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CONTROLLED AUSTEMPERING OF HAMMER FORGINGS AIMED AT PSEUDO NORMALIZED MICROSTRUCTURE DIRECTLY AFTER DEFORMATION

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The study concerns cost-effective realization of controlled thermomechanical processing (CTMP) of medium-carbon and HSLA steel aimed at producing microstructure and properties equivalent to normalized condition directly after forging. The results of theoretical and physical modeling of hot forging with subsequent heat treating adopted for industrial realization in continuous manner were verified in semi-industrial conditions of a forge plant.

Key words: controlled thermomechanical processing, direct cooling, temperature, microstructure, mechanical properties

INTRODUCTION

Accuracy limitations of hot forging processes make some geometry features and close tolerances of impression-die forgings hardly achievable with bulk forming operations. It obviously does not allow forged parts to be quench-hardened directly after forging. Subsequent machining is a restriction against producing excessive hardness in as-forged condition. Therefore, forged parts prior to machining are subject to normalizing [1].

Normalizing annealing is one of the treatments used by forgers or most commonly delivered to constructors ordering semi-products in the form of die-forged parts, next to quench-tempered [2].

One of the rules of cost-effectiveness of the controlled direct cooled process is elimination of reheating. However, no reheating means limited possibility to amend for inhomogeneities in grain size, chemical composition etc. Therefore all differences are inherited by as-forged material. Therefore, while comparing the effects of direct heat treating of drop forged parts the evaluating should not be assessed in terms of accomplishments in relation to conventional process effects, but rather in terms of prevention from deteriorating the microstructure and properties.

To bring desired effects the normalizing annealing must rely on proper initial grain structure of hot deformed material. As a principle, to produce refined, uniformly distributed grain after transformation of the hot-forged material, homogeneous chemical composition, uniform straining conditions, resulting in balanced development of austenite substructure after dynamic recrystallization, are needed as well as uniform cooling conditions in the bulk on cooling.

As far as direct cooling is concerned, it is obvious that none of the above is fulfilled. Variation in deformation history and inherited from forging process temperature gradients in superposition with cooling rate differences in the bulk determine discrepancies occurring in the forged parts. However, proper selection and control of the condition of the as-forged austenite and cooling conditions in critical points of interest, allow obtain microstructure equivalent to normalize-annealed condition.

The presented study not only indicates the dependence of the pseudo-normalized microstructure on CTMP conditions, but also deals with reproducibility of the conditions into industrial practice.

MATERIALS AND METHODS

The idea of the study was to represent the actual industrial process of direct heat treating of drop forgings, depending on annealing for normalized conditions. The experiment involved full scale modeling of controlled cooling directly after forging in order to obtain strain and temperature similarity conditions by realization of the deformation and subsequent cooling in the industrial hammer-forging line and full-size industrial conveyor incorporated into the forging assembly. The test consisted of two parts: 1) laboratory assessment of cooling cycle, and thereby, process parameters producing required cooling rate as well as differences in the cooling rate in selected points in bulk, 2) verification in the industrial conditions with use of the laboratory cooling line Quench-TubeLab [3] installed within the production line.

The steel grades selected for the study were a low carbon Mn alloyed steel S355J0 (DIN St52-3) - designation “A”, and its equivalent microalloyed grade modified with addition of 0,08 % V - designation “B”.

Both laboratory and semi-industrial tests involved the geometry of the elongated part with variable cross-

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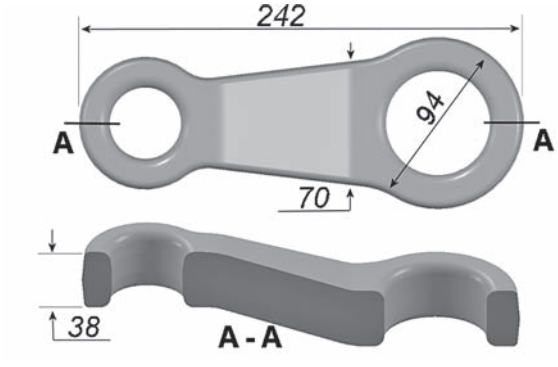

Figure 1 Geometry and dimensions of the processed part

section (Figure 1), the geometry and forging sequence of which are representative of numerous components of machines, automotive, handtools and many other applications. The forging plan included two variants: 1) in accordance with current forging regime - heating up to 1 230 °C, and 2) the modified variant: the forging temperature reduced by 50 °C (Table 1).

