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DESIGN OF CONTROLLED PROCESSING CONDITIONS FOR DROP FORGINGS MADE OF MICROALLOY STEEL GRADES FOR MINING INDUSTRY

DOBÓR WARUNKÓW OBRÓBKI CIEPLNOMECHANICZNEJ ODKUWEK MATRYCOWYCH ZE STALI MIKROSTOPOWYCH DLA GÓRNICTWA

Effect of plastic processing and controlled cooling on microstructure and mechanical properties of experimental steel grades with microalloyed with Ti, V and/or Nb, varying in the content of Mo is presented as an offer for mining industry for replacement traditionally heat-treatable hardenability grades. The goal of the work is producing microstructure condition, which after controlled hot forging and direct heat treatment, involving quenching and self-tempering, are meant to provide good combination of mechanical properties, such as TYS 800 MPa, UTS 1050 MPa, elongation to fracture at least A5 15% and/or impact strength at room temperature KCV 60 J/cm^2. Hardenability assessment and dilatometric examination allowed formulation of direct heat treatment guidelines, taking into consideration fields of temperature and strain in a typical hot forging process, estimated numerically, with the use of plastometric tests results, as well as the use of unique cooling cycles after forging.

On the basis of numerical analysis of thermomechanical parameters and temperature progression, hot forging and direct cooling conditions were selected to achieve assumed structural components, morphology and dispersion of both grain and precipitates. For established heat transfer model and experimentally plotted cooling curves numerical analysis of direct cooling, enabled by definition of characteristic points of austenite transformation and CCT diagrams was conducted. The modeling aided with dilatometric characterization enabled prediction of transformation products distribution. The formulated conclusions were verified in the experimental sampling of forging, evaluating the applicability of designed combinations of chemical composition and cooling cycle for selected forged part for mining industry.

Keywords: microalloyed steel, thermomechanical processing, direct cooling, hammer forging, grain control

Przedstawiono badania wpływu warunków odkształcania na gorąco i kontrolowanego chłodzenia na efektywność umocnienia eksperymentalnych stali z mikrododatkami Nb, Ti oraz V o zmiennej zawartości Mo. Pierwszym etapem pracy było zaprojektowanie składów chemicznych stali mikrostopowych, które po kontrolowanym kuciu na gorąco oraz obróbce cieplnej, polegającej na zahartowaniu i samoodpuszczeniu odkuwki bezpośrednio po kuciu, pozwolą na uzyskanie właściwości mechanicznych, tj.: granicy plastyczności 800 MPa, wytrzymałości na rozciąganie 1050 MPa, wydłużeniu A 5 15% i udarności w temperaturze otoczenia KCV 60 J/cm^2. W oparciu o wyniki badań hartowności i analizę dylatometryczną opracowano wytyczne bezpośredniej obróbki cieplnej, uwzględniając obliczenia równowagi faz i wpływ temperatury na udział wydzieleń w wybranych wytopach oraz wyznaczone numerycznie pola temperatur dla typowego procesu kucia na gorąco, oparte o próby plastometryczne na symulatorze Gleeble 3800, oraz kontrolowane chłodzenie po kuciu.

W oparciu numeryczną analizę parametrów termo-mechanicznych i zmian temperatury odkuwki modelowej dobrano warunki procesu kształtowania oraz schematy chłodzenia mgłą oraz przyspieszonym powietrzem, mające zapewnić założony skład strukturalny, morfologię oraz rozdrobnienie ziarna i cząstek umacniających. Na podstawie wyznaczonych punktów charakterystycznych i wykresów CTPc dla opracowanego modelu wymiany ciepła oraz uzyskanych krzywych chłodzenia wykonano analizę numeryczną bezpośredniej obróbki cieplnej, określając udział produktów przemian, podczas anizotermicznego chłodzenia bezpośrednio po kuciu. Wyniki modelowania zweryfikowano w doświadczalnych próbach kucia przeprowadzonych dla wybranych wariantów składu chemicznego i warunków chłodzenia, określając stosowalność opracowanych kombinacji składu chemicznego i obróbki dla wybranej odkuwki dla górnictwa.

1. Introduction

Advances in materials technologies and economical considerations stimulating research and development of cost-effective technologies are expanding into new application branches [1, 2]. After vast number of implementation into manufacturing processes of plastic formed parts for automotive, gas transport, and last but not least, heavy machin-

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ery, way of effective replacing traditional forging-heat treating processes, with a use of high strength low alloy steels (HSLA) are sought for [3, 4]. In order to control the grain structure condition after deformation and subsequent cooling, advanced thermomechanical processing (TMP) technologies are used, which allow simultaneous use of different strengthening mechanisms to achieve best possible combination of strength and ductility. For the energy savings reasons attempts are made to utilize heat attained in the metal after deformation, utilizing direct cooling from deformation-end temperature as a cost-effective alternative to traditional water or oil quenching and subsequent tempering, which sometimes can also be replaced. The required combination of static tensile strength and impact strength properties, superior to those typically provided for these steels after QT treatment, are to be obtained here with TMP employing controlled cooling directly after forging, taking advantage of synergic combination of several strengthening mechanisms, such as austenite grain refinement, austenite transformation and producing fine precipitates, mostly carbides and carbonitrides, on subsequent cooling to control its products fractions and morphology [5, 6, 7, 8]. Assumed energy savings are associated with eradication reheating prior to normalization and quenching as well as the use of blast air instead of cooling media and facilities associated which call for costly installations [9].

