A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
Volume 56 2011 Issue 1
DOI: 10.2478/v10172-011-0011-2

P. SKUBISZ*, H. ADRIAN*, J. SIŃCZAK*

CONTROLLED COOLING OF DROP FORGED MICROALLOYED-STEEL AUTOMOTIVE CRANKSHAFT

KONTROLOWANE CHŁODZENIE ODKUWEK MATRYCOWYCH WAŁU KORBOWEGO DO SAMOCHODU

Certain aspects of determination of continuous cooling conditions directly after forging and their applicability to industrial conditions are discussed. On example of high-pressure-pump crankshaft problems concerning realization of drop forging of microalloyed-steel forged shaft with thermomechanical treatment involving subsequent direct controlled cooling are presented.

The paper is focused on determination of both forging conditions and subsequent cooling parameters, which in combination with modelling of precipitation kinetics in the analysed steel allowed accomplishment of required final mechanical properties of the forged part. For the determined conditions of thermomechanical treatment experimental trials in industrial conditions were carried out. Obtained in simulation pattern of continuous cooling was realized with a line consisting of six stages of controlled rate of stirred air flow. Satisfactory level of mechanical properties, exceeding minimum of the assumed requirements was reported, as well as uniform fine grained microstructure regardless of cross-sectional dimensions, meeting the requirements of automotive industry.

Keywords: thermomechanical treatment, controlled cooling, drop forging, mechanical properties, numerical modelling, hardness, ductility

Przedstawiono niektóre zagadnienia dotyczące doboru warunków kontrolowanego chłodzenia odkuwek matrycowych bezpośrednio po kuciu i ich stosowalności w warunkach przemysłowych. Na przykładzie odkuwki wału korbowego pompy wysokociśnieniowej samochodu osobowego przedstawiono próbę zastosowania obróbki cieplnoplastycznej z uwzględnieniem warunków technologicznych jej realizacji dla odkuwek ze stali z mikrododatkami.

W pracy skupiono się na określeniu zarówno warunków kucia matrycowego, jak również parametrów bezpośredniego chłodzenia z temperatury kucia, co w połączeniu z modelowaniem kinetyki wydzielania pozwoliło na uzyskanie założonych finalnych własności mechanicznych odkuwki. Dla określonych drogą modelowania numerycznego warunków obróbki cieplnoplastycznej przeprowadzono weryfikację doświadczalną w warunkach przemysłowych, przy wykorzystaniu specjalnej linii do ciągłego chłodzenia, składającej się z kilku stref chłodzenia z kontrolowaną szybkością. Wykonane próby przemysłowe zapewniły uzyskanie wymaganego poziomu własności mechanicznych i plastycznych odkuwki, a tym samym potwierdziły zasadność przyjętych warunków technologicznych.

1. Introduction

Manufacture of structural elements for high-duty applications forces an incessant pursuit of good mechanical properties without a negative impact on cost-effectiveness of production. The tendency of lightweight structure oriented design, attaining high performance triggers the needs for improvement of steels characterized by high strength, high yield stress, crack resistance and good weldability [1, 2]. This is especially true for the automotive industry, where production of high-duty parts, such as transmission systems, suspension and chassis components or crankshafts induce economical and environment friendly manufacture process. In fact, this can be accomplished by means of either the development of new grades or improvement in the technology.

Direct cooling has become a commonly used alternative for traditional quenching-tempering method of treatment of steel products, offering good combination of strength and ductility at significant costs savings, hence finding increasing number of applications in automotive applications [3, 4]. Additions of alloying elements and controlled processing depending on a synergic combination of plastic deformation and heat treatment is now

* AGH – UNIVERSITY OF SCIENCE AND TECHNOLOGY, FACULTY OF METALS ENGINEERING AND COMPUTER SCIENCE FOR INDUSTRY, 30-059 KRAKÓW, 30 MICKIEWICZA AV., POLAND

a common way of reducing manufacturing costs to improve mechanical properties of a forged part [5, 6].

