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DETERMINATION OF DIRECT COOLING CONDITIONS OF UHSS DROP FORGINGS

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Abstract

Results of direct cooling tests of drop forgings made of UHSS steel grade 4130 are presented. The studies include determination of forging and direct cooling conditions in aspect of realization of thermomechanical treatment directly after forging oriented at producing required microstructure and mechanical properties. For estimation of forging temperature and most favourable cycle of cooling, experimental tests of forced-air cooling in laboratory conditions were carried out with application of controlled-cooling line, which unlike the most of the industrial conveyor, is facilitated with automatically controlled system. The results have been implemented into industrial forging cycle, conducted with use of the same portable cooling device. Obtained samples underwent examination with metallographic work and tensile testing, which confirmed possibility of direct cooling with forced air and allowed formulation of guidelines for improvement of effectiveness of the cost-effective thermomechanical treatment.

Key Words: drop forgings, direct cooling, microalloyed steel, ultra-high strength steel

1. INTRODUCTION

Technical development focused on increasing performance with simultaneous reduction in energy consumption results in incessant pursuit of new materials, offering high strength combined with ductility crack resistance and other advantages. To meet the high requirements of high-duty automotive, aircraft, military, powerplant components and structures, from a wide variety of alloy steels so-called advanced high-strength steels have evolved. These include microalloyed, high-strength low-alloyed (HSLA), TRIP steels, designed for increased strength combined with good plasticity and ductility, achieved by means of various thermomechanical treatments.

Another generation of advanced steel grades for high performance in severe conditions, dedicated for higher strengths and thicker sections are ultra high-strength steels (UHSS). As their microstructure is generally composed of martensite and bainite, low toughness properties occurs, therefore, efforts are made to employ thermomechanical treatment in order to develop procedures for obtaining the best combination of toughness and other mechanical properties by careful control of the microstructure [1, 2]. Due to high content of alloying elements and good hardenability they offer high strength reaching 1500 MPa or more [3], attaining wide range of toughness, wear resistance, crack resistance, impact strength and ductility.

After hot forming a wide range of microstructures, such as martensite, bainite, and pearlite-ferrite, acicular ferrite, with or without strengthening precipitates, are produced, which allow superior mechanical properties of the high-duty parts [4]. With ultra high-strength steels, emphasis is placed on the maximum section size that a given alloy will respond to during heat treatment, and thus machining is generally done prior to heat treatment to optimize final property response. The ultrahigh-strength steels ordinarily are quenched and tempered to specific hardness levels, but for critical applications it

may be necessary to pull tensile specimens to ensure that a required combination of strength and ductility has been achieved.

Microstructures and mechanical properties of UHSS parts are closely related to the content of major alloying elements (mainly, manganium, chromium, nickel and molybdenum) and heat treatment cycle employed. From the standpoint of the chemical composition, three groups of UHSS are distinguished, that is, medium-carbon low-alloy steels, medium-alloy air-hardening steels and high-alloy hardenable steels [5]. As a rule, UHSS grades are heat treated by use of equipment and techniques do not particularly differ from those used for heat treatment of constructional alloy steels. However, in order to increase competitiveness the tendency is observed for application of thermomechanical processing technologies, which allow simultaneous use of different strengthening mechanisms, including grain refinement hardening, transformation hardening, as well as, precipitation hardening. On account of energy savings attempts are made at application of direct cooling to utilize heat attained in the metal after deformation. Such 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.

2. OBJECTIVES AND PROCEDURES

The objective of the study was determination of thermomechanical treatment cycles with application of direct cooling after forging made of steel 4130.

At the start of experimental part, the research material was characterized with metallographic work and dilatometric investigation. Estimated grain size and characteristic points were used in estimation of CCT diagram, which was numerically calculated in commercial code TTSteel.

Normalized and heated billets were subject to drop forging tests on a high-speed hydraulic-screw press in the hot work range to a shape shown in Fig. 1. The drop forging sequence involved four stages: 1) flattening, 2) edging, 3) blocker forging and 4) double-blow finisher forging. During the whole cycle temperature was measured with thermocouple mounted in the workpiece 10 mm under the head surface (location T2 in Fig. 1). In addition to this, after completion of forging, the temperature of the surface was measured with a stick-to thermocouple (T1 in Fig. 1). The measured temperature history was used to design favourable direct cooling scheme.