The idea of the study depends on application of this process for medium carbon alloy steel containing alloying elements to enable grain size control either during heating up and/or straining or transformation induced grain restoration processes.

Controlled processing of microalloyed steels is well established in stationary processes. TMP tends to prevail also in press forging technologies. Unfortunately, the thermomechanical processing used for high-strength low-alloy (HSLA) steel flat-rolled products cannot be readily transferred to hot forging. Grain growth and precipitate coarsening are rapid at these temperatures and are exacerbated by the mass effect of forgings compared with rolled sections [10].

Geometry-related setbacks are not the only problem to cope with. A serious obstacle in implementation of thermomechanical processing in forging technologies is associated with technological habits of moderate and small forge shops. While TMP calls for a higher culture of managing the process, conventional forging processes are featured by scatter of forging temperature and serious gradients of temperature and strain in the bulk. In result, within-part and piece-to-piece inconsistency and repeatability problems occur, both in press and hammer forging [7, 11].

Controlled processing temperature allows reducing the effect of excessive exposition to elevated temperatures of a portion of a hammer forged part, while the other is incremental preformed. To do so, the forging is directed so as to finish shaping as close as possible to recrystallization temperature. Microadditions of elements forming fine precipitates of carbides and carbonitrides help in control as-forged microstructure and can diminish detrimental effects of nonuniformities. Fine dispersive products of Ti, V and Nb precipitation slows down recovery and metadynamic recrystallization [10, 12] as well as, matrix-particle interface can form additional privileged spots for new grain nucleation [9]. This feature can be advantageous in hammer forging processes, characterized by high values of Zener-Holomon parameter (high strain rates and low temperature), favoring selective deformation and discontinuous recrystallization, which result in inhomogeneity of deformation and grain structure of low stacking fault energy alloys [13, 14].

The idea of the study concerns employing controlled processing conditions for hammer forging process, taking advantage of action of carbides, nitrides and carbonitrides precipitating prior to, during and after high-strain rate hot deformation, to assess controllability of microstructure and versatility of mechanical properties produced in conditions typical of hammer forging with utilization of cost-effective cooling directly from selected forge-end temperature. Slight modification of common medium carbon low alloy grades with microalloys is bound to meet the requirements towards forgings of mining applications if appropriate TMP schedule is provided.

2. Materials and methods

On the basis of final properties requirements, chemical compositions of HSLA steels were proposed, obtained by modification of standard medium carbon steel grades commonly used for heat-treatment hardened forgings. Starting with numerical calculation of volume fraction phase constituents in Thermocalc, chemical composition of low/ medium-carbon microalloyed steels with V, Nb and Ti were designed for experimental heats. On the basis of phase equilibrium calculation, the effect of temperature on stability and content of phases and precipitates was determined. Ingots weighing about 100 kg were hot rolled to break down cast structure and get cross-section of forging billet and processed in variable conditions of hot forging and controlled direct cooling.

Thermomechanical treatment of the specimens cut out from as-received bars involved heating up to 1180°C, soaing up for 10 minutes and cooling down to forge-start point. In forging tests, conducted on a hydraulic press of capacity 5 MN at working speed 20 mm/s, which for flat billet resulted in strain rate corresponding to its average level observed during soft blows of hammer forging of the part concerned, forged specimens of square cross-section 30×30 mm were deformed with true strain 0,48. After hot deformation the specimens were subject to controlled cooling with accelerated air with and without mist, varying increased cooling rate, realized in a laboratory controlled cooling simulator, an extended version the forced-air based cooling conveyor [15, 16]. On the basis of thermocouple measurements cooling curves were plotted. These were used for modeling of transformation of austenite on direct cooling, for which CTP diagrams were calculated in TTSteel software based on additivity rule and finite element method [17, 18], validated with dilatomerically established characteristic points. Specimens derived from the samples were examined in metallographic work and tension tests. Tension tests were conducted on Zwick/Roell Z250 testing machine at velocity 3 mm/min. on specimens of diameter 3 mm, gauge length 30 mm, with a use of 15 mm extensometer.

The research was oriented at implementation into actual forging technology of a hammer forged part (Figure 1). To define actual hot deformation conditions during the laboratory test and predicted thermo-mechanical conditions and energy-load parameters of target industrial process, numerical modeling of forging was conducted in code QForm3Dv7.2, successfully used in simulation of complex forging technologies [19, 20], based on finite element method. Rigid-plastic model of the deformable body was assumed and Levanov friction model. Rheological behaviour was described on a basis of compression tests carried out on Gleeble 3800 corrected with inverse method [21, 22].

