat treatment in order to develop the best mechanical properties from the steel grade.

Heat treatment, before final machining and quality inspection, is based on normalization followed by quenching and tempering to obtain a tempered martensitic fine structure.

In this paper ingot casting, heating, forging and heat treatment operations to obtain a special forging in 30NiCrMoV12 steel grade have been simulated with two commercial softwares: ProCAST (FEM casting simulation) of ESI-Group for ingot casting and DEFORM (forging and heat treatment simulation software) of SFTC for heating, forging and heat treatment.

Investigation has been focused on hydrogen entrapment originated in ingot casting operation and on its evolution during following operations.

Hydrogen flakes are defects involved in decrease of fatigue limit and its early failure; original hydrogen concentration is spread across ingot cross section both during solidification (where it mainly concentrates in last solidified areas) as well as forging and heat treatment, becoming what is defined an open die forging internal defect [3].

Experimental measurement of hydrogen ppm in molten steel as well as shrinkage porosities and casting defects in ingot have been used as an input to track hydrogen evolution during production cycle until post-forging heat treatment [4].

Simulation results have been checked with experimental measurements at shop floor level in order to validate model robustness and reliability.

**MATERIAL**

The steel grade object of this study is the high strength alloy steel 30NiCrMoV12, widely used all over the world for special applications.

The main characteristic of this steel is high fatigue strength together with notch sensitivity value similar to standard steel grades.

In following table, chemical composition of 30NiCrMoV12 steel is shown.

<table>
<thead>
<tr>
<th>30NiCrMoV12</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Cu</th>
<th>Mo</th>
<th>Ni</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.26</td>
<td>0.4</td>
<td>0.6</td>
<td>0.4</td>
<td>2.7</td>
<td>0.08</td>
<td>0.015</td>
<td>1</td>
<td>0.2</td>
<td>0.6</td>
<td>3.3</td>
</tr>
</tbody>
</table>

*Table 1: 30NiCrMoV12 chemical composition (maximum percentage contents - heat analysis)*

Material characterization is a fundamental task to be able to simulate complete production cycle of forging from ingot casting to post-forging heat treatment.

For ingot casting simulation mandatory properties are: conductivity, density, specific heat, latent heat, solid fraction between liquidus and solidus temperature and viscosity [6].

All these properties must be defined as a function of temperature and moreover, during cooling under solidus temperature, also as a function of phase present with that particular cooling rate, both in mold as in air after ingot stripping.
For heating, forging and post-forging heat treatment a bigger number of information should be given to simulation software, involving both mechanics and thermodynamics\[^7\]. Constitutive equations describe the nonlinear relationship that exists among such process variables as effective stress, effective strain rate, and temperature at different deformation levels. In this paper also microstructure and diffusive phenomena has been described, requesting to add the capability also to define flow-stress curve not only as a function of temperature only but as a function of phase percentage present at each zone of workpiece.

Hydrogen tracking along production cycle has requested a particular attention because this element has different solubility in steel, according temperature and phases\[^8\], like shown in picture 2, and moreover no diffusion is possible under low temperature value.
For casting simulation software ProCAST gas diffusion is computed automatically with a dedicated feature called Advanced Porosity Module \cite{9,10}. This module is a general framework for the modeling of porosity formation in multi-components alloys with more than one gaseous element. Equations of this model are coupled to a macroscopic resolution of Darcy-mass balance equation governing the pressure drop in the mushy zone.

Heating, Forging and Heat Treatment have been simulated with software DEFORM and general diffusion model implemented in code has been customized to consider hydrogen migration. Model is based on Fick’s laws for diffusion phenomena; in DEFORM general formulation is based only on temperature and element concentration.

A Fortran user routine has been written and implemented as hard-coded to consider FEM-time hydrogen solubility in different phases (austenite, ferrite, pearlite and martensite)\cite{11,12,13} and under different external load situation\cite{14,15,16,17}, completing in this way DEFORM approach to this phenomenon.

According to Lucchini RS experience, for these steel grade a lower cut-off temperature value of 300 °C has been set as threshold for macroscopic hydrogen flakes appearance.

An additional point for user routine definition has been the introduction of a turn-off for hydrogen flaking when hydrogen concentration is located in zones where shrinkage porosities are still present.