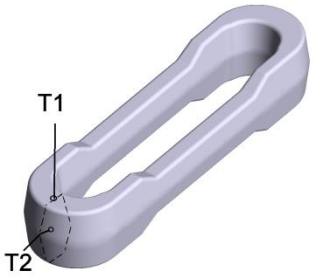
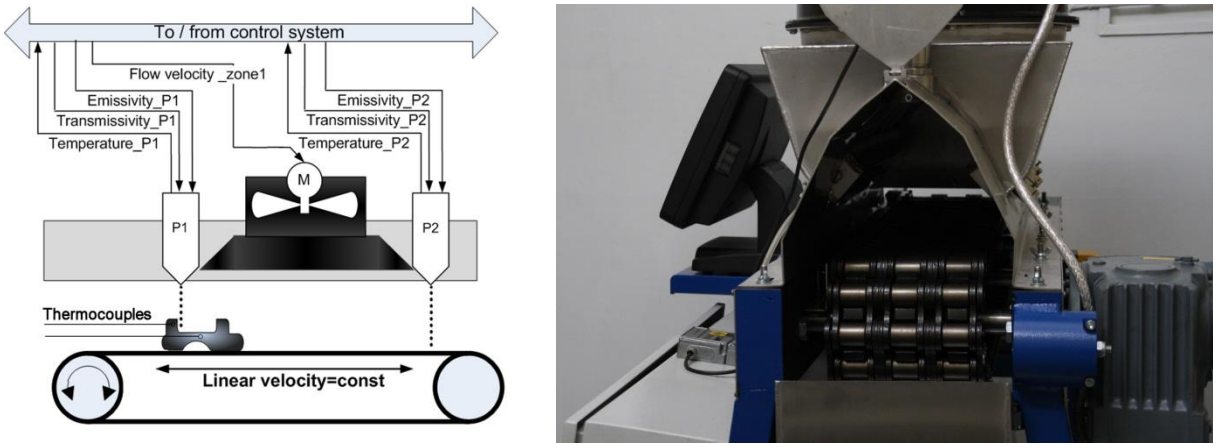


Fig. 1. Geometry of the forged part with location of thermocouples for temperature tracing during forging

Knowing the forge-end temperature direct cooling was simulated. Because of difficulties with formulation and selection of models for numerical modelling of continuous cooling, associated with varying in time character of cooling, as well as correct definition of transformation heat, direct cooling tests were realized with forced air in a laboratory continuous cooling simulator. The schematic of the cooling simulator is shown in Fig. 2 [6]. The simulator is facilitated with reverse movement conveyor, imitating continuous transfer of forged parts in industrial conditions. Between reverses the air flow velocity can be changed, simulating variable cooling rate in consecutive cooling zones of industrial line. At the ends of the conveyor pyrometers P1 and P2 are installed. In addition to pyrometers, thermocouples are available for temperature measurements. The device allows simulation of any cooling cycle sequence attaining resemblance to the action of the industrial cooling line.

The experiment consisted of two stages: 1) modelling in the simulator aimed at correlating cooling conditions with cooling curves' plots on the background of CCT diagram, and 2) industrial experiment at the forge plant assembly, with assumption pre-designed direct cooling conditions.



(a) (b)

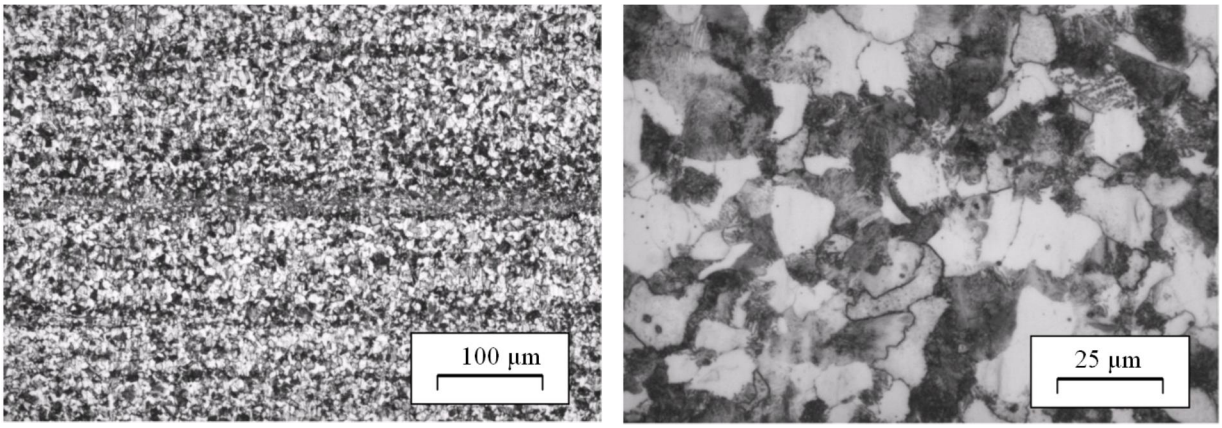
Fig. 2. Simulator of an industrial continuous cooling line: a) scheme, b) side view of the chamber