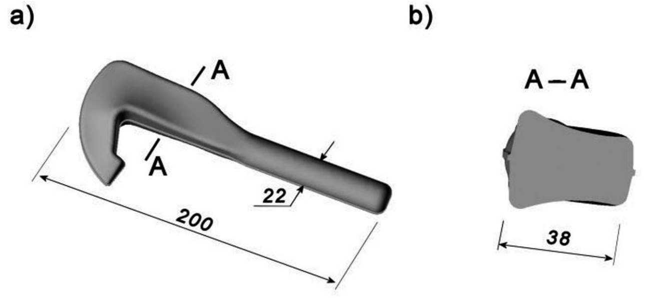


Fig. 1. Example of the target application of the designed experimental steels and treatments

2.1. Industrial considerations

The elaborated chemical compositions are designed for application of direct cooled impression-die forgings for typical products, e.i. hooks, joints, bolts, anchors, forks etc., in hot forging operations. Forging operations can be realized on presses and press-alike equipment and, due to more liberal energy restrictions, on hammers. The latter makes implementation of the DC-based TMT process even harder. Mechanical and phenomenological response of high-strain-rate deformed steel and gradients of temperature and typically nonuniform distribution of strain vary forge-end (cooling-start) temperature between locations and diversifies initial microstructure condition. Therefore, applicability of the steel-treatment combination must be considered individually at least for comparable shape-weight coefficients. Here, it is evaluated from the standpoint of a part representative of hook-type geometry group – screw-hook (Figure 1), currently made of plain carbon steel subject to traditional quenching-tempering (QT) sequence. The forging technology of this part is shown in Figure 2, where major stages are depicted.

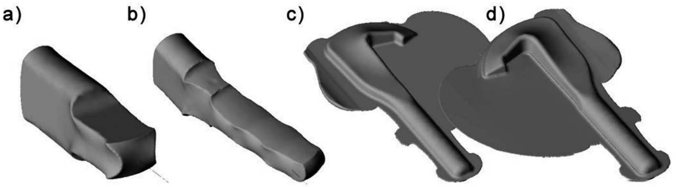


Fig. 2. Major stages of the industrial forge sequence: a) flattening, b) cogging, c) blocker impression, d) finisher impression

By means of numerical simulation and pyrometer measurements temperature changes and thermo-mechanical parameters of deformed steel could be defined. Distribution of effective strain on the axial cross-section of the part is shown in Figure 3 in selected forging operations.

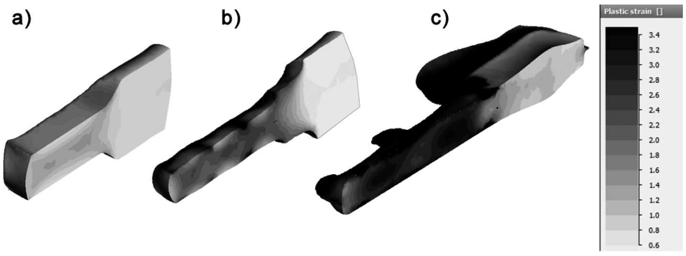


Fig. 3. Progression of effective strain distribution in selected stages of forging

Its values in the point of interest, along with temperature, are set together in Table 1. As it can be seen, after initial strain, the region concerned remains unaffected by deformation while the shaft is being shaped, reaching its strain level in very last operations, just before quenching.

TABLE 1

Analysis of thermo-mechanical conditions in the forged part in the hook section

Operation	Flattening	Drawing out	Cogging	Blocker forging	Finisher forging
End temperature	1124°C	1108°C	1096°C	1112°C	1095°C
Effective strain	0.62	0.62	0.62	1.15	1.18

3. Results

3.1. Material design and characterization

One of the most important issues playing role in convincing the forgers to implement advanced kinds of controlled processing is offering versatile solutions with possibility of wide range of operational properties to be obtained. It applies both to the equipment systems and to materials used. As the forge plant most readily rely on as least as possible number of steel grades used, versatile chemical compositions are sought for to enable as wide as possible variety of structural components and mechanical properties. In this light, the presented efforts concern replacement of medium carbon steels, such as C45, which prevail in QT condition in service.

Among proposed combinations of chemistry, two grades were selected, made up on the resemblance to commonly known 30MnVS6, but with modified content of minor alloying elements, e.i. Nb and Ti, listed in Table 2. Main assumptions of the designed compositions were proper hardenability and possibility of the grain control during heating up, hot deformation and subsequent cooling, where it is also supposed to bring about precipitation hardening. To enable lower forging, carbon and substitute elements content was reduced to minimum offering cracking resistance and hardenability required to complete post forging actions, before essential cooling treatment is commenced. Both of the alloys studied have similar composition, differing in Mo addition in Steel 2 for plasticity enhancement. Owing to Mo presence, Mn could be slightly reduced, maintaining hardenability comparable to Steel A.

TABLE 2

Chemical composition of experimental heats of microalloy steels used in the study

Steel	%C	%Mn	%Cr	%Si	%Mo	%Ti	%V	%Nb	%N	Ac$_1$, °C	Ac$_3$, °C
A	0,30	1,50	0,42	0,26	0	0,011	0,09	0,039	0,011	809	784,9
B	0,28	1,24	0,42	0,27	0,2	0,019	0,067	0,047	0,010	728	727

For the designed compositions volume fraction of phases and precipitates in function of temperature were calculated with code Thermocalc. The results are presented in Figure 4.

