DIE-CASTING: S.D.C. STEEL, A CONTINUOUS METALLURGIC INNOVATION TO MEET WITH THE PROBLEMS

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The S.D.C. steel grade has been especially designed for large-size toolings used in die-casting applications with the objective of increasing the fatigue resistance of the material and the tool life. A fundamental and integral approach has been undertaken to understand and measure the temperature and stress conditions at the surface during service, get a full multi-scale description of the steel microstructure and define the relationship between microstructure and its evolution and thermal fatigue resistance. The new grade with the associated optimised heat treatment offers superior mechanical properties and shows improved performance in its die-casting industrial applications.

KEYWORDS: Die-casting, steel grade, microstructure, multi-scale observation, heat-treatment, hardenability, forging process modelling.

INTRODUCTION

For light alloys casting and more specifically pressure die-casting, the 5% chromium steel family grades (H11, X37CrMoV5, 1-2343) are widely used. Their performance measured by the total number of manufactured parts and the amount and cost of repair operations has been through the years increased by better casting process control and progress in the metallurgy and the heat treatment of the moulds. Higher hardness has a positive effect on tool life, but remains limited to guarantee a minimum toughness. A breakthrough was necessary in the metallurgical conception of the grade: beyond the measurement of conventional mechanical properties, our research program was focused on the global understanding of all the metallurgical and thermo-mechanical phenomenas involved. Hereafter are described some aspects of our scientific analysis, and the basic properties of the new improved S.D.C. steel.

THERMOMECHANICAL LOCAL CONDITIONS OF THE WORKING SURFACE DURING SERVICE

During parts production in the pressure die-casting process, the tool surface is submitted to thermal shocks at two times within every cycle:
- a hot shock when liquid metal is injected inside the mould
- a cold shock when lubricant is sprayed on the surface.

Temperature gradients induce high shear stresses at the surface of the material:
- compression stresses during the hot shock which induce plastic deformation in compression mode,
- tension stresses during cold shock with associated plastic deformation in tension mode and further crack initiation; at this stage, cracking may occur.

In industrial conditions, the heat flux through the tool surface has been measured (Fig. 1) and the surface temperature

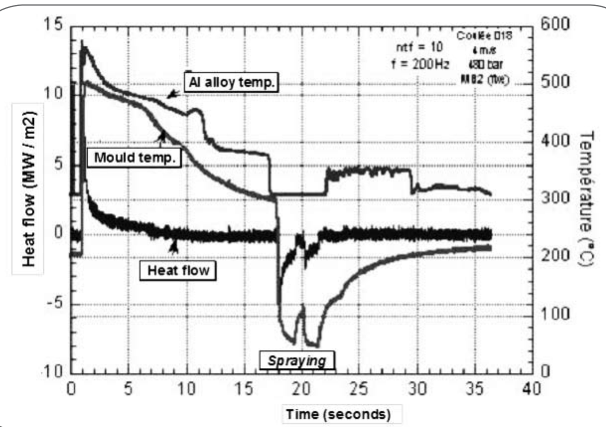

Fig. 1

Typical thermal recording of one cycle during production of pressure-die cast parts.
Registrazione tipica della temperatura dello stampo in esercizio.

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	C %	Si %	Mn %	Ni %	Cr %	Mo %	V %	Others
H11	0.38	1.00	0.35		5.00	1.30	0.50	
Low-Si H11	0.36	0.25	0.35		5.00	1.30	0.50	Low trace elements content
S.D.C.	0.36	0.25	0.35	1.50	5.00	1.75	0.65	

Tab. 1 **Compositions of reference and S.D.C. steels.**
Composizione chimica di riferimento e acciai S.D.C.

calculated with special devices and techniques (1).
The main results are the following:
- heat flow during the contact with molten aluminium may raise to a peek of more than 5 MW/m2 for about one second
- the true temperature at the surface of the tool cannot be measured directly by thermocouples, but must be calculated from the heat flow with reverse methods. The temperature of the aluminium part surface may be measured with a fiber optical sensor and an associated specific calibration,
- a temperature gap of 30 to 80°C is observed between the aluminium and the mould surfaces,
- the values in heat flow and temperature maps are highly dependant from velocity of liquid aluminium and pressure,
- the maximum temperature on the mould surface is significantly lower than the tempering temperature during heat treatment.