3. MATERIAL CHARACTERISTICS

The grade used in the study was a very common general purpose grade of medium carbon, Cr-Mo steel, referred to as 4130 (or UNS G41300, AMS 6350, DIN 1.7218). Chemical composition of the steel is presented in Table 1. The research material was received in as-rolled condition, whose microstructure is presented in Fig. 2.

Table 1. chemical composition of analysed steel 4130

Element	C	Si	Mn	Cr	Mo
Content, (weight %)	0,28÷0,30	0,22÷0,24	0,48÷0,52	0,87÷0,92	0,17÷0,19



(a) (b)

Fig. 2. Microstructure of research material in as-received condition at various enlargements

The material in as-received condition was characterized with dilatometric analysis. In result, the following characteristic points were defined:

A_{c1s}: 750°C,

A_{c1f}: 785°C,

A_{c3}: 820°C.

The most probable temperature of chromium carbides dissolution was estimated to 1050°C.

The characteristic points enabled to define the work range for the analysed steel. However, they were not sufficient for design of the direct cooling cycles. Therefore it was necessary to estimate CCT diagram for that steel. The CCT diagrams were calculated with commercial code TTSteel used for numerical modeling of heat treatment and mechanical properties after quenching and tempering [7]. The CCT diagram obtained for analysed steel 4130 on assumption of grain size 30 µm is shown in Fig.3. As it can be seen from the diagram, a very good consistency was obtained in relation to experimental determination of characteristic points. This allows usage of the diagram for further direct cooling design, as well as interpretation of temperature measurement plots and the transformations during cooling.

