

Effect of thermomechanical processing schedule on microstructure and mechanical properties of ultra high strength steel forgings

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Abstract. The paper presents results of determination and industrial verification of cooling cycles in thermomechanical processing (TMP) of steel AISI 4130, designed to produce good combination of strength and ductility directly after forging and quenching. The results indicate possibility of replacement costly high alloy steels with common grades offering higher strength in combination with good plasticity after cost-effective TMP cycles utilizing blast-air cooling from controlled forge end temperature.

Keywords: *thermomechanical treatment, hot forging, direct cooling, ultra-high strength steel 4130*

Introduction

Increasing requirements towards high-duty automotive, aircraft, military, powerplant components and structures, results in a development of a wide variety of alloy steels so-called advanced high-strength steels. One of the newest generations of advanced steel grades for high performance in severe conditions, are referred to as ultra high-strength steels (UHSS). These steels offer high strength reaching 1500 MPa or more [1], attaining wide range of toughness, wear resistance, crack resistance, impact strength and ductility for sections of any thickness. As these properties depend on high content of alloying elements and their microstructure is generally composed of martensite and bainite, low toughness properties occur, therefore, efforts are made to employ thermomechanical treatment in order to develop procedures for better combination of toughness and other mechanical properties by control of microstructure [1, 2].

Although the equipment and techniques involved do not particularly differ from those used for heat treatment of constructional alloy steels, advanced thermomechanical processing technologies tend to be used, which allow simultaneous use of different strengthening mechanisms, including grain refinement hardening, transformation hardening, as well as, precipitation hardening [4]. For reasons of energy savings attempts are made at application of direct cooling to utilize heat attained in the metal after deformation. This alternative to traditional water or oil quenching is presented in the paper, where application of direct cooling is investigated for drop-forged complex-geometry part with utilization of forced-air velocity control.

The objective of the study was determination and industrial verification of cooling cycles in thermomechanical processing (TMP) of steel with relatively low carbon and other alloying elements, AISI 4130. The high-strength properties, which are typically produced with this steels after quench-tempering are to be obtained with direct-cooling to get directly after forging and quenching, as had been successfully utilized for both microalloy and low alloy steels [5, 6]. The results are expected to indicate possibility of replacement costly high alloy steels with common grades offering good combination of strength and ductility after cost-effective TMP cycles without use of any cooling media by mere control of processing regime and cooling rate.

Methods and procedures

As the realization of TMP cycles involves hot forging and subsequent controlled cooling, there are several degrees of freedom while designing forging and/or cooling regimes for given mixture of structural components and/or grain size of austenite transformation products. The major parameters to control include forging temperature (end of forging), which can be selected knowing characteristic points of steel, and cooling rate on a cross-section. In order to check applicability of blast-air cooling for a massive forged part, instead of small sized specimens, factual-shape automotive part, weighing 1,2 kg was selected as a specimen, shown in Fig. 1a). In result, instead of thermomechanical simulator (eg. Gleeble) the forging was carried out on industrial high-speed machine. It provided significantly bigger specimen to be forged and direct-cooled, simulating industrial cycle.

The study of effect of forging temperature in combination selected cycle of controlled cooling, experimental tests of forced-air cooling were carried out in the laboratory cooling simulator facilitated with automatically controlled fans, producing wide range of cooling rates. Selected forging-cooling schemes have been transferred to forging trials conducted in industrial forging line assembled with the same cooling device, closely described in [6], of which the schematic is shown in Fig. 1b).