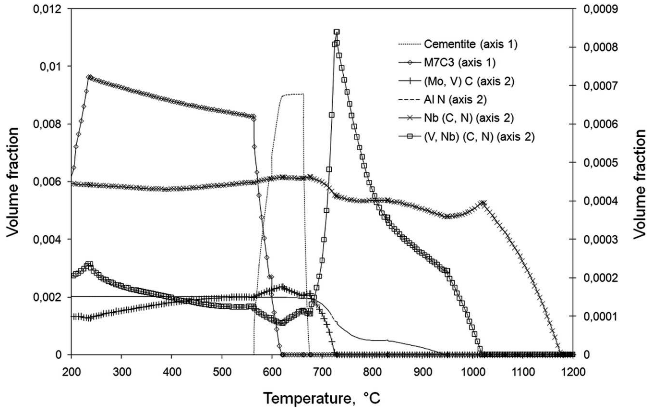


Fig. 4. Calculated volume fraction of precipitates in steel B in equilibrium condition

The slight differences between the two steels are reflected by insignificant difference of precipitates stability ranges and their volume fractions.

As the equilibrium conditions differ from thermodynamics of accelerated cooling processes, for the needs of modeling of transformation decomposition products and design of direct cooling cycles, thermal analysis with dilatometer was carried out to establish characteristic points of the steels. In heating with a rate of 2°C/s A$_{c1}$ and A$_{c3}$ were determined. and used further on for validation of CTP diagrams. The diagrams were elaborated by means of multiple regression in software TTSteel, with corrections of characteristic times and temperatures on the strength of formulas proposed by Bhadesia et al. [23], presented in the background of Figures 7 c) and d).

In order to characterize the rheological behavior of the alloys and to enable numerical calculation of the metal flow, strain-stress curves were elaborated in compression tests. The temperature range of hot compression tests covered the temperatures and strain rates predicted for experiment, 5 s^{-1} to 50 s^{-1} at 850÷1150°C. The obtained stress-strain curves are shown in Figure 5.

3.2. Hot forging and controlled cooling

Physical modeling of the forging process involved compression in flat dies with use of high strain rate. Modeling concerned only the final stage of forging the most critical section of screw-hook in the – the hook (section A – A in Figure 1b). Specimen geometry and forging schedule was determined on the basis of analysis of the industrial sequence of analysed technology. Despite incremental-alike character of forging this part, which should suggest simulation by continuous cooling deformation, one can notice that the hook alone undergoes double reduction: in the beginning while flattening, and only in blocker impression (coining character of finish forging actually do not affect total strain). Hence, simple compression of a 25 mm high flat bar as the model is justified. The forging tests were intended to reflect industrial considerations, both of forging and direct cooling. Therefore, after hot deformation material was held about 5 s to be transferred to the cooling device, as to simulate trimming operation. Having passed 800÷500°C range, the cooling rate was slowed down, producing a kind of an equalizing hold (Figure 6b and Figures 7 c,d), reducing thermal stresses on one hand, and time provision for Nb carbides precipitation [3].

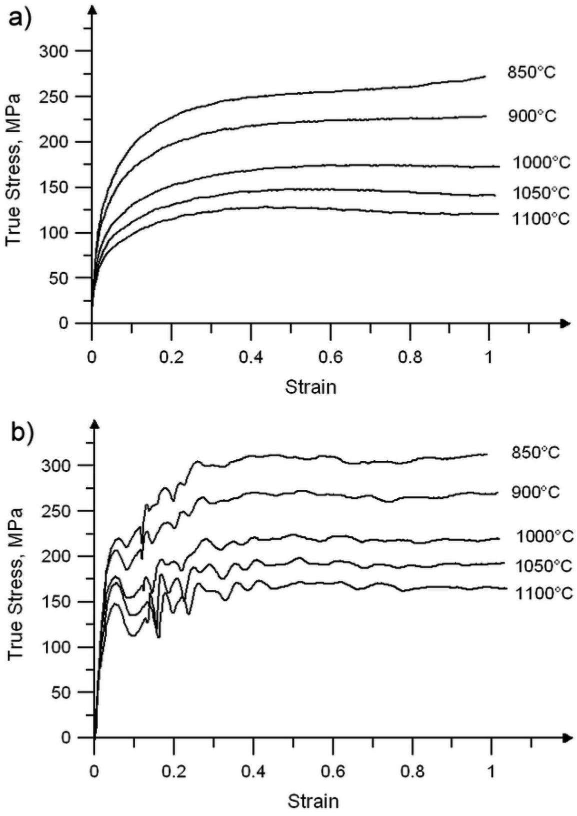


Fig. 5. Inverse-method corrected strain-stress curves derived from uni-axial compression tests for temperature: a) 5s^{-1}, b) 50s^{-1}

Knowing the strong effect of temperature on the kinetics of precipitation of strengthening particles as well as on the strengthening efficiency, resulting from their quantity and dispersion, variable forging temperature was used (Figure 6a). In each run, the same cooling conditions were imposed, however, slightly differentiated by random effect of the cooling system inertia. Aware that the deformation temperature should be high enough to avoid deformation induced ferrite transformation and cooling rate after deformation should be rapid enough to avoid ferrite precipitation during subsequent cooling stage after deformation [24], the lowest forging temperature 900°C was selected, which due to material transfer and die-chill was 880°C. The experiment conducted showed that the deformation temperature is high enough to avoid ferrite nucleation, which adversely affects strength properties [14, 25].

