CONTROL OF MICROSTRUCTURE-PROPERTY COMBINATION IN MICROALLOY STEEL FORGINGS BY SELECTION OF THERMOMECHANICAL PROCESSING CONDITIONS

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Abstract

The presented study is focused on elaboration of the processing conditions of forging and controlled cooling for medium-carbon steel alloyed with micro additions, so as to meet the requirements of special civil engineering applications. Based on assumption of utilization of the heat attained in the forged part after hot deformation, austempering cycles were investigated so as to meet the microstructure-property combination required by special application. Laboratory tests of thermomechanical processing conditions were designed for different model heats of microalloy steel, were subject to semi-industrial verification in real process of forging. The laboratory investigation was based on the numerical analysis of evolution of strain and temperature in the forging process of the selected part, which provided data for theoretical prediction of the processing conditions. Wide range of microstructure-property combination achieved under different processing conditions, produced strength properties ranging from 620 to 1340 MPa and elongation-at-fracture up to 22 %. One of them, which was found the most proper for the application, was further used for definition of processing conditions of semi-industrial verification in the thermomechanical processing of a complex shape forged part. Thus, in addition to dependence of the material response on austempering conditions, transferability and reproducibility of laboratory tests' results into industrial conditions was studied.

Keywords: Forging, thermomechanical processing, controlled cooling, martempering, grain refinement

1. INTRODUCTION

Increasing requirements for safety indices, as well as regulations tending to reduction of energy consumption bring about technical development of manufacturing processes and emerging of new generations of steels [1]. Although number of advanced high-strength steels groups are developed [2, 3], medium or low carbon microalloy steels are still in favor, where the high strength offered by quenched-tempered steels are in excess of the required end-use requirements. To fit the material for the operational needs, microalloy ferrite-pearlitic appear sufficient to meet load bearing requirements and performance. Synergic conjunction of chemical composition and processing conditions allow wide possibilities of controlling the final microstructure and mechanical properties.

Taking advantage of versatility of structural composition and selection of material-process parameters, controlled processing has been implemented to forging practice and lots of scientific work can be found devoted to thermomechanical controlled processing of microalloy steel forged parts [4, 5]. However, there are still many aspects of controllability of uniformity and transfer of the result into industrial process. The aim of this work is to cope with this problem by means physical simulation of theoretically described and experimentally tested - controlled cooling schedules. In other words, both determination of effect of processing conditions on microstructure and properties and successful implementation of the selected cycles into hammer forging process is addressed, with special care for meeting similarity criteria of forging conditions, cooling rate. Conjunction of the physical model, including simulation in a full-scale model of cooling and reliable model of forged part, and the knowledge of the action of strengthening mechanisms offered by the microalloy elements, available in the analysed steel under defined austempering or martempering conditions, enable comprehensible analysis of the results of thermomechanical processing. Application of full-scale physical modelling, makes semi-industrial physical simulation subsidiary and gives the results more utilitarian aspect.

2. MATERIALS AND METHODS

The goal of the study is design and semi-industrial verification of thermomechanical processing schedules, which involved hot forging and the subsequent cooling realized directly after forging in continuous manner through four sections of the laboratory cooling simulator of the industrial line (**Figure 1**). The processing schedule is comprised of two-stage hot forging and subsequent controlled cooling directly after deformation, maintaining the dwell times and intermediate intervals corresponding to an industrial process of die forging. The forging billet in the form of hot rolled bar was induction heated up to 1190 ºC with 180s soaking. Hot forging process involved two-stage flattening of a rectangular bar with unit reductions on height ε_1 = 40% followed by ε_2 = 50 %, which simulates the industrial sequence of forging, to fulfil strain and strain-rate similarity criteria.

With intent of utilization of heat attained in the forged piece, the cooling methods were designed to reduce the consumption of cooling media and get rid of the conventional quenching installations. The forged samples were conveyed through the cooling line zones facilitated with atomized mist, spray or water nozzles in conjunction with accelerated air of regulated speed. The cooling schedules were designed so as to simulate different course of cooling curved, representing three variants of anisothermal cooling.

With assumption of two methods of cooling - accelerated air produced with vents, and the high dispersion air-atomized spray with provision of water pressure 1.5 bar, aided with the air accelerated to 15 m / s, and two forge temperatures - three processing cycles were designed: 1) continuous cooling with accelerated air, 2 and 3 - discontinuous cooling with interval for isothermal holds, differing in deformation temperature and temperature of the isothermal stop. The controllable isothermal hold was realized by switching off the atomizers, and it was designed to provide conditions for isothermal transformation kinetics with simultaneous stress relieving. To fulfil the production yield controlled by travel speed, isothermal stop required faster conveying speed and faster reaching the isothermal temperature. The process parameters of the applied cooling schedules are conditioned by construction and functionality of the cooling line, as it represents the industrial process restrictions. For example, besides, time and temperature of isothermal hold is multiple period of passing the zone between cooling nozzles. Thus, three different combinations were made up, which could be readily copied into industrial line for implementation, if they turned out proper for final properties, as listed in **Table 1**. As it can be seen, the same cooling rate, difference in run-out table conditions resulted in varied level of the hold.