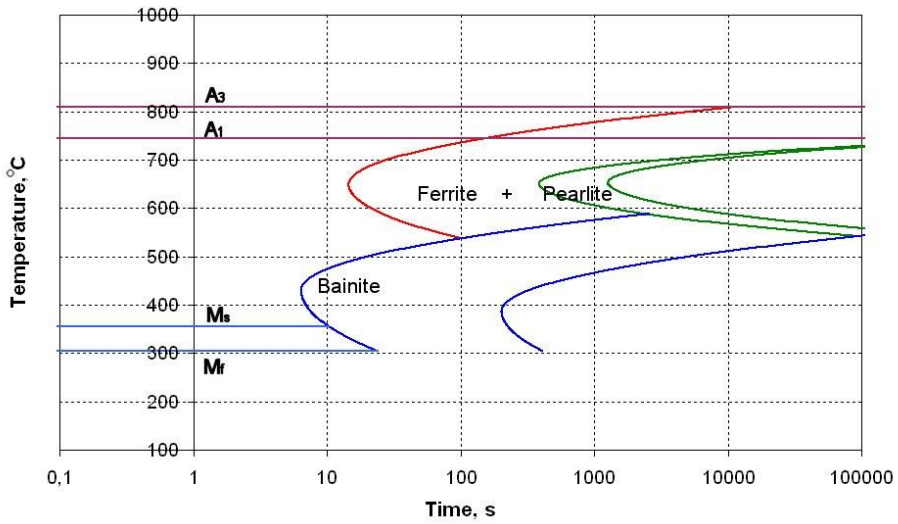


Fig. 3. CCT diagram calculated in program TTSteel for Steel 4130

4. DESIGN OF COOLING CYCLES

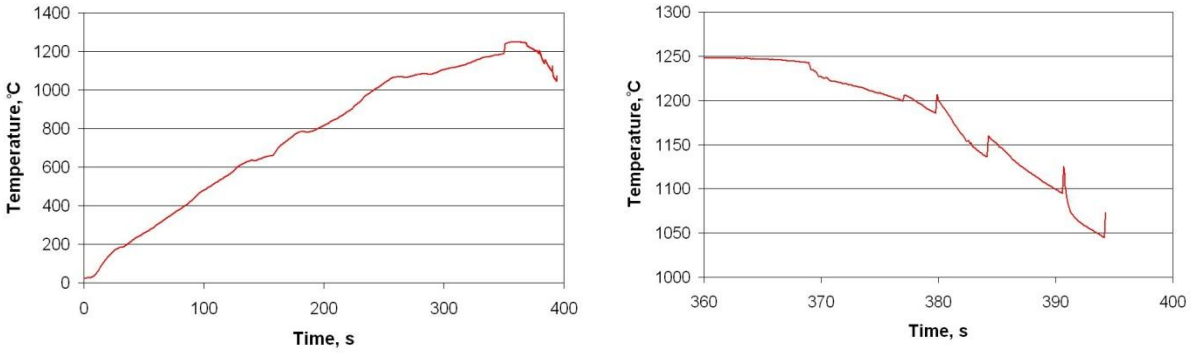
To determine the direct cooling cycles and selection of the most favourable combination of forging temperature, times and cooling rates, resultant from the conveyor and air flow velocities must be based on the knowledge of the end temperature of the finish-forging stage. In order to select forging temperature, thermocouple measurement was recorded, tracing its changes during forging. The results of the measurement are shown in Figure 4 a), illustrating the whole heat-up and forge sequence. For details, in Fig. 4 b) forging sequence is extended. As it can be seen, the thermocouple has covered the whole forging sequence, until finishing blow, however, the cooling needed to be modelled separately.

Above described temperature measurements, especially forge-end temperature, were used for the design of the direct cooling conditions. The background for industrial test was formed by initial trials in laboratory conditions, carried out with controlled cooling simulator, presented in Fig. 2.

Using a sample of exact geometry with thermocouple installed in location T2 (Fig.1), dependence of temperature plots on the cooling rate, varied by changes in forced air velocity. In diagrams obtained in result of the cooling tests, two kind of plots can be observed: a continuous one (red colour), illustrating thermocouple measurements, and impulse-alike plots, obtained from pyrometers at the ends of the cooling zone between consecutive passes. Interesting may be the fact that the surface measurements are higher than those of the undersurface location. Explanation for this can be the difference of cross-section in the locations measured. Thermocouple was located closer to the bottom surface which was in a contact with a conveyor chain, while pyrometers scanned the whole upper surface. Pyrometers enabled measurements down to 380°C, and below that point only thermocouple measurement was available.

The stretch of available cooling rates is determined by maximum (Fig. 5 a) and minimum cooling rate (Fig. 5 c). The highest cooling rate was produced with average 20 m/s air velocity (designed V2), measured with 3 aerometers. The lowest cooling rate resulted from natural slow cooling on air (designed V2). The reference to calculated CCT diagram indicates that the lowest cooling rate should produce ferrite-pearlite structure and perhaps small fraction of bainite. In cooling with the highest speed mostly bainite with fractions of ferrite or acicular ferrite could be expected. In order to prevent from formation of the upper bainite, elongation of the ferrite-pearlite transformation time was

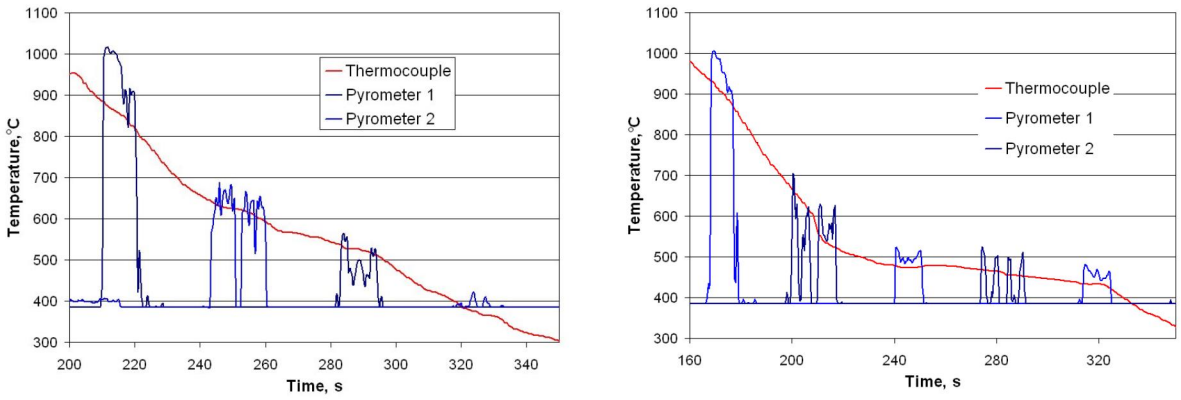
assumed, which was to be realized with a hold in temperature about 600°C, which additionally should provide fine-grained microstructure. In practice it did not fully succeed due to excessive overchill after passing one zone.