Obtained cooling curves are shown in Figures 7 a) and b), for steels A and B, respectively. For clarity, the plots are shifted between one another and the moment of deformation is indicated by plotting the forging load recorded (gray color). It is also the opportunity to observe unexpected dependence for Steel B of the load extreme on temperature, which at 1100°C exhibits higher straining resistance than at 1000°C. Presumably highest load at 900°C implies no occurrence of ferrite dynamic precipitation.

The kinetics of overcooled austenite was depicted with superposing the physical cooling curves onto calculated CTP diagrams (Figure 7 c) and d). From the analysis martensite-bainite microstructure can be predicted.

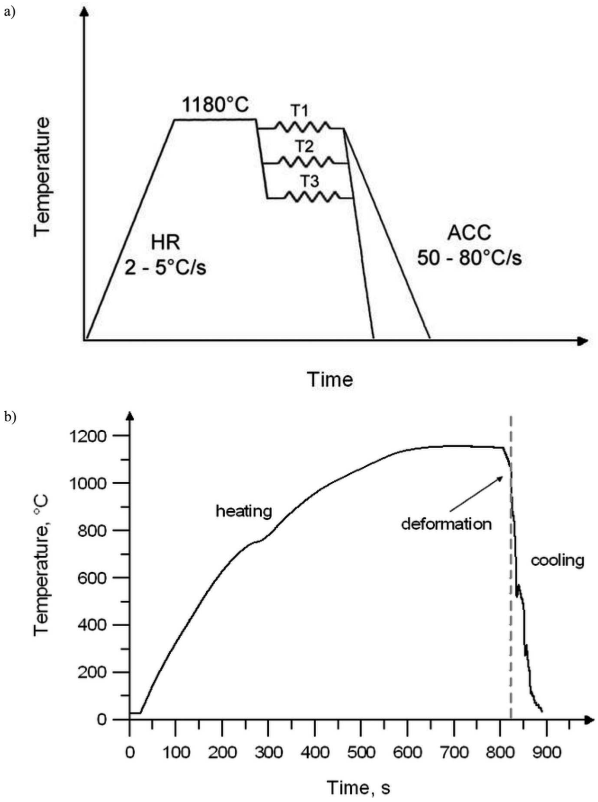


Fig. 6. Experimental tests: a) schematic of the plan of the TMT experiments, b) temperature plot recorded during a single test (deformation at 1100°C is depicted in the example)

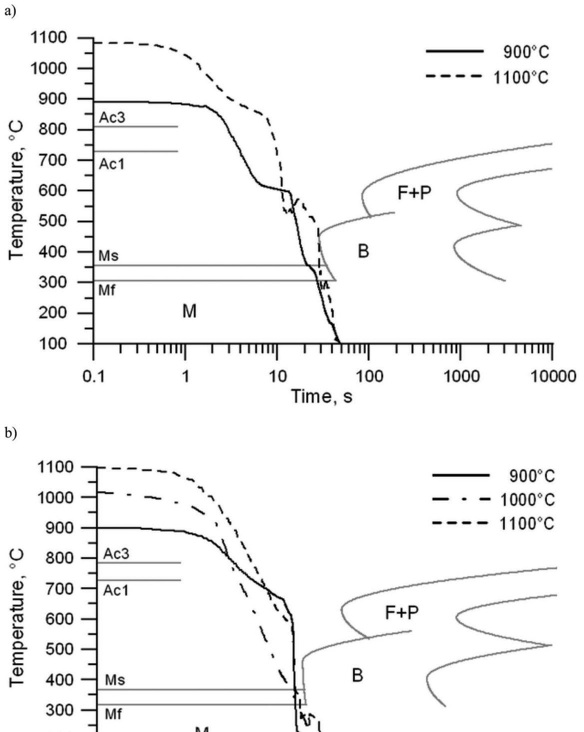
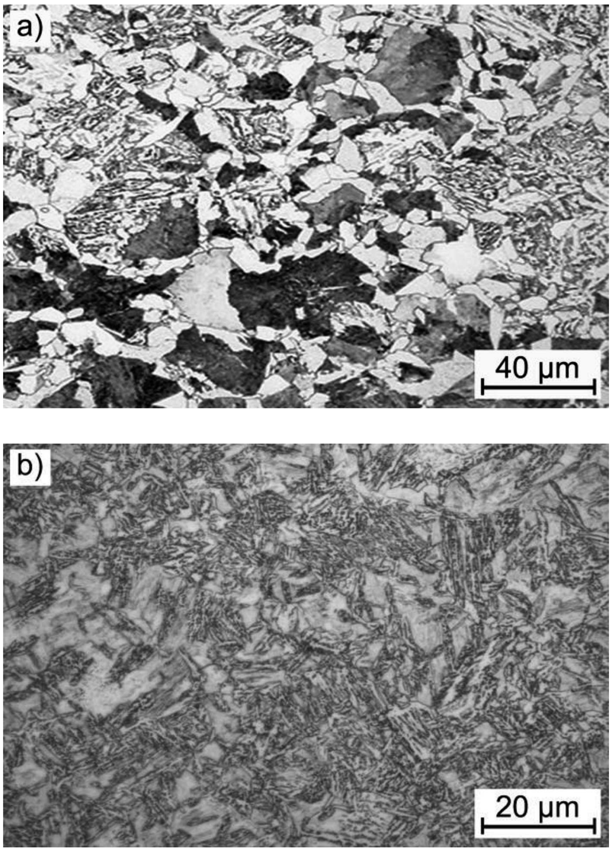