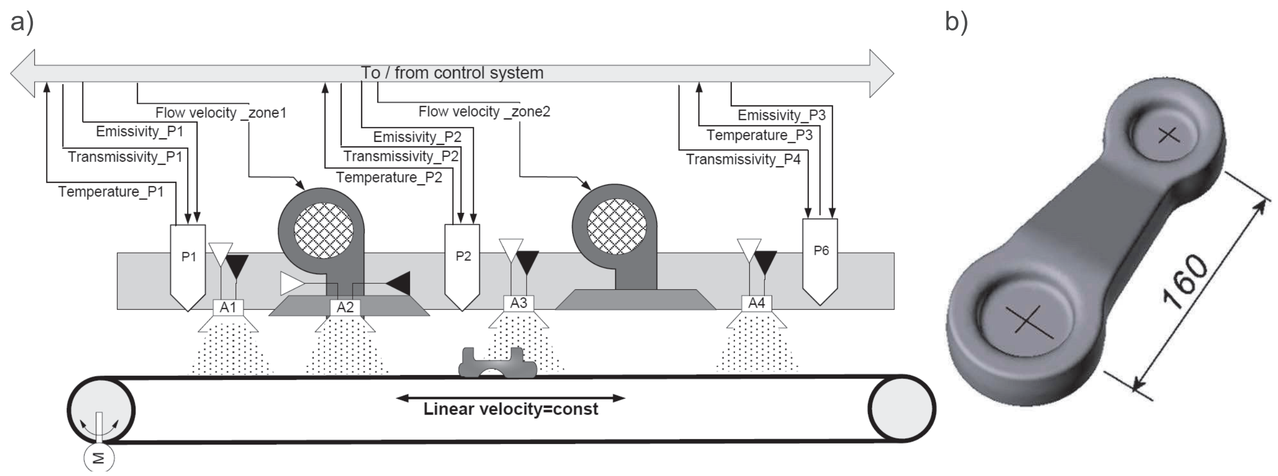

Figure 1 Scheme of the semi-industrial cooling simulator (a), and geometry of specimens: b) geometry of the sample used for industrial verification

Table 1 Parameters of the TMP schedules applied in the experiment

TMP schedule	Cooling medium	Forging 1 end temp. T_1	Forging 2 end temp. T_2	Isothermal hold temp. T_3, °C	Isothermal hold time t_3,	Conveyor speed
Cycle 1	Accelerated air, 45 m / s	1180 - 1190 °C	980 - 1020 °C	-	-	0.4 m / min
Cycle 2	Air 15 m / s + atomized spray		1060 - 1100 °C	520-670	240 s	0.5 m / min
Cycle 3				240-355	240 s	0.5 m / min

Three microalloy steel compositions were used (**Table 2**), representing low- and medium-carbon standard grades with moderate content of microadditions of V+Ti(+Nb), with reduced amount of alloying elements, e.g. Mn or C - designed with an intent of simulating grades featured by good ductility and high-strength, respectively. The experimental alloys are meant to represent cost-effective model of commercial grades such as ferritic-pearlitic steels 38MnSiVS5 or plain C38, C45 (steels A and B) or designed for fan cooling low-carbon C-Mn steels (steel C). Dilatometer analysis in combination with mathematical modelling in TT-Steel software, enabled construction of CTT diagrams, which were used for interpretation of the kinetics of austenite transformation on cooling.

Table 2 Chemical composition of the experimental heats of microalloyed steel

Content	%C	%Mn	%Cr	%Si	%Mo	%Ti	%V	%Nb	%N	Ac_1,°C	Ac_3,°C
Steel A	0.30	1.50	0.42	0.26	0.00	0.011	0.090	0.039	0.011	809	728
Steel B	0.28	1.24	0.42	0.27	0.20	0.019	0.067	0.047	0.010	784.9	727
Steel C	0.097	4.85	0.42	0.34	0.01	0.009	0.000	0.000	0.071	721	854

3. RESULTS

3.1. Physical modelling of CTMP

The first part of the study involved processing of the model-alloy heats under fully controlled laboratory conditions. Superposition of the measured temperature plots with calculated CTT diagrams (**Figure 3**), allow prediction of the transformation kinetics and indicate the expected products of austenite decomposition.