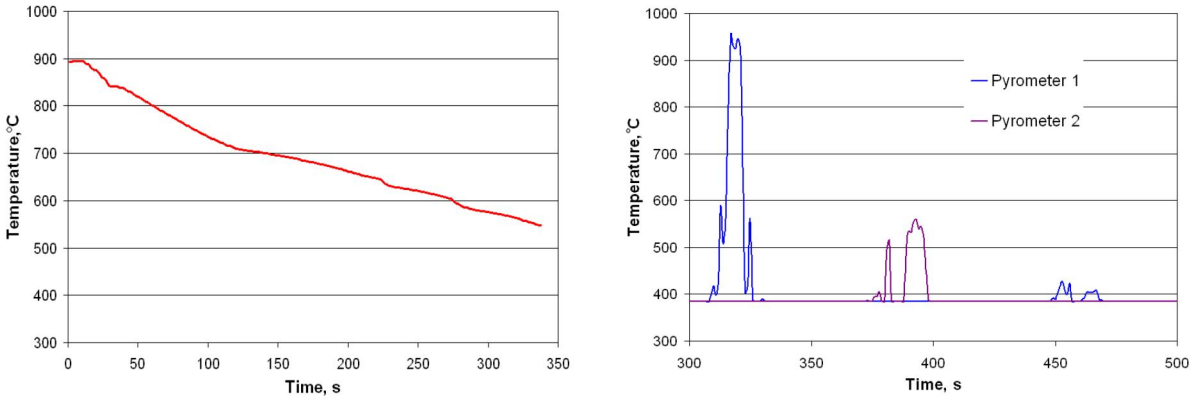
(a) (b)

Fig. 4. Temperature plot recorded during the forging process: a) including heating up, b) during forging operations

Eventually, industrial tests were carried out. The tests were carried out with use of the same equipment installed into the forging chain, to replace traditional annealing and heat treatment. From several variations for industrial tests, conditions used in attempt show in Fig. 5 b) were applied. It was decided to attain highest possible cooling rate in the first stage of transformation of austenite. Due to technical limitations of material transfer no thermocouples were used. The measurements of temperature relied only on the pyrometers indications. As an example, in Fig. 5 d) the plots of temperature measured during realization of variant 3 (V3).

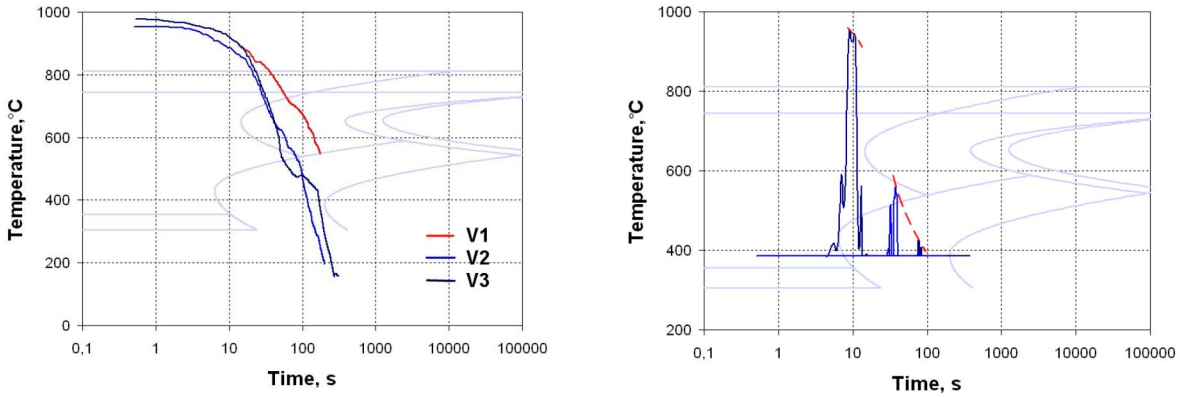


(a) (b)