Softening of the steel under the working surface is commonly observed and measured by microhardness tests. With the results of the heat flow and temperature measurements and calculations, it become obvious that the cause for softening is not a thermal origin but a mechanical cyclic softening. The same conclusions remain more or less the same for other casting processes, for instance gravity foundry when the steel tool is water-cooled to provide a very drastic cooling rate for a very fine solidification microstructure of the part.

MICRO-MACRO APPROACH FOR THE DEFINITION OF THE BEST MICROSTRUCTURE AND NOMINAL COMPOSITION

Cyclic softening of heat treated X38CrMoV5 steels on fatigue laboratory specimens has been observed (2) and quantified. During softening, the microstructural evolutions (3) are:
- moving of dislocations under the effect of stresses,
- modification of the distribution of dislocations inside the structure, with "cleaning of dislocations" inside the wide needles of bainite and martensite,
- Coarsening and coalescence of secondary carbides.

Softening is the result of the diminution of the density of dislocations (Fig. 2), and of the formation of large areas free of crystallographic defects. It has also been observed that large needle-shape precipitates that may have their origin in bainite formation have no positive effect to control the dislocation mobility.
Consequently, the best microstructure must be composed of:
- a martensite matrix with very fine needles and dislocations in high density and well-dispersed,
- carbide precipitates with an homogeneous distribution, a high density, and a small size to allow a very efficient pinning of the dislocations.

The combination of experimental techniques like Transmis-

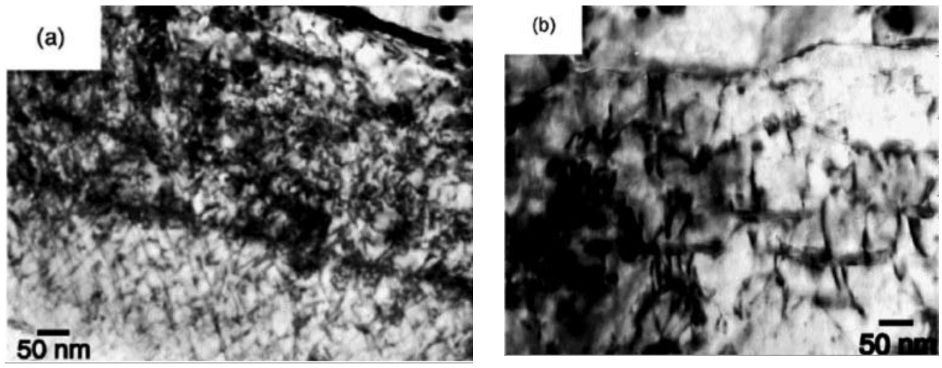


Fig. 2 **Low-Si H11 steel: Distribution of dislocations - a) as heat-treated for 43 HRC; b) after fatigue testing.**
Acciaio Low-Si H11: distribuzione di dislocazioni a) trattamento termico per 43 HRC; b) dopo i test di fatica.

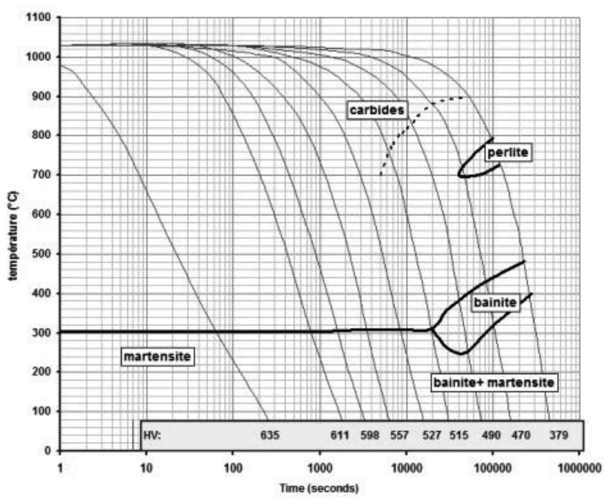


Fig. 3 **SDC: Continuous Cooling Diagram.**
Diagramma di Raffredamento continuo.

sion Electron Microscopy in high resolution mode and with observations on replicas, X-Ray diffraction on precipitates extracted by chemical dissolution, and Small Angle Neutrons Scattering (SANS) has shown that precipitates of the 5%Cr steels may be classified in two families of sizes: about 3 nm and 25/50 nm. Mechanical properties appear to be directly dependant from the density of the first family carbides of the (V,Mo)C type ; their density has been assessed to be about 1023/m^3 to 1024/m^3.