Efforts to introduce Nb into steel for hot-rolled sheets gave rise to development of important group of microalloyed steel, important for technical and economical reasons [7]. Benefits of microadditions in steel were fully revealed in High Strength Low Alloy steels (HSLA). Their final properties are provided directly after deformation process as a result of controlled cooling [8]. Nowadays direct-cooled steel parts can attain typically ferrite-pearlite, bainite, martensite or various types of bainite-martensite structures [6]. These days controlled cooling is well implemented both for stationary processes, such as rolling, and also for impression-die forging of parts of relatively uniform cross-sections, but for more complex shapes of forgings, the control of critical process parameters call for more considerations. In order to bring about proper run of transformation kinetics favourable distribution of thermo-mechanical parameters before start of cooling must be provided, as well as, appropriate rate of cooling in varying in dimensions sections of forged part.

The first tests of air-cooling directly from hot-working temperature date back to the seventies, which resulted in producing so-called 1st generation microalloyed steels. The most common steel of this group, 49MnVS3 – a medium-carbon steel with vanadium additions, was used for manufacture of responsible components such as crankshafts. Despite relatively high level of strength, hardness of those steels was relatively low. To increase hardness silicon in content of 0,5% was added and simultaneously carbon was reduced to 0,38÷0,27%. These additions were also to improve weldability and castability. The decrease in strength was compensated with high manganium (>1%), with minor content of nitrides and carbides forming elements. In following years new steels group was developed, giving rise to so called 2nd generation of microalloyed steels. Steel 38MnSiV5 may be referred to as a representative of this group [3, 4]. Since then, constant development in this field has been witnessed, with steel precipitation hardened during controlled cooling directly from the deformation temperature. Vast majority of application of these grades involved hot-rolling processes, while forging processes, on account of more complex determination of process parameters, were not so common [9, 10].

These days "SiV" steels are produced, which exhibit high strength and hardness, as well as good crack resistance and weldability associated with low carbon content. These are ferrite-perlite steels. Currently, contribution of products made of microalloyed steels in well-developed countries reaches 50% of the total amount of steel used in automotive industry and still an ever-increasing tendency is observed [8]. It is estimated that utilization of these sort of steels with thermomechanical processing in the manufacture of automotive forged parts brought manufacture savings of about 20%. What is more, structural components of HSLA steel, as compared to traditional structural steels, can bear the same loads at smaller cross-sections.

To benefit from thermomechanical treatment (TMT) in a forging process some technological setbacks must be overcome. They arise from diversity of shapes and sizes of forged parts, which calls for the necessity of determination unique forging and cooling process parameters. Mechanical properties of forged parts made of microalloyed steels are obtained by proper determination of forging process conditions, such as preheating temperature, forging temperature, dwell time and time of intervals between consecutive operations, as well as cooling conditions after drop forging operations. Another important issue is determination of preheating temperature, which must provide good forgeability as to obtain desired geometry at minimum number of blocker impressions and, on the other hand, appropriate temperature from the microstructure standpoint; keeping some of carbides undissolved and preventing from grain growth [11].

The mechanical properties of forged components made of microalloyed steels are obtained by proper determination of forging process conditions, such as preheating temperature, forging temperature, dwell time and time of intervals between consecutive operations, as well as cooling conditions after the forging operations have been completed. Another important issue is determination of preheating temperature which must provide good forgeability as to obtain desired geometry at minimum number of blocker impressions and, on the other hand, appropriate temperature from the microstructure standpoint; keeping some of carbides undissolved and preventing from grain growth.

As-forged material condition is reflected by the condition of microstructure resultant from strain distribution and temperature gradients in the volume. The nature of the forging process itself introduces additional variables which contribute to possible nonuniformity of obtained microstructure after forging. For complex parts, some sections significantly differ in thickness, causing both nonuniform distribution of deformation and local increase in strain rate, and in result, significant amount of deformation heat. Complex geometry produces a metal flow pattern resulting in completely different time of contact of deformed metal with tool surface. Although the temperature differences diminish during subsequent stages before cooling, such as trimming operation, in the aftermath of the temperature and strain gradients, local differences of microstructure occur.

