HUNGARIAN JOURNAL
OF INDUSTRIAL CHEMISTRY
VESZPRÉM
Vol. 39(2) pp. 243-249 (2011)

'BY' TREATING OF MICRO-ALLOYED STEELS SUPPORTED BY INTEGRATED 'IT' TECHNOLOGY IN THE FORGING FACTORY OF RABA

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In the forging industry typical in the 21st century, economical production requires environment-friendly manufacturing of integrated and complicated products of larger and larger masses. Difficulties to be solved require effective researches, technological developments and cost analyses. Most frequently, cost analyses call the attention to energy demand of forging, to tool costs and to the efficiency of raw material usage. Preservation and enhancement of competitiveness based on environment-friendly technological solutions are one of the most important challenges for the forging industry in the 21st century. Our case study presents BY *(The Best Yield)* treatment technology of a planetary carrier developed in the RÁBA forging plant. Development of the basic technology required integrated application of CAD *(Computer Aided Design)* – CAE *(Computer Aided Engineering)* and a test method using thermographic camera. Integration of IT *(Information Technology)* systems created a new design method, which enables relatively precise determination of cooling technology for BY treated products even in the design stage. The properly micro-alloyed basic material and cooling technology made it possible to omit the quench and temper heat treatment and to adopt an energy-saving forging process.

Keywords: BY, cooling, micro-alloying, simulation, thermographic camera.

Introduction

Micro-alloyed steels, at controlled cooling, are able to get the same mechanical properties as the heat treated steels. It means that a forging – that meets the same requirements – can be produced with significantly less energy and other additional costs.

The most important micro-alloying materials are vanadium, niobium and titan [1, 2]. Affinity of these elements to carbon and nitrogen is higher than that of iron. They are more stable even at higher temperature than iron carbide, that's why at the temperature of hot-forming they are forming carbides, nitrides and carbonitrides with carbon and nitrogen contents of steel.

In the English literature, these steels are called as HSLA *(High Strength Low Alloy)* steels, while in the German region they are called as AFP *(Ausscheidung-shartenden Ferritisch-Perlitischen – hardening by segregation, ferritic-pearlitic)*.

Nowadays, the micro-alloyed steels have higher toughness (accompanied by increase of ferrite content in the microstructure) as a result of decreased carbon content, and have higher strength as a result of increased silicon and manganese contents [1, 2].

An important factor in increasing the strength is grain refining, which increases not only the strength, but at the same time the toughness, too.

Strength increasing effect of grain refining is caused by the property of crystallite limits eliminating movement of dislocations. Fineness of secondary microstructure depends on primary microstructure, so grain size of ferrite depends on grain size of transforming austenite. Grain size of austenite is influenced by initial temperature of forging, degree of forming and kind of re-crystallization.

Transformation following forming is also affected by final temperature of forging, as overheating of austenite increases the number of ferrite crystal nucleuses, which results in finer microstructure. Strength increasing effect of grain size can be determined by *Hall-Petch equation.*

The other mechanism for increasing strength is performed by dispersive segregations, when a relatively small volume of alloys provides significant results.

Strength is largely increased by segregations, which occur at lower temperature, partly in the austenite and then during the transformation $\gamma \rightarrow \alpha$. Effect of these segregations is primarily expressed by decreasing the grain size of ferrite. The most effective micro-alloys are those that dissolve properly in austenite, segregate by making compound with carbon and nitrogen contents of ferrite, so they improve the strength in the following sequence: vanadium, titan, niobium [2].

The evenly distributed, spherical segregations eliminate movement of dislocations. Dislocations intersect the obstacles, depending on their size and kind, or go around them by leaving dislocation circuits.

Strength increase caused by particles of incoherent boundary means hardening by segregation. In the material containing the dispersive second phase, the moving dislocations are not able to go through the second phase, they go around. This process is *the Orowan-mechanism*. Each micro-alloy is segregating at different temperatures in steel. In case of vanadium and titan, nitrides and carbides are forming not in parallel, i.e.: formation of one beside the other can be neglected *(Fig. 1)*.