The new S.D.C. grade is derived from the 5% Cr standard steels with a nickel addition and a molybdenum and vanadium content adjustment in order to approach the perfect microstructure described before :

- the combination of the effect of all elements, overall nickel and molybdenum, provides a very high hardenability: bainite features with wide ferrite lathes and elongated harmful carbides are avoided even on large parts corresponding to lower quench cooling rates,
- martensite needles are small and dislocation density is high in the matrix,
- the density of the nanometric (small size family) carbides has been carefully adjusted by the vanadium content -0.65%- for an austenising temperature of 1030°C.

FINAL GENERAL PROPERTIES OF THE S.D.C. STEEL

S.D.C. quenched from 1030°C shows a very high hardenability (Fig. 3). As the common annealing treatment of conventional 5%Cr steels is not applicable to S.D.C., a specific cycle has been defined, which confers a hardness of less than 220 HB suitable for rough machining. The microstructure (Fig. 4) cannot be easily rated with conventional micrographic standard charts. Small-sized carbides are dispersed with a needle heredity distribution.

The curve defining hardness as a function of tempering temperature (Fig. 5) is not very different from the standard H11 reference. Charpy V impact test energy has been measured on a significative number of large size products in the conditions of industrial heat treatment and in conformity with NADCA Standard (Fig. 6). The results show an unusual homogeneity between specimens taken from the same place in the block, between different positions in the block (core, near-surface…) and between different products. This steel is from far less sensitive that nickel-free grades to the

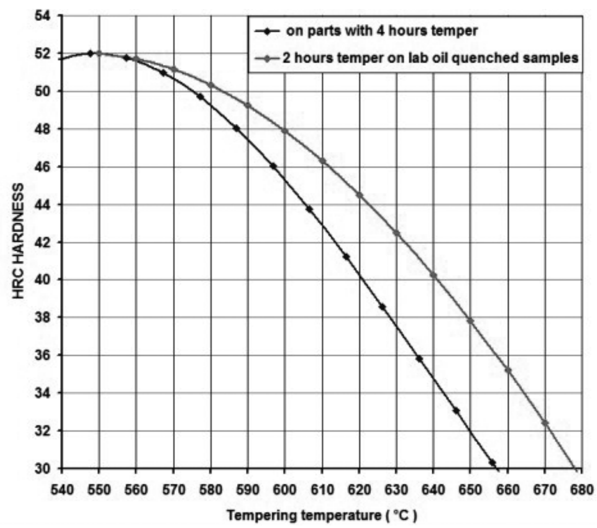


Fig. 5 **S.D.C. Hardness after tempering - Previous 1030°C austenisation.**
Durezza dopo il trattamento di tempra. Previa austenitizzazione.

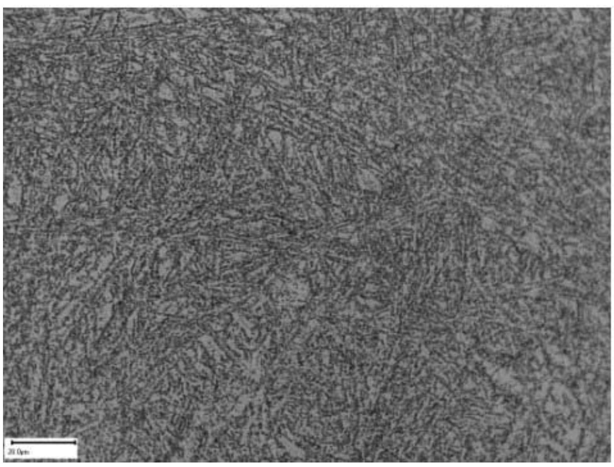


Fig. 4 **Microstructure in the annealed condition - original magnification: x500.**
Microstruttura in condizioni di tempra. Ingrandimento: x500.