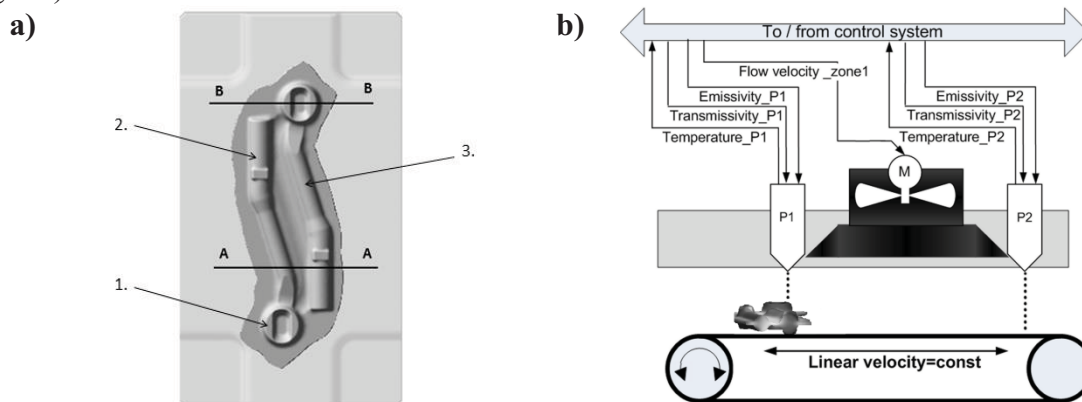


Fig. 1. Models used in experiment: a) forged specimen with location of thermocouples and cross-section of interest, b) schematic of the laboratory simulator of controlled cooling

To trace temperature changes during forging in points corresponding to thermocouples' and tensile specimens' locations, numerical analysis was carried out with use of QForm3D commercial code. Knowing the forge-end temperature direct cooling was simulated.

The experimental part of the study of TMP cooling cycles consisted of two parts: 1) controlled forced air cooling in the laboratory conditions, oriented at plotting curves of temperature versus time for variable forging temperatures and different cooling cycles, and 2) industrial validation of selected schemes of controlled forced-air cooling directly after hot deformation.

Chemical composition of the steel used in the study is presented in Table 1. The research material was received in as-rolled condition, with microstructure as presented in Fig. 2 a).

Table 1.

Chemical composition of steel 4130 used in analysis

Element	C	Si	Mn	Cr	Mo
Content, (wg %)	0,288	0,24	0,51	0,89	0,18

Before tests the material was characterized with metallographic work and dilatometer tests, which allowed estimation of initial grain size and definition of characteristic points of dilatometer curve. These points were further used for verification of calculation of CTT diagram. The calculated CTT diagram was used to illustrate probable kinetics of transformations during direct cooling curves obtained from experiment.

Results of forging simulation

Unlike in traditional forging and Q&T treatment, selection of austenizing temperature for heat treatment does not suffice. The start of cooling point is resultant from the finish forging operation, which in industrial tests is hard to achieve with thermocouple measurement. Hence, the initial condition for cooling process, such as temperature at the finish of forging and strain distribution were estimated by means of numerical simulation with finite element method (FEM). Numerical modeling was carried out with QForm3D commercial code, with assumption of Levanov friction model defined with friction coefficient 0,15 and friction factor 0,4. The rest of the boundary conditions were defined based on the factual industrial process conditions, such as: blow energy of a hammer 16 kJ and tool temperature 200 °C.

For temperature gradients evaluation maps of temperature in the end of forging were used (example in Fig. 2). However, to obtain full information of temperature changes, plots in selected points were made, which provided essential information as for expected cooling-start temperature. Example of such plots are presented in Fig. 3, for the most essential case of forging conditions.

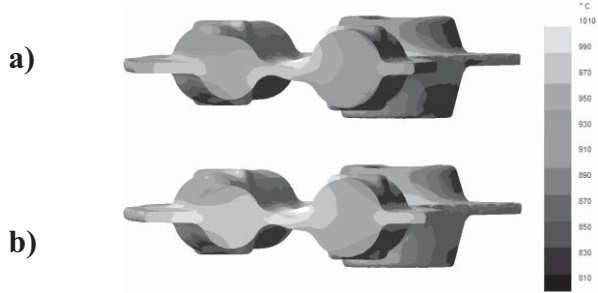


Fig. 2. Temperature gradients at the end of forging in cross-section A-A (in Fig. 1 a) obtained from numerical simulation for forging temperature: a) 950 °C, b) 1050 °C

Results of controlled cooling tests

Direct cooling tests with air-blast were realized in a laboratory simulator of continuous cooling. The reverse movement of conveyor, imitates transfer of forged parts in industrial conditions. At the ends of the conveyor pyrometers P1 and P2 are installed (Fig. 1 b). Consecutive indications on diagrams of cooling recorded come from both of them, interchangeably [5].