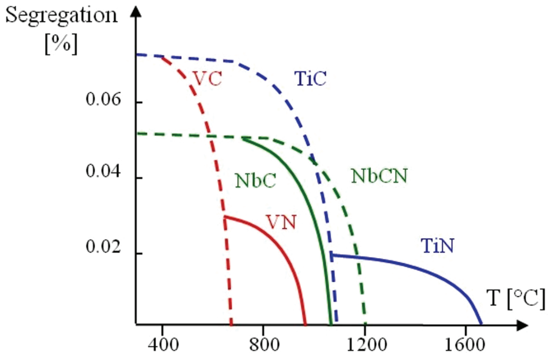

Figure 1: Example for segregation of micro-alloys

ZF steels are a certain group of steels micro-alloyed with vanadium. These steels have got their names from the German firm ZF Friedrichshafen AG, who produces carriers for various vehicles. Basic material of the planetary carrier is steel ZF59, whose conformity criteria (composition, hardenability, strength) are specified and stipulated in standards by this German company [3].

BY treatment of planetary carrier

As for its function, a planetary carrier has to meet high requirements for strength and toughness so that the dynamic loadings developed in the axle should perfectly be withstood.

When the mechanical and microstructure properties to be achieved with ZF59 micro-alloyed steel as per the *standard EN 10083* were adjusted, the precisely controlled cooling has got a very important role.

Basic material was continuously cast, which was important during the technological designing, because reduction ratio is a factor, which affects the forged microstructure. *(Fig. 2)*.

Based on the above, *the most important task was set: to elaborate the bases for BY treatment technology of micro-alloyed steels.*

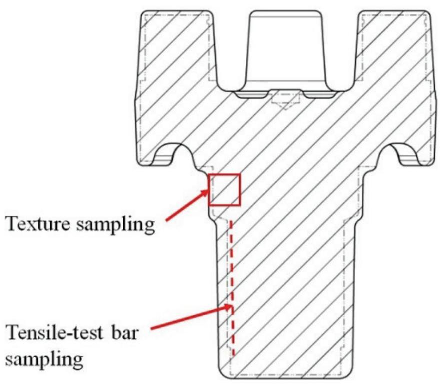

Figure 2: Locations of taking samples to qualification

A strict requirement for the forging process of the micro-alloyed basic material is scheduled production when stable temperature range is assigned to each phase.

In our case, use of cooling equipment was necessary, which stabilized the production capability. When the cooling technology was elaborated, CAD *(Pro/Engineer)*, CAE *(Simufact.forming)* design systems were applied for modeling the cooling process virtually.

The following simplifying assumptions were set for simulation inspections:

- the work piece is homogenous and isotropic
- heat distribution of the heated work piece is even in the whole volume, namely *(using Fourier-Kirchoff relation)*:

$$\dot{q} = -\lambda grad(T) = 0 \qquad (1)$$

where:

$\dot{q}$ - vector of heat flow density (W/m^2)
λ - thermal conductivity (W/mK)
T - temperature distribution (K)

- during the operations, distribution of heat flow is inhomogeneous, which is generated by forming work and cooling conditions:

$$\dot{q} = -\lambda grad(T) \qquad (2)$$

- basically, cooling is a function of heat energy lost by heat radiation *(using Stefan-Boltzmann law)*:

$$E = \sigma_0 \varepsilon \left(\frac{T}{100} \right)^4 \qquad (3)$$

where:

E - heat energy lost by radiation (W/m^2)
σ_0 - heat radiation factor of absolute blackbody (W/m^{2}K^4)
ε - blackness (w/o dimensional unit)
T - absolute temperature of radiating body (K).

Modeling was necessary so that later, during the experiments we could test the process in a well-defined way, primarily for cycle times and surface temperatures belonging to the critical process elements.

The following marginal conditions were stipulated:

- virtual temperature of the basic material (1) 1240 °C
- final temperature of forging on each surface element of the forged geometry is above Ac3 [1]
- the surface assigned for practical measurements is always the surface element of the highest temperature.