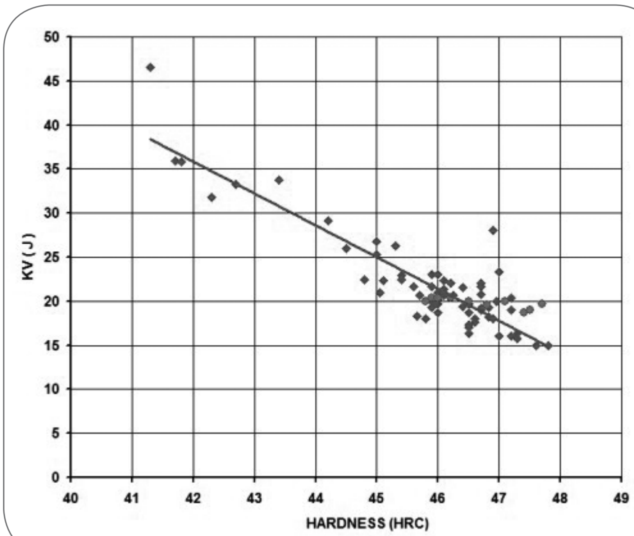


Fig. 6 **Charpy V impact test results on blocks in industrial heat treating conditions.**
Risultati dei test Charpy V, sui blocchi in condizioni di trattamento termico industriale.

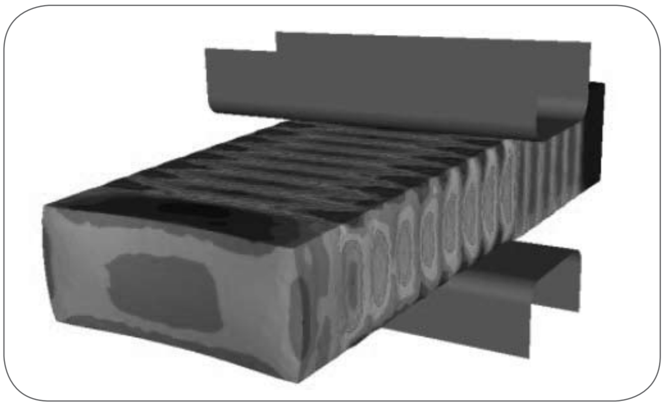


Fig. 7
3D numerical simulation of press forging.
3D Simulazione numerica dello stampaggio.

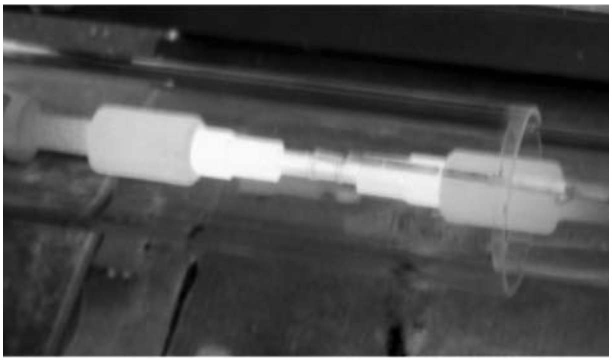


Fig. 8
Torsion tests for definition of recrystallisation formulas.
Test di torsione per le formule di ricristallizzazione.

loss of toughness (5) when, for heavy parts, the cooling rate during gas-pressure quenching decreases.

IMPROVEMENTS IN PROCESSING FOR BETTER METALLURGIC QUALITY

The grain size and homogeneity remains an important parameter for superior fatigue properties and requires a specific forging procedure with well defined routes including deep deformation sequences and intermediate re-heatings.
This procedure has been optimised by the contribution of numerical finite-elements modelling combining:
- thermomechanical calculations to get deformation and temperature maps (Fig. 7),
- experimentation in industrial context for adjustment of thermal transfer input data for the forging model,
- prediction of microstructure: recrystallisation percentage and grain size. This aspects requires a basic laboratory research for definition, from deformation (compression, torsion) tests (Fig. 8), of the specific recrystallisation rules for the grade,
- macrographic and micrographic measurement of grain sizes on real products for global validation of the simulation.