**INGOT CASTING SIMULATION**

Simulation of filling and solidification of 30NiCrMoV12 ingot has been done with FEM software ProCAST produced by ESI-Group.

Complete mould has been introduced, with pouring of steel which is starting from the top of column, as shown in picture 3 and as happening in real steel mill practice.
Filling and solidification simulation provides results for temperature, velocity, shrinkage porosities, scrap and inclusions entrapment as well as for air and gas both during pouring stage and also during solidification and cooling as calculation is performed with convective fluxes and radiation effect with view factors enabled[17].

It means that, according to increase of solid fraction across ingot thickness, steel is moving in mould with a velocity proportional to pressure drop due to growing mushy zone and lower temperature.

Solid fraction reduction, showed in following images, generates shrinkage porosity in ingot. X-ray criterion for pictures is a cut-off used to hide areas where solid fraction is too high to allow steel movement in mushy zone to compensate volumetric contraction. During this stage hydrogen, originally homogeneously present in molten bath with a concentration of 5 ppm, is rejected from mushy zone into last liquid area at center-line of ingot, according to major solubility limit of hydrogen in liquid phase compared to solid.
Results are not perfectly at center-line of ingots for two principal reasons: filling not symmetric and radiation effect between the two moulds due to view-factor contribution; simulation has been run with a fully coupled model for thermo-fluid dynamic solution and microstructure model solution, thus driving to achieve these results. As shown in picture 6 there is a strong asymmetry between inner and outer side of mould and this generates a different thermal gradient and cooling rate for steel. In addition to this effect also filling is not well balanced at center-line and this behavior is present also during solidification, like shown in picture 7. As a consequence asymmetric results for ingot in solid state are obtained.

![Picture 6-7: Temperature field of the mould at the end of solidification influenced by radiation view-factors (left) and slice at mid-section showing velocity vector plot during filling (right)](image)

An heterogeneous situation is developed for shrinkage porosity and hydrogen concentration according to following images.

![Picture 8-9: Slice at mid-section of ingot showing Shrinkage Porosity (left) and Hydrogen Concentration (right) at stripping time](image)
HEATING AND FORGING SIMULATION

Ingots, after stripping operation, are cut in smaller parts, removing riser and base, to be sent in heating furnace at 1200 °C before press forging. Original ingot is exported directly from ProCAST result file into a .key native DEFORM file, as represented in following picture where a slice of complete ingot is shown in DEFORM system, using the same FEM mesh.

Higher part of ingot has been selected to develop simulation analysis of heating and forging phases for manufacturing production. Heating cycle request to put ingot in furnace to reach a set point of 1200 ° C, a common value for press forging of this steel grade, maintaining that temperature for a not excessive time in order to avoid undesired grain coarsening but enough to grant homogeneous temperature across ingot thickness.

Picture 10: Slice at mid-section of ingot in DEFORM environment representing hydrogen concentration and an histogram of its distribution

Picture 11: Point-tracking of temperature for 3 points selected in ingot during heating before press forging
Even if at high temperature, diffusivity of hydrogen is happening only for a small area of ingot surface, as shown for picture 12 and 13, where a tracking of hydrogen is done at mid-plane along longitudinal axis and radius of component.

Picture 12: Tracking of hydrogen at mid-section along longitudinal axis at beginning of heating (top-left) and at the end (top-right)

Picture 13: Tracking of hydrogen at mid-section across the thickness at beginning of heating (top-left) and at the end (top-right)
Press forging operation is done with an hydraulic press; this operation is done to provide a raw round shape to starting from a round ingot. Reduction ratio of cross-section allows to obtain higher mechanical performance thanks to important contribution of recrystallization. This operation is able both to increase mechanical performance of forged component and to close internal voids of shrinkage porosities when high effective strain is reached in correspondence of these defects which in general occurs at center-line\textsuperscript{[19]}.

**Picture 14:** Forging operation showing effective strain on a longitudinal slice of ingot with DEFORM software

Press forging operation cycle requests hundreds of bites to obtain final round cross-section of forging, comprehensive of material allowance. Steel cannot be forged under 900 °C both to avoid premature microstructural transformation and to maintain steel plastic enough to be properly forged with selected press.

This request that in real production some re-heating operations should be done; for this particular study two re-heating stages at 1200 °C have been introduced when average temperature of ingot decreases under 900 °C.