According to the simulation, total duration of BY treatment is 3148 seconds [4]. Determinant process elements are finishing of finish-forging in the 59th second and start of intensive cooling in the 148th second. Duration of intensive cooling stage is 1200 seconds with controllable air flow, which has separate parameters.

Temperature of the virtually finish-forged planetary carrier was calibrated on a plain surface, which could be properly measured, in an inspection using thermographic camera. *(Fig. 3)*.

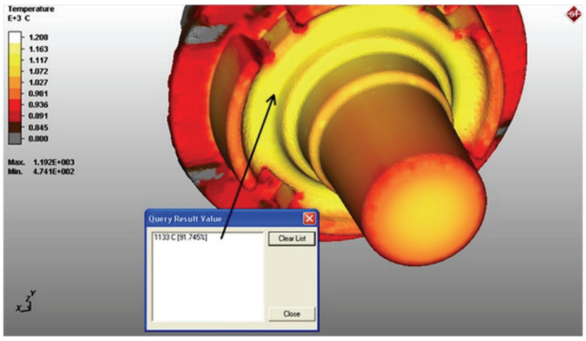

Figure 3: Surface temperature is 1133 °C at a properly measurable location

After practical testing, a more precise simulation was made in thermographic camera inspections *(high resolution VarioCAM thermographic camera)*. With the thermographic camera, the highest surface temperature was 1130.21 °C at the location selected for control measurement and 1080 °C at the sample taking location *(Fig. 4)*.

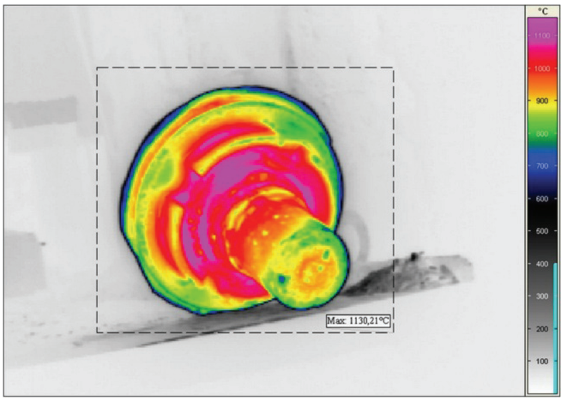

Figure 4: Photo taken with thermographic camera. Emission factor: 0.95

After validating the simulation, *cooling – grain refining* experiments as well as tests of *internal temperature distribution* were carried out [4].

Above 900 °C the effect of TiC grain refiner can be utilized in the finish-forging temperature range of 1000–1070 °C [5]. VN and VC are segregating at or below Ac3 transformation limit [2]. As forming of the planetary carrier requires high energy, our possibilities were limited in terms of the possible lowest temperature that finishes forming.

Cooling – grain refining experiments:

1. With limited austenite overcooling

- from normal (designed) heating temperature (~1240 °C)
    - in air flow, in defined loading order (designed) *(Fig. 5)*
    - without air flow, in defined order *(Fig. 6)*
- from higher heating temperature (~1290 °C)
    - in air flow, in defined loading order
    - without air flow, in defined order.

Figure 5: Planetary carriers cooled in cooling equipment, in air flow

Figure 6: Planetary carriers cooled in quiet air, without air flow

2. With limited austenite overcooling and minimal increase of Ti alloying (Ti 0.033% instead of max. 0.025%) [5]

- from normal (designed) heating temperature (~1240 °C)
    - in air flow (designed)
    - without air flow
- from higher heating temperature (~1290 °C)
    - in air flow
    - without air flow.

Based on the laboratory test results of the experiments we could supplement the determinant process elements of BY treatment with the temperature limits assigned to cycle times.

Process is started in the 0th second of the heated basic material from 1205–1255 °C. Finish-forging is completed in the 59th second, 1040–1080 °C is measured at the sample taking locations (location can easily be measured with manual pyrometer) and intensive cooling is started in the 148th second 1020–1060 °C. In the intensive cooling stage the forging is cooling to 530–570 °C on the measured surface. Speed of cooling equipment was set to 150 mm/min, air blow speed was set to 10 m/sec. Intensive cooling stage works only in the length corresponding to 1200 seconds *(Fig. 7)*.