The main challenge is to obtain, beyond the conventional minimum total deformation rate, industrial acceptable conditions for the generation of an uniform microstructure in the whole section and all along the bar, despite the large size of the product, the loss of temperature near the surface and especially in corners, the unavoidable gradients of strain and temperature, the discontinuous character of the multipass forging technique.
Finally, with the individual adjustments of forging parameters defined for every size of individual blocks or bars, the whole thermo-mechanical process including forging and annealing gives the potential of a full refined recrystallisation during austenisation at 1030°C (Fig 10b). The final heat treatment produces a fine typical martensitic microstructure without any evidence of wide bainite-like laths or platelets (Fig 10a).

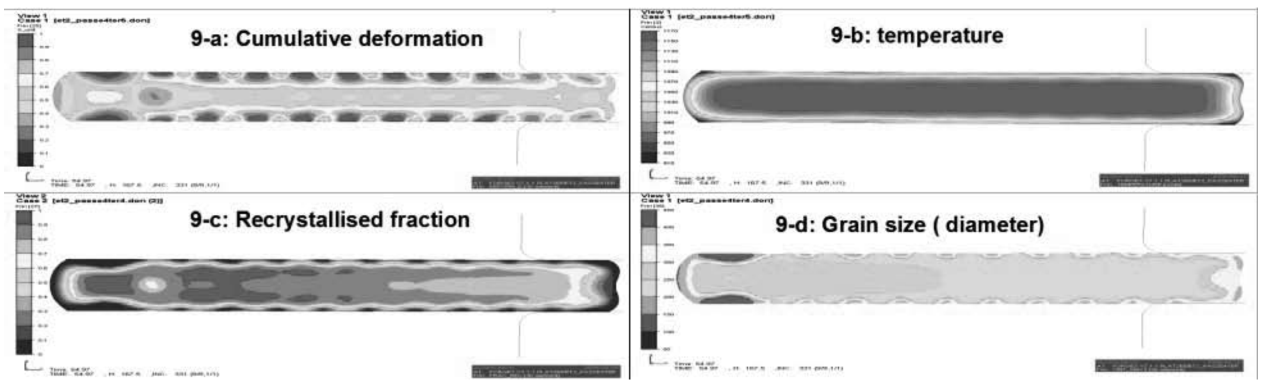
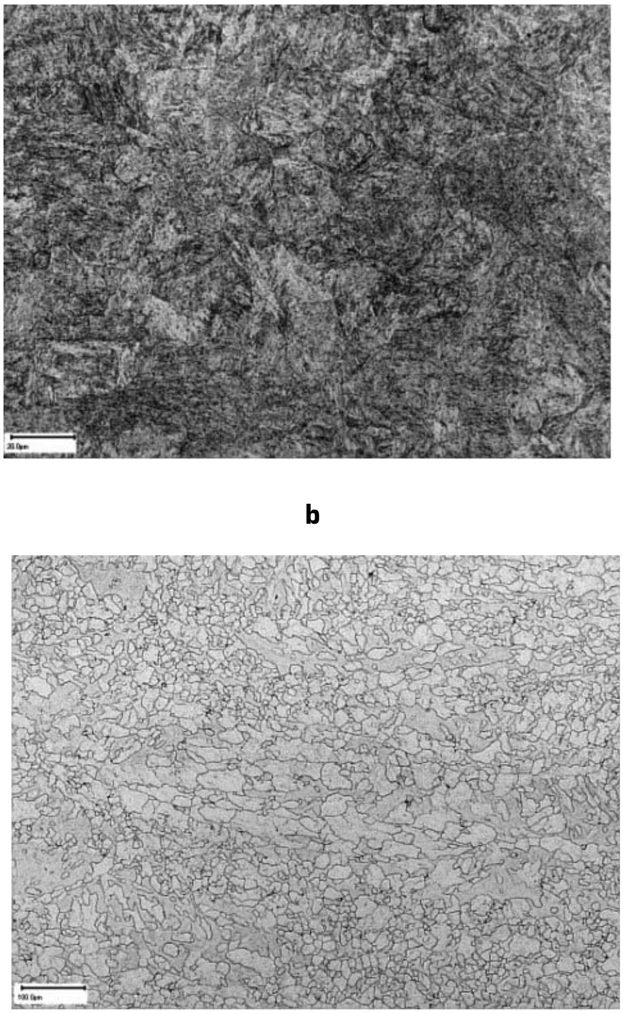


Fig. 9
TTypical results of numerical simulation of press forging: Maps of the different parameters in the section of the product.
Risultati tipici della simulazione numerica dello stampaggio sulla pressa: mappe dei differenti parametri nella sezione del prodotto.