(c) (d)

Fig. 5. Selected cooling cycles – temperature measured during cooling test in laboratory (a, b, c) and industrial tests (d), where: a) maximum air-cooling rate, b) maximum air-cooling rate with isothermal hold, c) slow air cooling (surface), d) industrial test of direct cooling (maximum air-cooling rate with a hold)



(a) (b)

Fig. 6. Plots of temperature measured: a) during cooling test in laboratory tests in reference to calculated CCT diagram, b) industrial test of direct cooling (maximum air-cooling rate with a hold; the red dashed line indicated approximate cooling rate for the surface)

5. EVALUATION OF THE RESULTS

Evaluation obtained in metallographic work and tensile testing shows significant effect of the cooling rate upon the final microstructure. Microstructures of the specimens taken from forgings cooled with patterns V1, V2 and V3 are shown in Fig. 7. The differences in grain size, as well as, structural components are distinct. In the sample cooled on slow air microstructure is composed of ferrite-

pearlite in a half of relieves' area, and the other one if a bainitic structure with possible amounts of acicular ferrite (Figs 7 a, b).

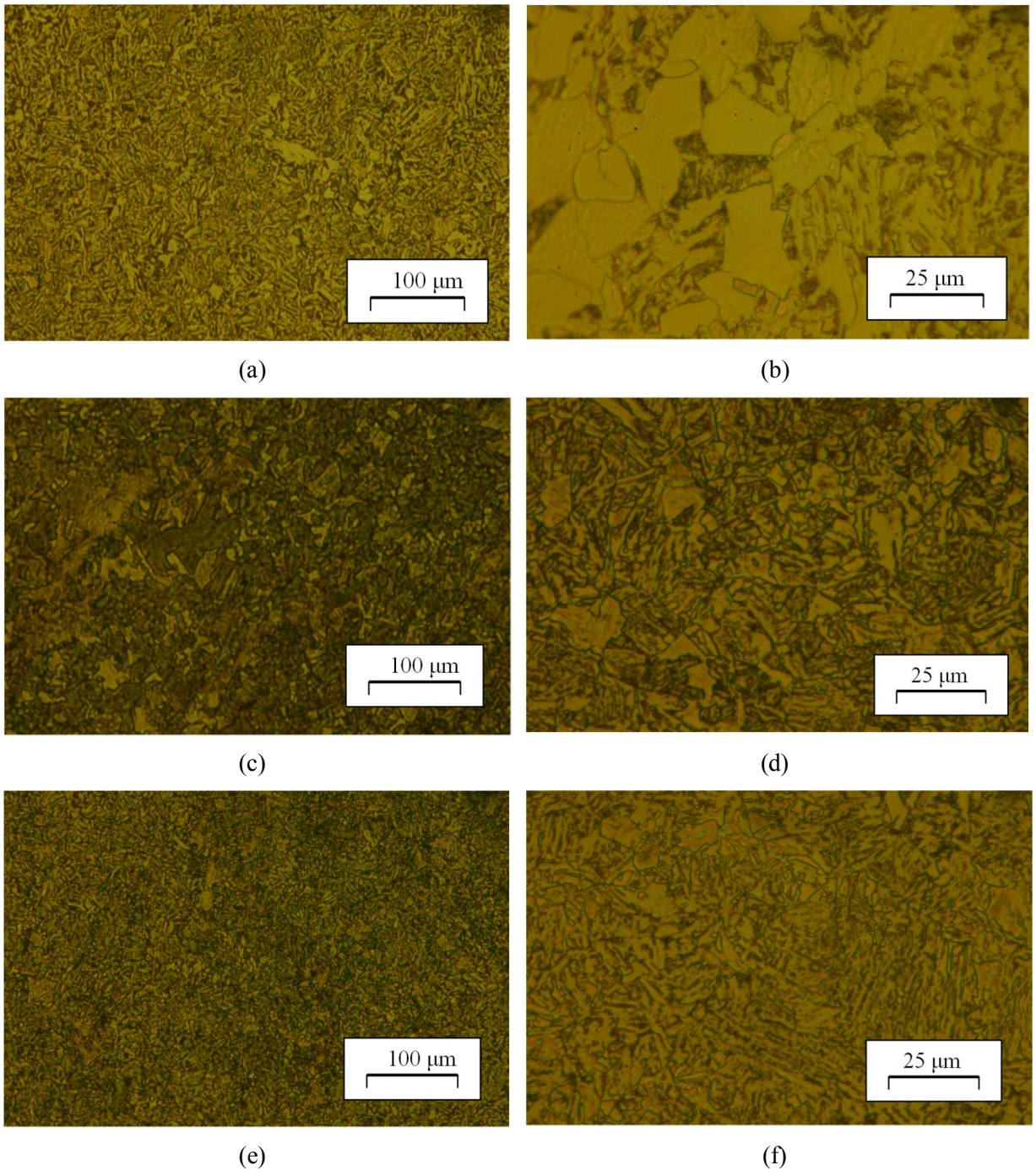


Fig. 7. Microstructure of the direct-cooled forgings with application of cycles: a), b) V1 , c), d) V2, e), f) V3 (maximum air-cooling rate with a hold)

Application of the maximum cooling rate in a continuous manner resulted in significant grain refinement and a microstructure composed of bainite with relatively large (about 20 μm) ferrite grains (Figs. 7 c, d). The same cooling rate with a 120 second isothermal hold also produced fine-grained microstructure of the same composition as V2, however, the grain size is significantly smaller. The differences can be attributed to supposed differences in the forging process. Most probable explanation may be effect of different time of hold in the furnace before forging or not reproducibility of dwell times between forging stages.

For quantitative comparison of the cooling cycle effects, mechanical examination in tensile tests was carried out. Due to dimensional limitations, gauge length of 30 mm was used. The results are summarized in Table 2. As shown, the direct-cooled forged samples with accelerated air velocity, in addition to fine-grained structure, gained higher strength properties. Continuous cooling with high rate (V2) resulted in ultimate tensile strength (UTS) 1114 MPa. Cooling with the same high rate with introduced isothermal hold gave no satisfactory results, producing lower strength, UTS 1006 MPa, and significantly lower elongation-to-fracture.