We should mention that the experiment with increased Ti content, with the volume indicated, did not provide any result.

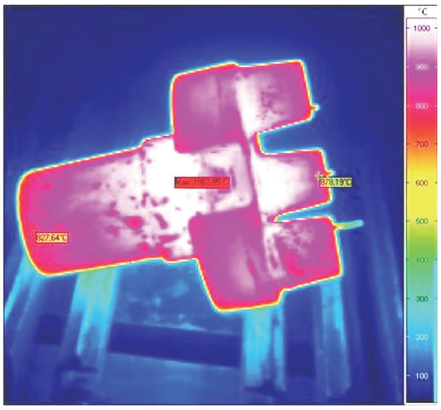

Figure 7: Photo taken by thermographic camera on start of intensive cooling stage. Emission factor: 0.95

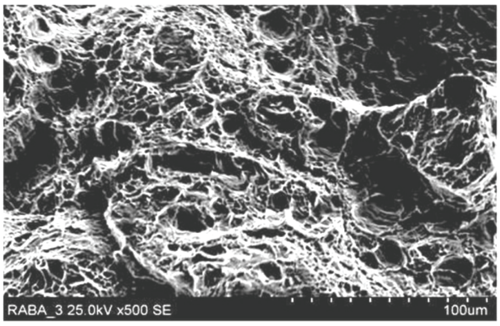

Figure 8: Electron-microscopic photo taken on the fracture

Higher Ti content did not increase significantly the number of TiC crystal nucleuses, however, increased the danger of formation of primary segregation TiN lumps. The electron-microscopic fracture and point analyzing inspections could not detect TiN lumps, however their effect was sensible through nearly 50% decrease of the contraction (Z%) *(Fig. 8).*

The experiments made at increased temperature (~1290 °C) proved the danger of grain coarsening near the surface and the presence of duplex microstructure in the core.

The inspections of *the internal temperature distribution* were primarily aimed at detecting the relationship between hardness distribution, grain size and internal heat distribution. Samples of cooling providing the best result were used in the inspections as the number of TiC crystal nucleuses was very important due to even and fine texture of the microstructure [5].

The inspection has detected that within the planetary carrier there is a heat distribution zone. In this range the microstructure can be made satisfactory to the expectations *(Fig. 9).*

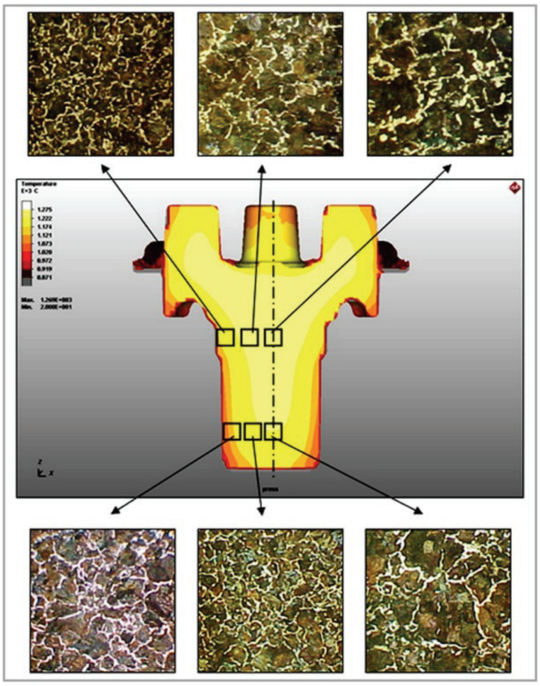

Figure 9: Relationship between the internal heat distribution and the microstructure