▲ *Fig. 10*
Microstructure in the fully heat treated condition of a 1000x380 section - a) standard etch original magnification: x500; b) specific etching for grain size visualisation original magnification: x 100.
Microstruttura nelle condizioni di trattamento termico della sezione 1000 x 380 - a) incisione standard ingrandiamento: x 500; 10-b: incisione specifica per la visualizzazione della dimensione del grano ingrandiamento: x 100.

BEST PRACTICES FOR HEAT TREATING

S.D.C. steel must be heat treated with similar equipment and procedures as common 5%Cr steels with the additional following instructions:
- the austenisation temperature must be 1025/1030°C after a pre-heating in he 750/800°C range,
- for best service performance, the target for hardness must be by 1 to 1.5 HRC more than the hardness of the reference 5% Cr steel for the same application.
- the first tempering must be at 550°C,
- the final expected hardness is obtained by temperature adjustment of the following tempering cycles,
- the full heat treatment may include two or three tempering steps; a third temper is recommended for very big blocks and if the temperature between quenching and first temper and between first and second temper has not reached a value below 100°C.
- SDC is less sensitive than conventional 5%Cr steels to variations of gas pressure and gas flow during quenching.

FIRST RESULTS IN PRODUCTION CONTEXT

Moulds from different sizes have been produced and put in production inside several plants, with an initial hardness in the 44 to 49 HRC range. To-day, several of them have produced more than 100 000 units and none of them is considered as ruined, so a direct comparison for the total production of the mould is still not available.
Nevertheless, results are considered as better than for reference steels of the H11 or low-Si H11 grades:
- production before first crack detection: better from 15 to 40%,
- percentage of damaged surface for a given production amount: better from 15 to 35%,
- maintenance operations: decrease from 20 to 80%,
To-day, no drawback has been identified about repairing by welding, distortion, or catastrophic cracking during heat-treatment and service. Distortion during heat treatment appear to be less important than for classic reference grades.
Moreover, efforts have still to be done to adjust precisely the parameters of heat treating in partnership with every heat treating plant.

CONCLUSIONS

The S.D.C. steel is a new material for tools and more specifically die-casting moulds, with superior properties obtained as the result of the combination of several innovative actions:
- a multi-scale approach for investigation in the microstructure,
- a definition of an ideal microstructure by the understanding of relations between microstructure and its evolution under thermo-mechanical loading during service,
- a new composition with a nickel addition and a precise adjustment of the balance between hardening elements and nickel, with a low level of trace elements
- a specific production route with an optimised forging and annealing process,
- a heat treatment with an accurate definition of parameters for austenising and tempering.
To-day, the S.D.C. toolings which have been put into production show an improved performance compared to reference materials. These results have to been confirmed; discussions and technical collaboration between all partners remain absolutely necessary to go ahead on the way of progress.

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ABSTRACT

PRESSOFUSIONE : SDC, UN NUOVO ACCIAIO PER ALLUNGARE LA VITA DEGLI STAMPI

Paole chiave: pressocolata, acciaio, proprietà

L' acciaio S.D.C. è stato concepito, in particolare, per gli utensili di grandi dimensioni, usati nelle applicazioni di pressofusione, con l'obiettivo di aumentare la resistenza alla fatica del materiale e la vita stessa dell'utensile. Per capire e misurare le temperature e le condizioni di sollecitazione in superficie durante la lavorazione, per ottenere una completa descrizione multi-scala della microstruttura dell'acciaio, per definire la relazione tra microstruttura e sua evoluzione e la resistenza alla fatica termica, è stato impiegato un approccio fondamentale e integrante. Il nuovo acciaio con il corretto trattamento termico ottimizzato, offre proprietà meccaniche superiori e migliori prestazioni nei processi di pressofusione industriale.