In order to reject unsatisfactory processing schedules and select most promising ones, laboratory tests were carried out. Examples of plots of cooling curves from variable temperature are shown in Fig. 4a). In addition to the effect of work temperature, different manners of cooling were involved in the tests. Selected variants are shown in Fig. 4b).

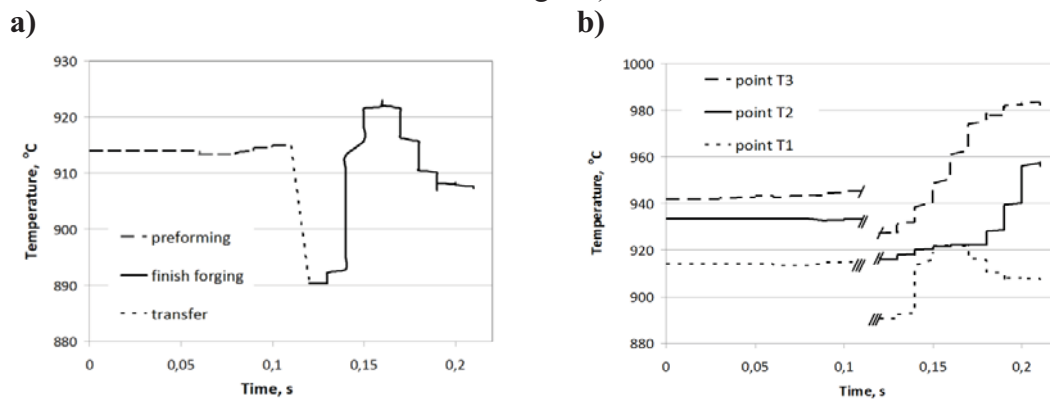


Fig. 3. Plots of calculated temperature changes in the forging process: a) in a selected point – example: point 1, b) plots in different tracking points for one work temperature – example: 950 °C.

On the basis of the laboratory tests forging temperature 1000 °C was selected for subsequent industrial tests. In Fig. 5 the results of pyrometers indications from industrial tests are compared for continuous and isothermal-hold cooling. From the both of the analysed cases specimens were taken for mechanical testing and metallographic work. The results are shown in Fig. 6, comparing results of analysed low-temperature schedules, discussed below.

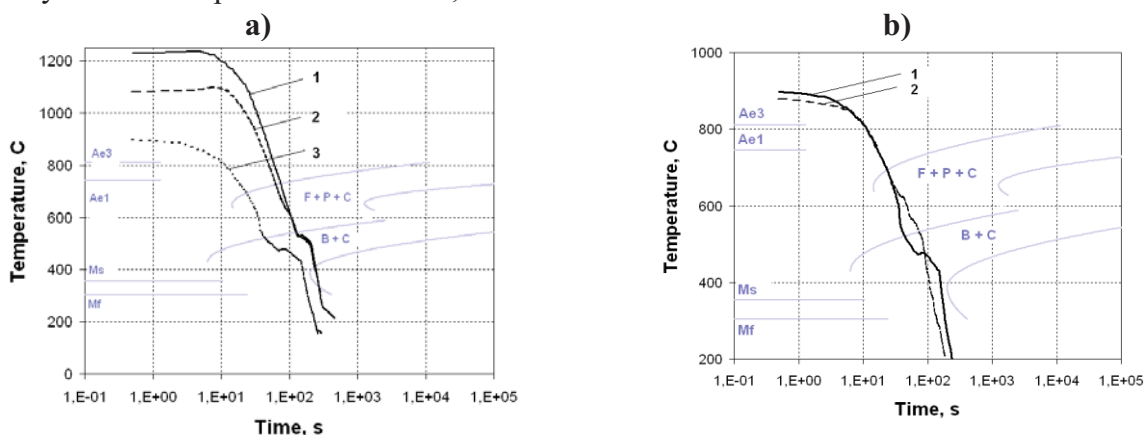


Fig. 4. Plots of physically simulated cooling curves in laboratory conditions, for variable: a) work-end temperature, where 1- 1200 °C, 2 - 1100 °C and 3 - 950 °C, b) cooling schedules: 1- with isothermal hold, 2 – continuous cooling (for one work temperature 950 °C)