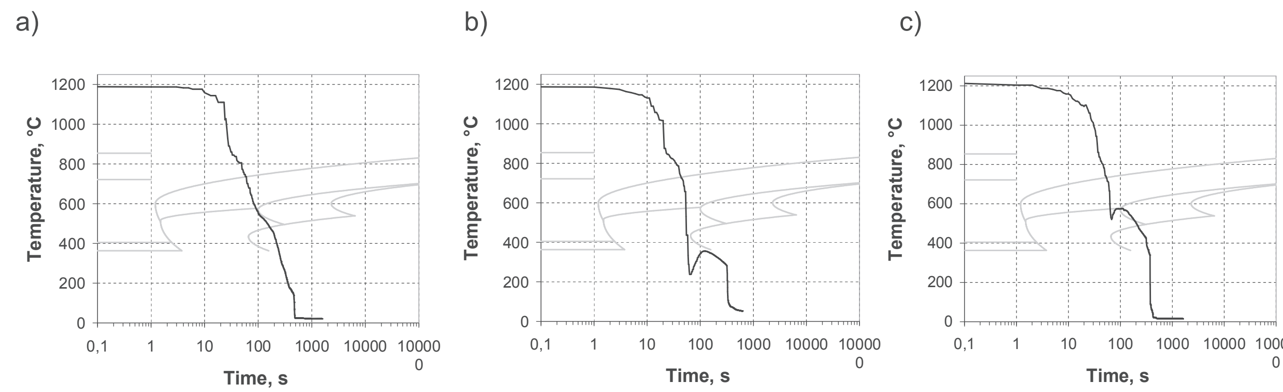

Figure 2 Experimental temperature plots recorded for: a) cycle 1, b-c) cycles 2 and 3, respectively, on the background of CTT diagram of Steel 3

Semi-industrial verification of the designed TMP cycles was realized in forge plant, employing laboratory cooling line adapted to industrial forging line. Selected processing cycles were transferred to industrial conditions for verification on bulk geometry of a real forged part. Progressive succession of cooling zones is reflected in the plots by temperature peaks measured by pyrometers, with online correction of emissivity, attaining reliable indication irrespective of measured temperature [6]. The plots of the recorded temperature changes in time are shown in **Figure 3**. In **Figure 3a**) industrial realization of cycle 1 is shown, and in **Figure 3b)** result of austempering trial is shown. Going along with the idea of cost-saving and assumption of optimizing the redundant strength, no effort of martempering (Cycle 3) was undertaken.

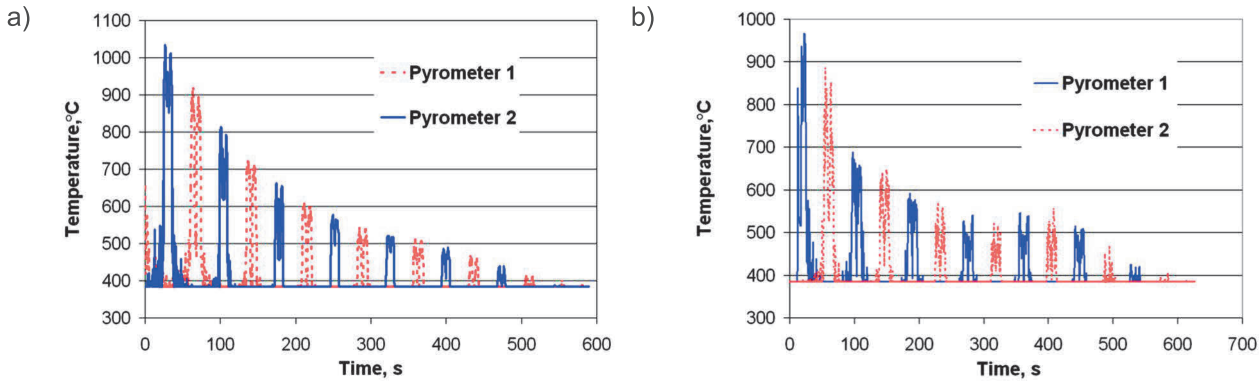

Figure 3 Cooling curves plotted by surface temperature in semi-industrial modeling: a) cycle 1, b) cycle 2