Fig. 7. Cooling curves recorded with thermocouple on the background of calculated CTP diagrams for steel A and steel B, respectively (a, b)

3.3. Microstructure and mechanical properties

Comparison of the as-received (Figures 8a) and 9a) to output microstructure indicate evident grain refinement of the as-forged material (Figures 8 and 9 b-d). Optical metallographic examination of processed specimens confirms expectations



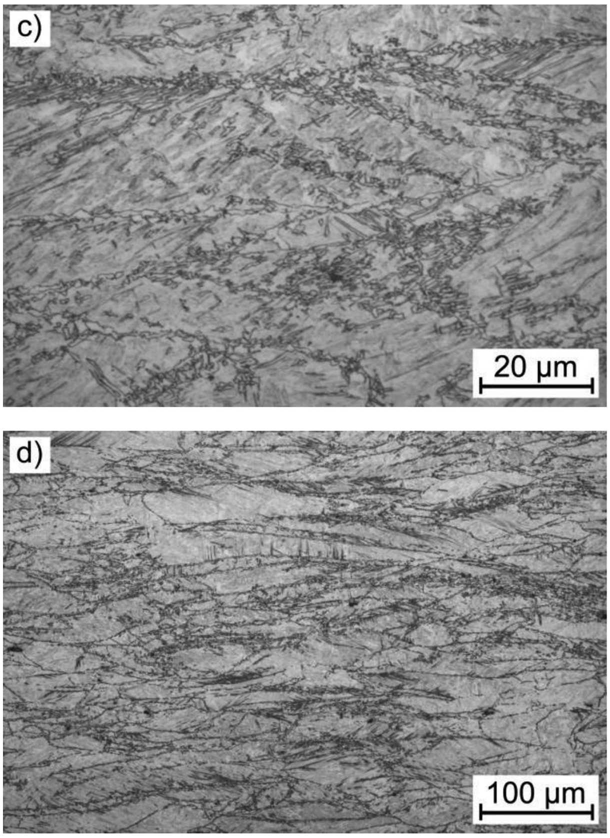


Fig. 8. Optical micrographs of steel A in particular processing conditions: a) as-received, b), c) deformed at 1100°C, 900°C, respectively, d) deformed at 900°C – lower magnification. Etched in 5% nital

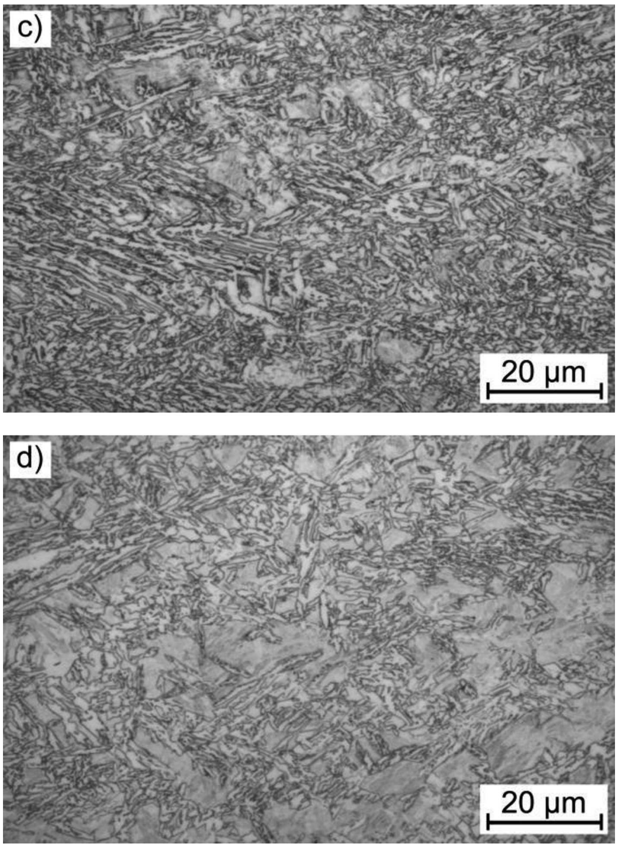
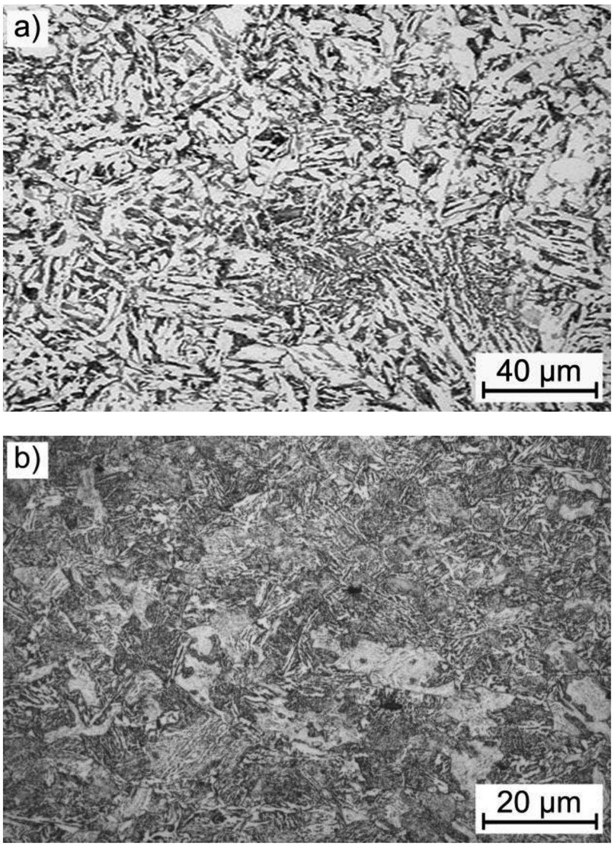