Selection of cooling cycle was established based on the forge-finish temperature calculated in code QForm3D with the use of thermo-mechanical coupled simulation, with boundary conditions for finite element modeling (FEM) as well as data on times of machining taken from industrial conditions. In addition to setting proper cooling conditions, within-part gradients of temperature and strain were estimated.

Table 1 **Process variables of the selected austempering cycles**

Process parameters	Variant 1	Variant 2
Heating temp./°C	1 240	1 190
Min. start cooling temp./°C	840	840
Isothermal stop temp./°C	670 ÷ 700	
Isothermal hold temp./°C	730 ÷ 780	
Atomized water pressure	1,5 bar	
Atomized air pressure/atm.	2 bar	

The principle of normalizing annealing is producing uniform austenite and cooling it down to the ferrite-pearlite region with a cooling rate preventing the growth of the transformed grains. In order to enhance grain refinement through the austenite-ferrite transformation efforts were made to design a cooling cycle with repeated transformation in the aftermath of equalizing temperature during properly maintained isothermal hold on cooling. The illustration of the concept is shown in Figure 2, and applied process conditions are shown in Table 1.

RESULTS AND DISCUSSION

Evolution of temperature during forging

Dynamic changes of temperature during hammer forging and resultant gradients do not allow viewing a massive part with variable cross-section as a uniform body. The current process involve 3 free-hand preforming hammer blows, 2 blocker and 1 finisher-die blows. Multiple forging stages call for the analysis of strain and temperature changes in points of the interest. Whereas in the real process only the surface is accessible and the uniformity of the conditions in the bulk can only be evaluated after the complete process, numerical simulation can give light to its evolution. The curves illustrating temperature in different points on a cross-section are plotted in Figure 3. As shown, after initial decrease all the forging stages produce serious increase in temperature due to heat generation under quasi-adiabatic heat exchange conditions.

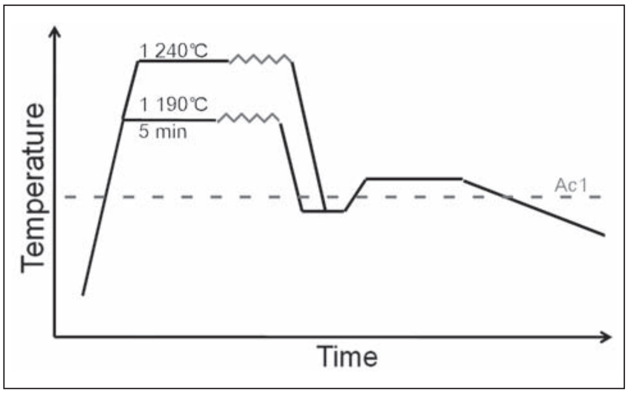

Figure 2 Diagram of austempering treatment designed for direct cooling tests

Design of the austempering schemes

On the basis of the modeling results, cooling schemes were designed knowing the actual run-out table temperature. The plotting of pyrometers' measurements during accelerated cooling selected for semi-industrial tests is shown in Figure 4. To elucidate the expected transformation kinetics, the plots are set together with CTT diagram.

Tests in semi-industrial conditions

Installation of the laboratory cooling line into the industrial process enabled the key stage of the study - repeating the laboratory cycles as a continuation of the forging process. Thus, the full similarity of straining

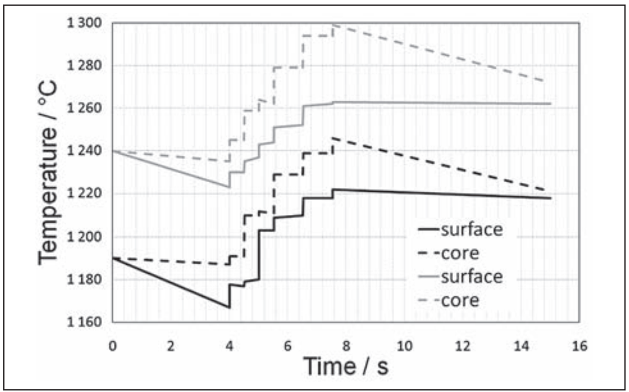

Figure 3 Numerically calculated temperature evolution in consecutive forge operations