3.2. Mechanical properties and microstructure

Applying presented TMP conditions into drop forging allowed obtain satisfactory properties produced by the multiple-phase microstructures. The cooling rate lower than that of immersion in water, insufficient to omit the diffusion driven transformations resulted in ferrite-pearlite or acicular ferrite microstructure. Isothermal interval on cooling allowed for control of structural components, dependent on the temperature of the isothermal hold, which resulted from forging regime. Thus, forging regime had a double effect on the cooling conditions: firstly, isothermal threshold occurs at adequately higher temperature, and secondly, coarser recrystallized grain was produced, which can be observed comparing 2nd (forged at 1000 °C) and 3rd row (1100 °C) in **Figure 4**. It has a straight connection with mechanical properties (**Table 3**). The samples processed at lower forging temperature exhibit higher strength, in addition to apparent refinement of grain and pearlite colonies (**Figure 4 e, f** and **h, i**) which is bound to improve toughness [7]. Lower hardenability of steel B, resulted in formation of bainite with acicular ferrite, producing combination of good strength and ductility. Air-cooling of medium-carbon samples brought about ferrite microstructure with about 8-13 % of pearlite. Due to lower forging temperature, the ferrite as well as pearlite colonies inherited smaller size than those produced by cooling from 1100 °C, and in the low-carbon alloy, steel C, it obtained the best combination of strength and ductility, meeting requirements towards automotive parts made of BY-treated microalloy steels [6]. In this respect, experimental grades A and B attained higher strength reaching level comparable to hardenability grades, grade AISI 4340, or MS steels, used for crankshafts [8], but contrary to steel C, indicated shortage in elongation, which hardly exceeded 10 %. In evaluation of elongation achieved by steel A or B one must consider the fact that no additional tempering was carried out, while the samples weighing 0.6 kg were not large enough for martempering [9], contrary to what is expected in real applications. Strength properties of steel C can be readily improved by using higher carbon or by decreasing forge-end temperature, maintaining cost-effective processing cycle. It needs to be said that the considerations are based on semi-industrial conditions imposing technical difficulties with implementation of theoretical design, and the limitations resultant from use of employing conveyor-based cooling line. These limitations have little impact on microstructure of the forgings. As shown in **Figure 5**, the ferrite grain in coarser and more inhomogeneous than that obtained in laboratory conditions. The cooling cycle was adapted to ongoing industrial process with no interference into the forging regime. What is more, the final mechanical properties meet the requirements of corresponding standard grades - 38MnSiSV (Steel 1 or 2) or S355J0 (Steel 3)