Final hydrogen distribution at the end of forging before cooling is represented in picture 14; press reduction has been able to close shrinkage porosities but hasn’t modified concentration of hydrogen in the bulk. Analysis has been done computing total amount of hydrogen on volume of final single forged component as during press forging from a single steel block are obtained
multiple forged pieces. Histograms show that hydrogen distribution has similar peak value even if now its distribution is narrower.

*Picture 14: Comparison between hydrogen concentration at the beginning (top) and at the end (bottom) of press-forging cycle.*

This is due to peculiarity of the press-forging process which isn’t so long to allow an efficient migration of hydrogen outside the component and to the fact that hydrostatic pressure applied to forged part has no benefit to reduce size of gaseous areas.
**POST-FORGING HEAT TREATMENT**

Post-Forging Heat Treatment cycle requests cooling in air followed by multi-step heating, as represented in following graph.

![Graph 3: Post-Forging Heat Treatment Cycle scheme](image)

Cooling from forging operation generates a microstructural transformation from austenite to ferrite-pearlite with no real effect on hydrogen migration or its re-distribution. In case of temperature going under threshold of direct flakes generation, in zone at center-line appears area where hydrogen is no more further able to move, like shown for P1 and P2 of picture 15.
Hydrogen distribution evolution during cooling. P1 and P2 are exposed to flakes generation.

Heating cycle for this simulation is performed with two different temperature step. First set-point temperature is very close but lower than austenitizing temperature in order to reduce stresses induced by microstructural transformation.

Areas of interest for hydrogen tracking can be identified with P1 (center of the special forging); P2 (surface point in correspondence of half of the special forging); P3 (point at center-line of ingot in correspondence of radius variation); P4 (point at mid-radius location).

Evaluation of this point can easily show how temperature and microstructure allows hydrogen to move in order to satisfy quality standard for retained gas content at the end of cycle.

Following pictures describes temperature plot and hydrogen concentration evolution for post-forging heat treatment.
Slope variation for hydrogen tracking graph in correspondence of second step of temperature represents phase transformation from pearlite-ferrite to austenite. Request to achieve target of hydrogen concentration under 0.6 ppm takes long time as shown from these results.
EXPERIMENTAL RESULTS

To validate results of simulation tests have been done to detect hydrogen flakes in special forgings.

In pictures 18 two areas of analysis are highlighted; zone A is area where flakes are supposed to form if cooling before post-forging heat treatment is too severe, like described in previous picture 15, while zone B is a location where hydrogen remains in case of too short maintenance time at heat treatment temperature, like shown in previous picture 16.

No evidence of hydrogen flakes if final percentage is lower than 0.6 ppm on blank product.

![Picture 18: Location of zone A and zone B: A center-line; B mid-radius](image)

Lucchini RS tests on components have shown that cases of hydrogen flake really appears at attended locations, as shown in following photos and SEM pictures.

![Picture 19: Photography of hydrogen flake in zone A](image)
CONCLUSIONS

Production cycle of a special forging in 30NiCrMoV12 has been simulated and studied to track hydrogen concentration in every operation, starting from ingot casting until heat treatment before machining.

Dedicated material description has been written to consider, according to Darcy and Fick's laws, hydrogen diffusion in liquid and solid phase; in addition, particular triggers for non-mobility of hydrogen has been introduced to consider behavior in different microstructures.

From cross-check between simulation results and empirical experience it results that press-forging operation has a very low effect on hydrogen removal from forged component.

Excessive cooling after press-forging operation drives to hydrogen flakes formation, as resulting from SEM analysis.

Due to low diffusivity values of hydrogen in austenite, post-forging heat treatment must take time enough to allow migration of gaseous hydrogen from forging thickness, as shown in post-forging heat treatment simulation and validated on real component.

In the manufacturing of special forgings, there are many stages, each of which is a link in a chain, whose strength depends on the quality and reliability of all.

Especially, the two main macro-phases of this complex process are summarized as follows:
- Manufacturing processes of the blank product;
- Machining, assembling and service of the final forging.

Lucchini RS has implemented qualified and reproducible manufacturing processes, to minimize "surprises" on the product of a process divided into different activities, from which it is often difficult to trace the exact causes of abnormal results.

We hope the people could also discover, in reading this presentation, the complex technologies required to develop special forgings, the considerable rigor and passion that flows from this fascinating activity.
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