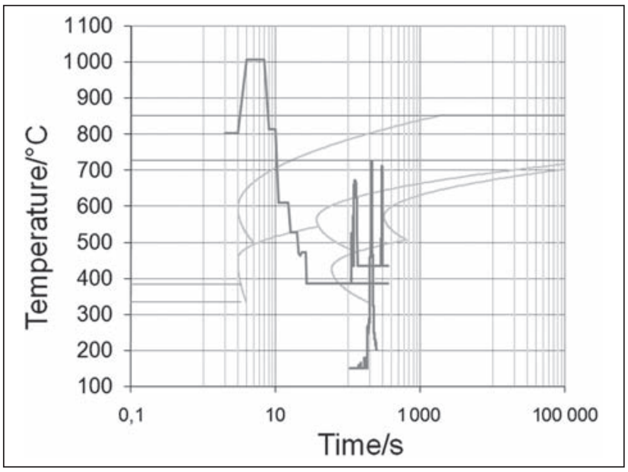

Figure 4 Superposition of physical modeling results for selected austempering cycle with continuous cooling time-temperature (CTT) diagram of steel S355J0

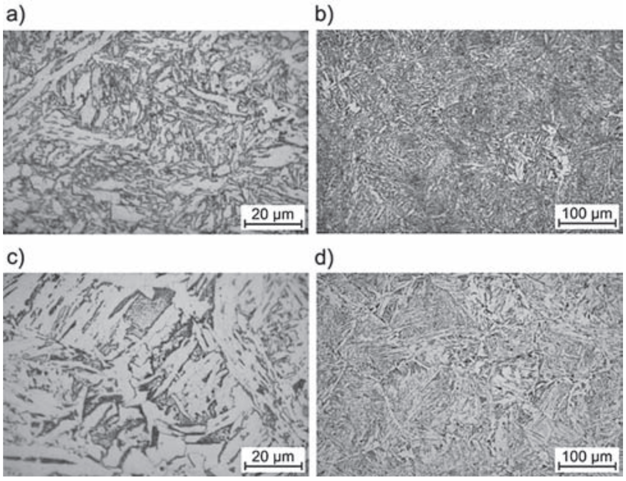

Figure 6 Microstructure of forgings in direct-cooled condition after forging at 1 240 °C, where: a), b) microalloyed steel (steel B) and c), d) conventional steel (steel A)

conditions and temperature was attained. The temperature measurements recorded in continuous mode of action for consecutive parts are shown in Figure 5, where subsequent pyrometers indicate temperature of the surface before and between passing neighboring cooling zones. As can be seen, satisfactory reproducibility and repeatability of the laboratory cycle was achieved; except for differences in indications of pyrometer 1, associated with an inconsistency in measured point due to irregular handling by the forger as well as deliberate changes of forging regime (see Table 1).

Microstructure and mechanical properties

The ultimate estimators of the results of the applied austempering conditions are microstructure and, to a greater extent, mechanical properties. Although it is rarely included among the requirements as for the quality of the forged-heat treated components, the microstructure is used as the indicator of the effect of processing conditions.

The condition of the both steel variations after hammer forging and controlled direct cooling in the manner typical of austempering treatment is shown in Figures 6 and 7, for the two forging temperatures applied, respectively. As expected, the microstructure of microalloyed steel is composed of finer grains than that of conventional grade S355J0. However, which was not so obvious, the ferrite grains produced in microalloyed heat exhibit wide scatter in linear dimensions (Figure 6 c, d), which is the result of restrains in grain boundary migration while dynamic recrystallization, and its kinetics at large strain-rates [4].