Table 2. Tensile testing results

Cooling variant	***UTS** [MPa]*	***TYS** [MPa]*	***Elongation** [%]*
V1	932,2	678,4	16,9
V2	1114,5	731,0	14,3
V3	1006,8	704,6	11,7

Obtained levels do not exploit the potential of the material in aspect of both strength level and ductility indices. The achieved UTS levels are lower than those referred in the literature, and only 200 MPa higher than chilled on slow air. Whereas, the latter comparison can result from small cross-sectional dimensions of the processes part, the absolute level of strength do not correspond to those achieved for thicker sections. The reason lies in the forging process. Analysis of temperature changes during forging proves what the micrographs may indicate – forging temperature is was high. In the aftermath, autenite-ferrite transformation point was relatively higher than could be with reduced forging temperature. Taking the dilatometric analysis results into consideration, the temperature could be reduced to 1050 °C with excess. Contribution to unsatisfactory strength could bring nonuniformity of billet microstructure, clearly visible in Fig. 2. Nevertheless, the results get the information as for the mechanical properties achievable in conventional process, without interference into forging regime, if the direct-cooling is applied.

6. CONCLUSIONS

Although the obtained results do not take full advantage of the chemical composition, allow formulation of kind of guidelines for processing steel 4130, which can be summarized in following conclusions:

- Replacement of the traditional quenching heat treatment of steel 4130 can provide ultimate tensile strength exceeding 1100 MPa and tensile yield stress 730 MPa in combination with elongation-to-fracture over 14%.

- Optimization of forging temperature, which according to dilatometric investigation can be reduced to 1050°C, is expected to improve the mechanical properties and microstructure. Lower deformation temperature allows for lower transformation point and expected fine-grained ferrite or acicular ferrite.
- Obtained levels do not exploit the potential of the material in aspect of both strength level and ductility indices. The results get the information as for the mechanical properties achievable in conventional process, without interference into forging regime, if the direct-cooling is applied.

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