In the work, the possibility of utilization thermo-mechnaical treatment is investigated on the example of drop-forged high-pressure pump crankshaft of steel 38MnSiVS6. To take advantage of the benefits offered by combination of microalloyed steel application and utilization of heat attained after forging an estimation of actual temperature profile and strain gradients in characteristic cross-sections of the part is necessary. For this reason numerical calculations of the whole forging and cooling cycle is needed, which in combination with the knowledge of included in numerous literature sources data on precipitation kinetics form a sort of input data for controlled cooling process parameters.

2. Objective and assumptions

The subject of the work are issues associated with selection of conditions of controlled cooling and process parameters which enable technological realization of the determined time-temperature-deformation regime in drop forging process with subsequent direct cooling. The aim of the research was determination of forging process conditions, which in combination with theoretically estimated cooling rate, based on calculation of precipitation kinetics, would provide required final mechanical properties of forged parts made of medium carbon microalloyed steel.

Steel used in the study was to meet final properties requirements typical of automotive high-pressure pump crankshaft that is: UTS 820 MPa, TYS 550 MPa, elongation 12% and area reduction at fracture 22%. For the needs of experiment, special heat was cast. Detailed composition of the heat used in experiment, which is further referred to as 38MnSiVS6, is shown in Table 1. On account of diversified cross-sections and relatively simple geometry allowing for one-stage forging, crankshaft of geometry presented in Fig. 1 was selected to the research.

TABLE 1

Chemical composition of the 38MnSiVS6 steel heat used in the experiment

Element	C	Si	Mn	P	S	V	Al
Content, %	0.36	0.56	1.35	0.008	0.055	0.08	0.012

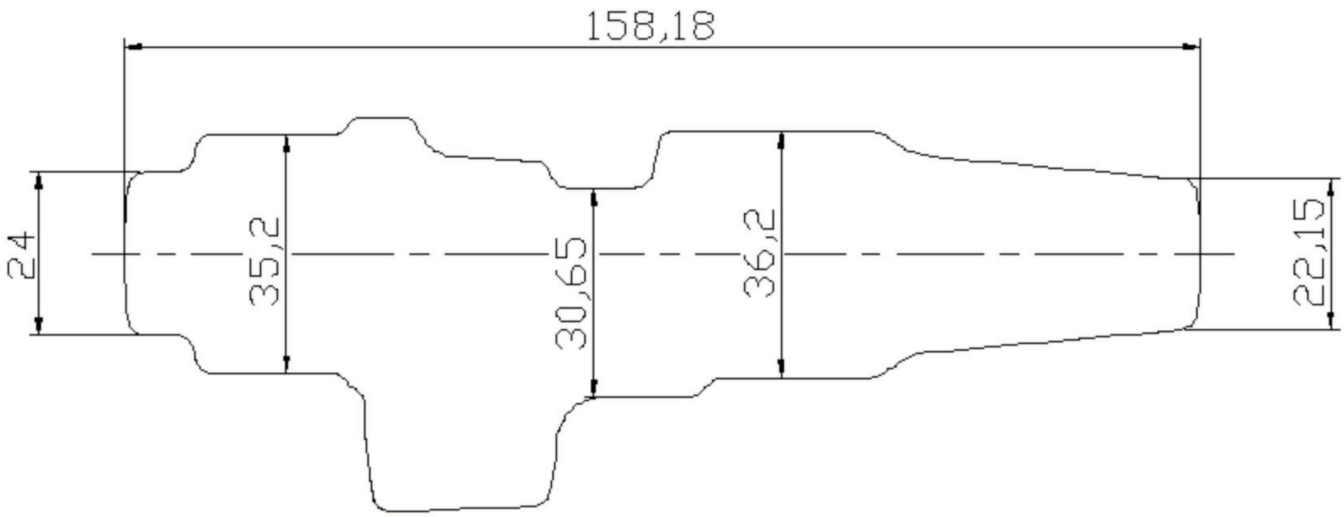


Fig. 1. Geometry and dimensions of the analysed crankshaft forging

Despite relative complexity in geometry of the part, varying in transverse dimensions (Fig. 1) it was assumed that complete fill-up of die impression involve minimum forging stages and throughout the whole length of the part length uniform degree of deformation in produced in each of characteristic cross-section. Determination of the forging conditions was based on numerical calculations of the forging process. Of fundamental importance here was an estimation of appropriate start-of-forging temperature and the geometry of the billet, which in connection with forging equipment kinematics would result in determined temperature of end of forging. For easier control of the temperature changes and temperature gradients on the cross-section due to cooling on tool and better reproducibility of samples, it was decided to use finish-only die impression to complete the deformation in a single blow.