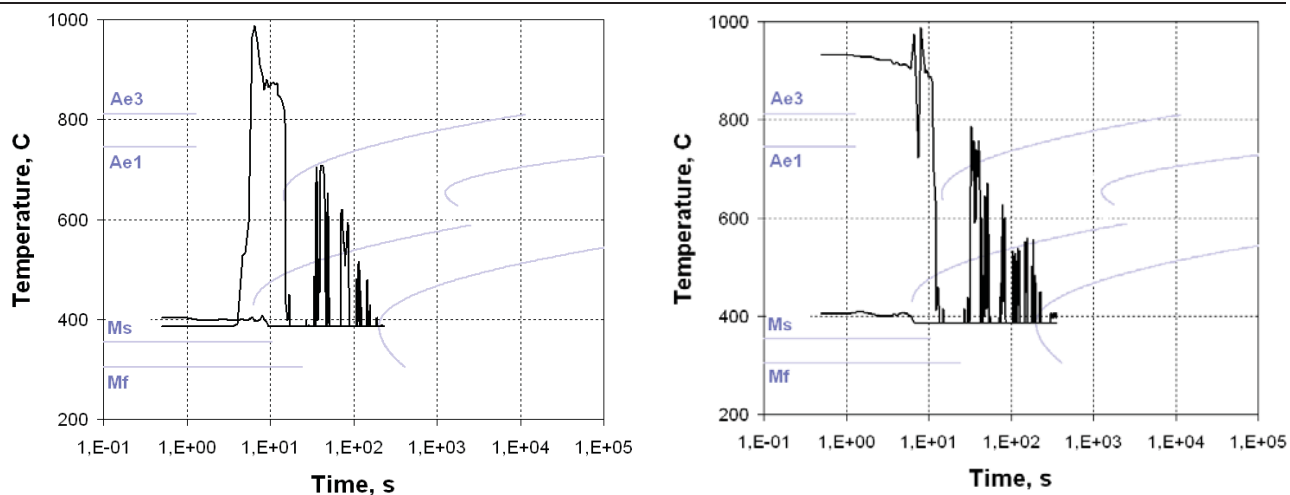


Fig. 5. Plots of pyrometer measurements during direct cooling tests in industrial conditions:
a) continuous cooling, b) continuous cooling with isothermal hold