Fig. 9. Optical micrographs of steel B in particular processing conditions: a) as-received, b÷d) deformed at 1100°C, 900°C and 1000°C, respectively (see Figure 7). Etched in 5% nital



assumed from Jominy tests and modeling of austenite transformation during anisothermal accelerated cooling. Microstructures produced in the aftermath of accelerated cooling are composed of martensite and bainite, differing in fractions of the constituents. The cooling rate of 20 degrees per second suffices to omit the diffusion driven transformation of recrystallized austenite. However, for the real industrial forging-direct cooling process, die-chill and material transfer must be taken into account. As indicated in the physical simulation included in the study, post forging dwell and transfer on air necessitates increasing the cooling rate to over 120 degrees per second, which is sufficient for martensite transformation. As shown in Figures 8 b) and c), after forging at 900°C non-recrystallized microstructure abundant in crystallographic defects, such as shearing bands and sub-cells with sort of very fine grains at grain boundaries was obtained.

The obtained microstructure of the samples is reflected by accomplished mechanical properties. In this respect, Steel A exhibits higher strength, with UTS 1688 MPa after forging at 900°C and 1486 MPa for 1000°C forged specimen (Figure 10). As expected, Steel B indicated better ductility in the aftermath of Mo addition. Compared to 5% of elongation of direct-cooled Steel A, Steel B reaches over 8% elongation, which is a satisfactory results, taking into account that no tempering were conducted, and the flat forged samples are too small to accommodate heat for self-tempering.

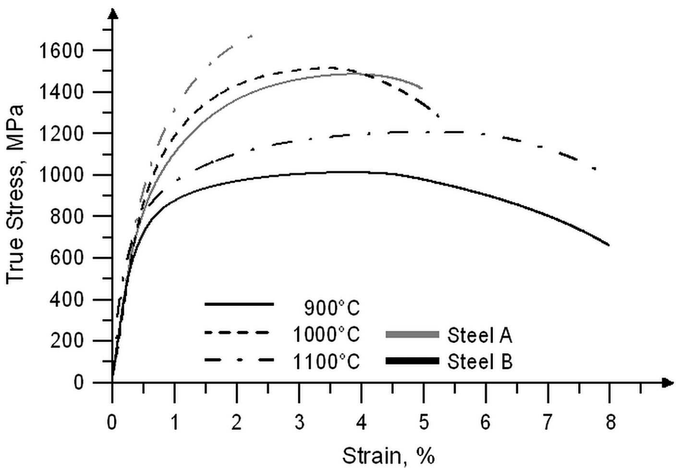


Fig. 10. Tensile properties of the TMT-processed steels

4. Summary and discussion

Physical simulation of hot forging and direct accelerated cooling of two experimental grades of microalloyed medium carbon steel, presented in the study, was a kind of tentative evaluation of microstructural and mechanical response of the elaborated alloys to imposed conditions of thermomechanical processing. On the other hand, it formed a verification of the TMP cycles alone as for their potential in producing mechanical properties expected from forged parts for mining industry. Design of the chemical composition of both of the alloys assumed simplicity and attractiveness to forging industry, reflected by low costs and feasibility of keeping imposed limits by steelworks.

In analysed alloys the designed contents of microalloying elements is kept within assumed limits, which is crucial from the standpoint of microstructure development and interaction precipitates – microstructure defects during forging and cooling.