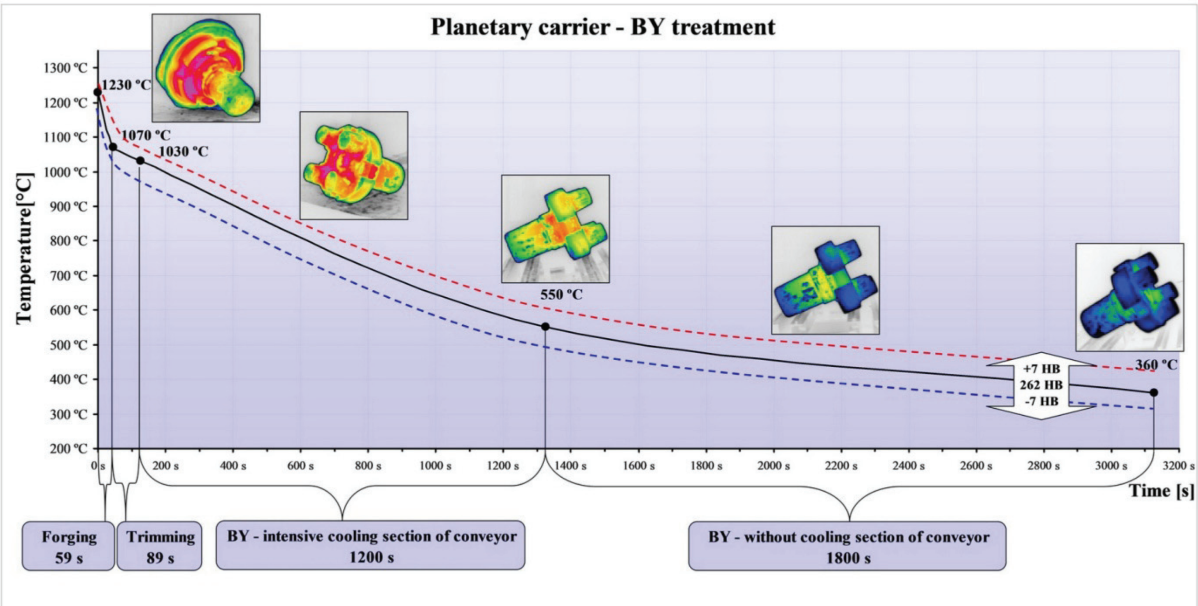

Figure 10: Cooling diagram of planetary carrier

In order to stabilize the microstructure it is practical to widen and optimize this zone in a simulation-directed way [6]. Possible and real means for widening are further grain refining, which is a slight increase (some thousandths) of Al alloying [1, 4], increasing the reduction ratio, introduction of V/Ti > 5 proportion. Until this zone is widened, the elaborated cooling technology shall strictly be kept *(Fig. 10)*.

When the technology shown in the diagram is applied, the temperature measured at the sample taking location meets the expectation. Temperatures measured with manual pyrometer were in the range of 1015–1067 °C. Cooling in air flow provides the possible highest degree of VC and VN segregations through an intensive cooling stage [2].

Monitoring indexes of the process are process capabilities (p_p, p_{pk}) calculated from the results measured in sample taking hardness inspection. The process capability meets the requirement of ±4σ (67 ppm).

Summary, conclusions

The trimmed forging had to be cooled on the cooling equipment, loaded in a defined loading order, in air flow provided by a vent, within a specified period of time. During the controlled cooling a defined *temperature - time program* was run [6] *(Fig. 11)*.

Figure 11: Planetary carriers on BY equipment

The essence of the process is: after forging is finished to cool the planetary carrier still in austenitic condition with a cooling speed, which allows the ferrite-pearlite microstructure and the specified hardness, that corresponds to hardening and tempering by the end of the process. By controlling the speed and the volume of the blown air, the ferrite-pearlite proportion as well as hardness, tensile strength of the microstructure can be varied and adjusted near a value specified within a dimensional range.

In case of larger forgings (due to their sizes), this method cannot be utilized with safety, as due to the high cooling speed as well as the large cross-section some deviations can be detected in the microstructure, near the surface and in the core.

Deviations in the cross-section and their degrees can only be proven in destructive material inspections. The regular surface hardness measurements – in the presence of several disturbing factors (e.g.: surface decarburization) – can only indirectly provide information about the internal microstructure of the forging.

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