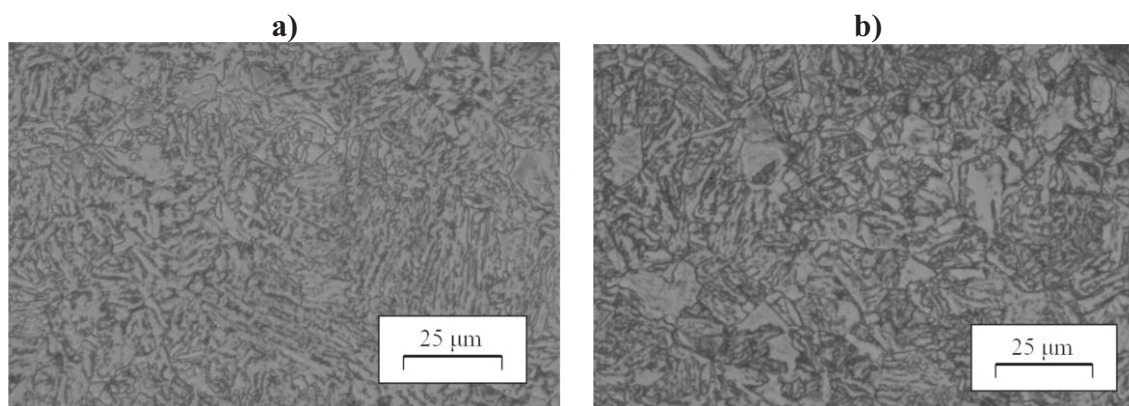


Fig. 6. Microstructures obtained after cooling cycle: a) continuous (plot 1 in Fig. 4b), b) with isothermal hold (plot 2 in Fig. 4b)

The presented study indicates applicability of TMP utilizing direct cooling to low-alloy structural steels to produce good combination of strength and ductility. Results obtained for as-forged steel 4130, which features intermediate hardenability and typically gains its mechanical properties after oil or water quenching, followed by tempering, has sufficient hardenability to attain bainitic or ferritic-bainitic microstructure if air cooled with forced convection of 20 m/s.

Table 2.

Results of mechanical testing (designation as in Fig. 4b)

Cooling variant	UTS [MPa]	TYS [MPa]	Elongation [%]
1	1148	868	6,9
2	1062	791	11,3
As-forged (slow air)	892	648	16,7

Discussion and conclusions

Controlled cooling cycle in combination with control of forge-end temperature provides the steel with uniform fine-grained microstructure. As concluded from direct cooling from variable work temperature, where the best properties were obtained with 20 m/s air-cooling in forging at 950 °C, lowering the forging regime prevents from excessive grain growth after dynamic recrystallization. By optimization of forging temperature in high-speed forging, producing significant amounts of deformation heat, according to dilatometric investigation can be reduced to 950°C. Lower deformation temperature allows for lower transformation point and expected fine-grained bainite or bainite-ferrite microstructure. Fine grained austenite promotes fine-grained mixtures of hard and ductile structural constituents. Controlled cooling with accelerated air offers wide range of possibilities of controlling fractions of transformation products. Continuous cooling schedule results in higher strength bainite, whereas the same cooling rate with isothermal hold produces small frac-

tions of troostite and ferrite, increasing ductility.

Although the obtained results do not take full advantage of control of processing conditions, indicate a kind of guidelines for processing steel 4130, which allow mechanical properties typical of Q&T treatment, such as UTS exceeding 1100 MPa and tensile yield stress over 850 MPa in combination with elongation-to-fracture near 9%. The results can be found encouraging in the light of moderate hardenability of analysed steel and utilization of mere air for cooling schedules. As such, the results show big potential of controlling mechanical properties and microstructure of low alloy steels by means of direct cooling in controlled-processing conditions of thermomechanical schedules.

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Взаимосвязь упругих деформаций четырехвалковой системы при формировании профиля и плоскостности прокатываемых полос

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Аннотация. В статье рассмотрена математическая модель формоизменения полосы при тонколистовой прокатке в четырехвалковой клети. Представлена методика количественной оценки эффекта самовыравнивания вытяжек по ширине полосы.

Ключевые слова: тонколистовая прокатка, четырехвалковая система, самовыравнивание вытяжек по ширине полосы, упругие деформации.

Известно, что четырехвалковая система при прокатке полос испытывает упругие деформации – прогиб рабочих и опорных валков, упругое сближение их осей, сплющивание поверхности рабочих валков в контакте с полосой.

Упругий прогиб осей рабочих валков δS_{np} и их упругое сплющивание в контакте с полосой δS_R являются определяющими для формирования величины выпуклости профиля поперечного сечения прокатываемой полосы δh_1 . Кроме того, на величину выпуклости профиля поперечного сечения влияют станочная профилировка рабочих валков δS_{nf} , а в случае наличия устройств осевого перемещения рабочих валков и величина сдвижки A :

$$\delta h_1 = \delta S_{nf} + \delta S_{np} + \delta S_R + \delta S_A. \quad (1)$$

Станочная профилировка опорных валков влияет на величину выпуклости профиля по-