The precipitates greatly contribute to hardening of the alloy, however, the efficiency of their strengthening action depends on the volume fraction and size of the precipitates [26]. Depending on the particle's relation to dislocation parameters it can pile up and loop the dislocation or be sheared by it. According to the results of precipitates volume fractions modeling, in case of the alloys concerned we have to do with both instances. Among the produced carbides and carbonitrides TiC and Ti(C,N) are of the largest size. They appear in the form of cubic-alike shapes ranging to a micrometer in diameter, and they can be visible in immersion optical pictures. In turn, the smaller particle diameter have Nb carbides. Although, they need high resolution techniques to be observed, they are reported to have spherical shape and size of dozens of nanometersand its contribution to the total strength enhancement reaches 90 MPa [3, 27]. Thus, they are supposed highly effective in pining grain boundaries while deformation and grain restoration processes.

The calculated volume of these precipitates allow expect significant microstructure controllability brought about by Nb(C,V), as long as heating up regime is maintained to introduce the whole Nb content into solution. As calculated, temperatures 1170÷1190°C must be exceeded to do so. The applied Nb content is meant to retard recystallization, which allows lowering the forging temperature.

In addition to hardenability, expressed by the depth of martensite layer and hardness of the layer, bulk mechanical properties were examined. It shows, the final as-forged/direct-cooled microstructure and mechanical properties controlled cooling in order to draw a cooling curve plot favourable for the proper kinetics of precipitation does not take full advantage of the strengthening and plasticity enhancement potential of an HSLA steel. Grain refinement contribution is a serious constituent of the overall final strength level due to Hall-Petch mechanism, which adds on up to 250 MPa [27]. In case of both of the analysed alloys, this effect is enhanced by N and Al presence, as an increase of the nitrogen content lowers the tendency for coagulation of V(C,N), reducing the amount of vanadium dissolved in the austenite [28], as well as, decreasing self-diffusion of iron, N reduces grain growth inclination [29], as long it does not exceed the content necessary for VN formation [30].

The results confirm, that controlling the forge temperature regime is effective in increasing both UTS and elongation-to-fracture indices. Decreasing forging temperature from 1180°C to 1000°C, resulting in lowering the forge-end point from about 1210°C to 1034°C, produced fine-grained structure, forming a base for fine colonies of pearlite or bainite after accelerated cooling. In result, the ambient temperature tensile properties of the material forged at 1000°C exhibits largest strength improvement at considerable plasticity. From the analysis of optical micrographs of produced microstructure, one can conclude decreasing grain size with lowering forging temperature. However, contrary to higher temperature trials, forging at about 900°C produced microstructure abundant in crystallographic defects, such as shearing bands and non-recrystallized sub-cells with sort of very fine grains at grain boundaries, which can be attributed to discontinuous dynamic recystallization, resulting in selective renovation of grains, typical of high strain-rate and/or low temperature deformation [31, 32], encountered in hammer forging processes. On the other hand, it means that deformation took place below temperature at which rectystallization can occur and/or strain-induced precipitation provided static recrystallization inhibitors [33].

Mechanical effect of such a mixture of fine recrystallized grains and strain-hardened ones was significant strengthening, resulting in UTS of 1700 MPa, goes along similar studies [34], however, accompanied by low plasticity, reaching at most 8,4% of A_{10} elongation to fracture. However, in the real industrial process, better plasticity should be expected, be-unlike, the small laboratory samples, whose microstructure in hot-forged direct-cooled condition calls for additional tempering, the massive parts allow self-tempering effect to occur, offering ductility improvement without any additional heating stages. In the context of the target destination of the presented study, in ductility evaluation it must be noted, that the forging test, which were in fact compression of flat specimens, did not produce any privileged grain flow direction, but on the contrary, in the location of gauge area of the tensile specimens, the direction was perpendicular to the tension direction. If the forging of the hook the situation is different – the metal flow pattern produces evident longitudinal grain flow, which is in the favour of ductility enhancement, as for accomplishment of the minimum required elongation 10% is assumed.

5. Conclusions

The presented study implies meeting requirements of forged parts for mining industry by thermomechanically processed high strength low alloy steels with minor additions of alloying elements as a successful substitute for plain medium carbon steel. Correspondingly, traditional heat treatment can be replaced by cost-effective continuous cooling directly after hot forging, offering versatility of thermomechanical treatments, which enables variety of structure compositions.

Accelerated cooling with forced air of 25-40 m/s flow velocity, as well as utilization of increased humidity in the form of mist, allow for bainite-martensite microstructure in sections up to 40 mm or martensite alone in forged sections up to 12 mm. In case of ending forging cycle below 900°C selective deformation occurred, leading to mixed microstructure of fine necklace-alike and non-recrystallized grains. However, no grain boundary ferrite was observed.

Producing UTS about 1700 MPa the highest, and 1000 MPa in excess, where best plasticity indices were observed, implies the designed microalloyed steels are suitable for cost-effective industrial process of production of elongated hammer-forged parts for mining applications. The ductility observed in bound to be increased in industrial process, as the massive parts processed enable self-tempering to be employed, and the grain flow direction provides maximum failure resistance.

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