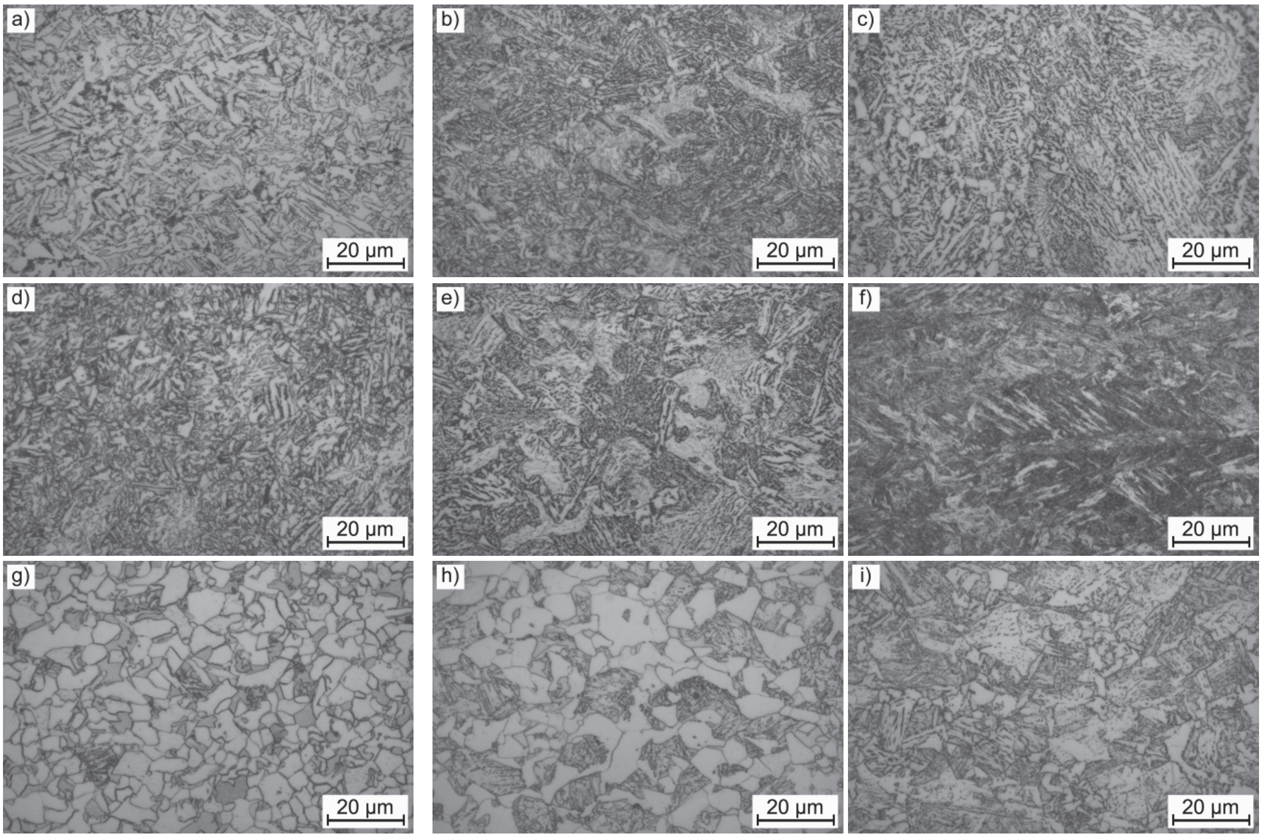

Figure 4 Microstructure of forged and direct-cooled laboratory samples: a) - c) steel A, d)-f) steel B, g)-i) steel C, for treatments: a),d),g) - cycle 1, b),e),h) - cycle 2, and c),f),i) - cycle 3; etched in 5 % nital

Table 3 Mechanical properties obtained in the laboratory tests and semi-industrial verification of CTMP

Steel grade	Forge-end temperature	TMP cycle	TYS, MPa	UTS, MPa	Elongation A_{10}, %	Reduction %	V-notch W, J / cm^2
Laboratory tests							
Steel A	1000 °C	1	683	922	10.0	44	26
	1000 °C	2	715	966	9.9	65	28
	1100 °C	3	663	1306	8.8	14	23
Steel B	1000 °C	1	609	1001	10.5	28	18
	1000 °C	2	1276	1442	5.7	46	21
	1100 °C	3	757	1012	11.0	57	28
Steel C	1000 °C	1	552	744	15.2	63	114
	1000 °C	2	419	750	17.1	58	40
	1100 °C	3	382	670	19.9	56	60
Semi-industrial verification							
Steel A	1060 °C	2	509	807	18.9	54	n.d.
Steel B	1100 °C	2	556	778	15.4	65	n.d.
Steel C	1080 °C	2	532	810	16.1	58	n.d.

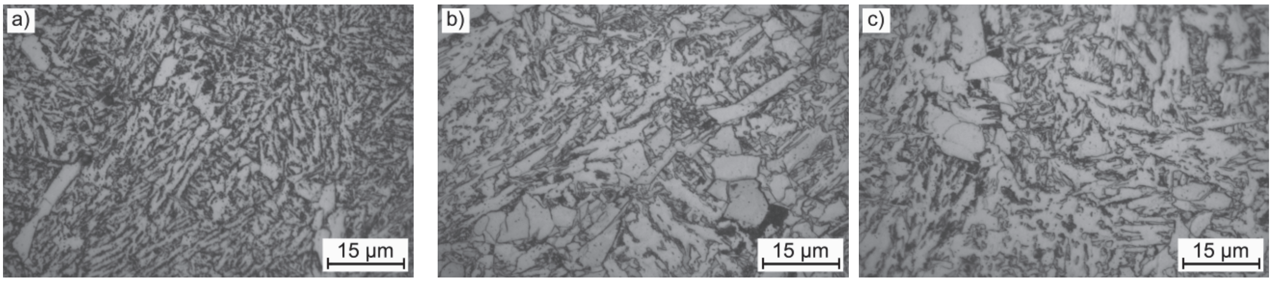

Figure 5 Microstructure in the core of the forged part from Figure 1b obtained for: a) steel A, b) steel B, c) steel C, after austempering (cycle 2) in semi-industrial conditions; etched in 5 % nital

4. CONCLUSIONS

Semi-industrial tests allow formulation of technical consideration for successful implementation of theoretically established and numerically investigated technological design.

Utilization of heat attained in forged parts for controlled TMP with use of accelerated air or atomized spray cooling directly after deformation enables versatile formation of multiple-phase microstructure, offering wide range of strength and ductility.

Proper design and manipulation with the hot forging and direct cooling conditions allow for significant modifications in fraction of structural components and resultant mechanical properties, within narrow and sustainable chemical composition of microalloy steel. In result, sparing alloying elements it is possible to form tailor properties for special applications in a cost-effective cycles of austempering or martempering.

ACKNOWLEDGEMENTS

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