In the microstructure observed for plain steel S355J0 (Figure 6 a, b) the grains are less regular and larger sized. Some of them are elongate, which can be the aftermath of overheating resulting in Widmanstaetten ferrite. Too much lesser degree it occurs in the samples forged at reduced temperature (Figure 7 b), which suggest that the lowering temperature, even as slight as 50 grades, improves material homogeneity in plain carbon steel, which can be said by the former austenite grain size. The same can be said of microalloyed grade forged at lower temperature (Figure 7 a), as the regime 1 (1 240 °C) is beyond action of precipitates, which form on subsequent cooling. It is apparent that austempering treatment is effective in the standpoint of grain refinement and strength enhancement, which obviously can be attributed to the effect of precipitates, which are unaffected by normalizing [5].

While the microstructure gives an auxiliary information, the essential estimator of the results of the controlled thermomechanical processing (CTMP) in this

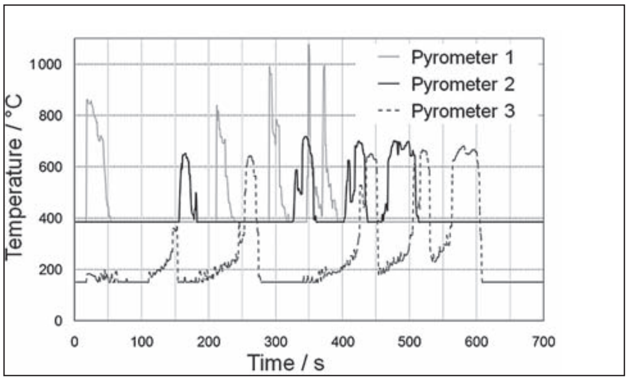

Figure 5 Temperature measured with pyrometers located: at the entry of the cooling line (pyrometer 1), after cooling zone 1 (pyrometer 2), after cooling zone 2 (pyrometer 3) during semi-industrial tests

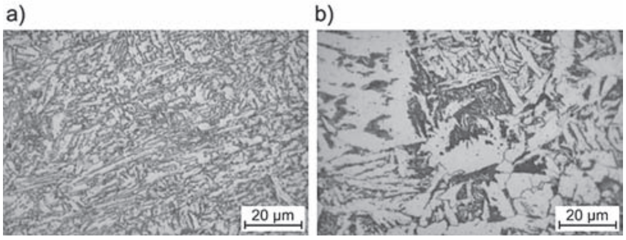

Figure 7 Microstructure of forgings in direct-cooled condition after forging at 1 190 °C, where: a), b) microalloyed steel and conventional steel, respectively

aspect of application are mechanical properties. Comparing the tensile properties of the forged samples (Table 2) the microalloyed grade offers bigger elongation with significant increase in tensile yield stress and strength levels. Both of these indices significantly increase with decreasing deformation temperature, as tensile strength is improved by over 80 MPa. Obviously, all these parameters are second to those obtained by conventional normalizing, however as they are, they meet the requirements towards normalized condition of the forged part concerned. Keeping in mind the fact that most of the components are designed with excessive surplus of cross-section, as well as serious benefits from reduced energy consumption due to successful elimination of reheating in the semi-industrial testing runs, the results can be readily transferrable to many similar items.

Table 2 **Mechanical properties of direct-cooled die forgings**

Sample	*Re* / MPa	*Rm* / MPa	A_{10} / %	*Z* / %	*KV*/ J/cm^2	HV
1A	498	781	20,1	55	36	172
1B	362	565	19,0	63	14	144
2A	532	810	18,1	58	53	190
2B	462	640	20,0	62	16	148
Req. level	-	>580	>13	-	>30	< 187

A_{10} - elongation to fracture, 10-fold gauge base
Z - area reduction at fracture
I - V-notch Charpy impact energy
HV - hardness with loading 5HV

CONCLUSIONS

The presented study indicate possibility of meeting requirements as for the mechanical properties of drop forgings delivered in normalized conditions by means of controlled forging and accelerated controlled cooling with control of heat balance during isothermal hold in transformed ferrite/pearlite region.

The microstructure obtained after controlled thermomechanical processing was composed of irregular ferrite grains, which in case of microalloy grade took on acicular morphology, whereas for plain steel it was needle-like, twice as large linear dimensions.

Application of temperature and pressure of cooling media, as well as times of passing through and holding in the cooling zones enables accurate control of transformation and precipitation kinetics so as to produce satisfactory condition which in case of favourable geometries might replace traditional normalize annealing.

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