As the forged shaft was meant to undergo controlled cooling directly after forging, the key issue is to provide favourable course of cooling curves in each section of the part by means of end-of-forging temperature and cooling rate. To obtain the required rate of temperature decrease ensuring thereby proper run of precipitation process, numerical modelling with use of finite element method was carried out.

Also an investigation of process conditions which affect the mechanical properties after thermomechanical treatment were carried out by means of numerical simulation, including both forging process and subsequent cooling. The investigation in the forging operations was aimed at getting favourable distribution of deformation and temperature profile at the end stage of forging, to provide optimal initial conditions of direct cooling. With a use of obtained temperature and strain levels as input data multistage direct cooling was simulated to cue cooling curves pattern for transformation and precipitation kinetics. Hence, having obtained proper temperature profile after forging, cooling curves in the characteristic cross-sections of the forged part were plotted for variable cooling rates. In result, correlation between cooling rate in cross-sections concerned and calculated cooling medium flow rate was obtained.

Designed time-temperature regime of direct cooling was afterwards verified experimentally. The controlled cooling was realized in continuous manner in a special tube-alike cooling line containing six cooling zones, which made it possible to independently control cooling intensity in each of them in order to obtain unique temperature regime in consecutive cooling stages. Temperature measurement was done with pyrometers mounted at each of the cooling stations.

The process of impression-die forging to a degree gives some freedom of selection of process conditions. In aspect of thermomechanical treatment by direct cooling the most crucial parameters are resultant distributions of temperature and strain. However, from technological standpoint, the most suitable level of temperature and/or amount of deformation often calls for additional changes, which are sometimes hard to accept on account of forging process economy or machines capacity limitations.

For the analysed crankshaft the forging temperature (forging billet preheat) in traditional process involving medium carbon steel is normally held at about 1200°C to provide plasticity and tool life. However, working speed of used mechanical press of 0.5÷0.8 m/s produces excessive amount of deformation heat in areas of large reduction. In conventional technology that makes little problem as final properties are formed with subsequent quenching-tempering (Q&T) heat treatment, contrary to microalloyed steel forging. Here, the initial billet temperature was reduced to 1050°C. Lower temperature is more convenient in term of further cooling, as well as getting closer to recrystallization point provides finer austenite grain to turn into ferrite or pearlite [10]. On the other hand, decrease of forging start point results in load increase. Although convenient in the light of subsequent cooling, excessive lowering of temperature could bring about the necessity of additional forging operation, therefore further decrease in temperature will be obtained by rapid cooling with stirred air.

From the direct-air-cooled forged crankshafts specimens for mechanical testing were derived to measure ultimate tensile strength, tensile yield stress, hardness and impact strength, as well as metallographic investigation.

3. Numerical modeling

3.1. Modeling of forging operation

Numerical analysis with finite element method (FEM) was carried out with a commercial code Qform3D on assumption of visco-plastic model of deformed body, rigid model of tools and three-dimensional state of deformation. Boundary conditions, as well as the mechanical press characteristics were based on industrial conditions, predicted for experimental sampling,

To illustrate the levels of exit temperature and its gradient in individual sections, in Fig. 2 transverse profiles maps are presented for sections designated with A÷F.

As the results show, temperature profiles are featured with temperature gradients, resulting in significant difference between local extreme values. These extreme temperatures are located in the surface – minimum, and in the are of the flash gutter – maximum. However, it must be said that such gradient are typical of forgings with significant differences in transverse dimensions and therefore its influence upon final properties must be examined and minimized within subsequent cooling operation.

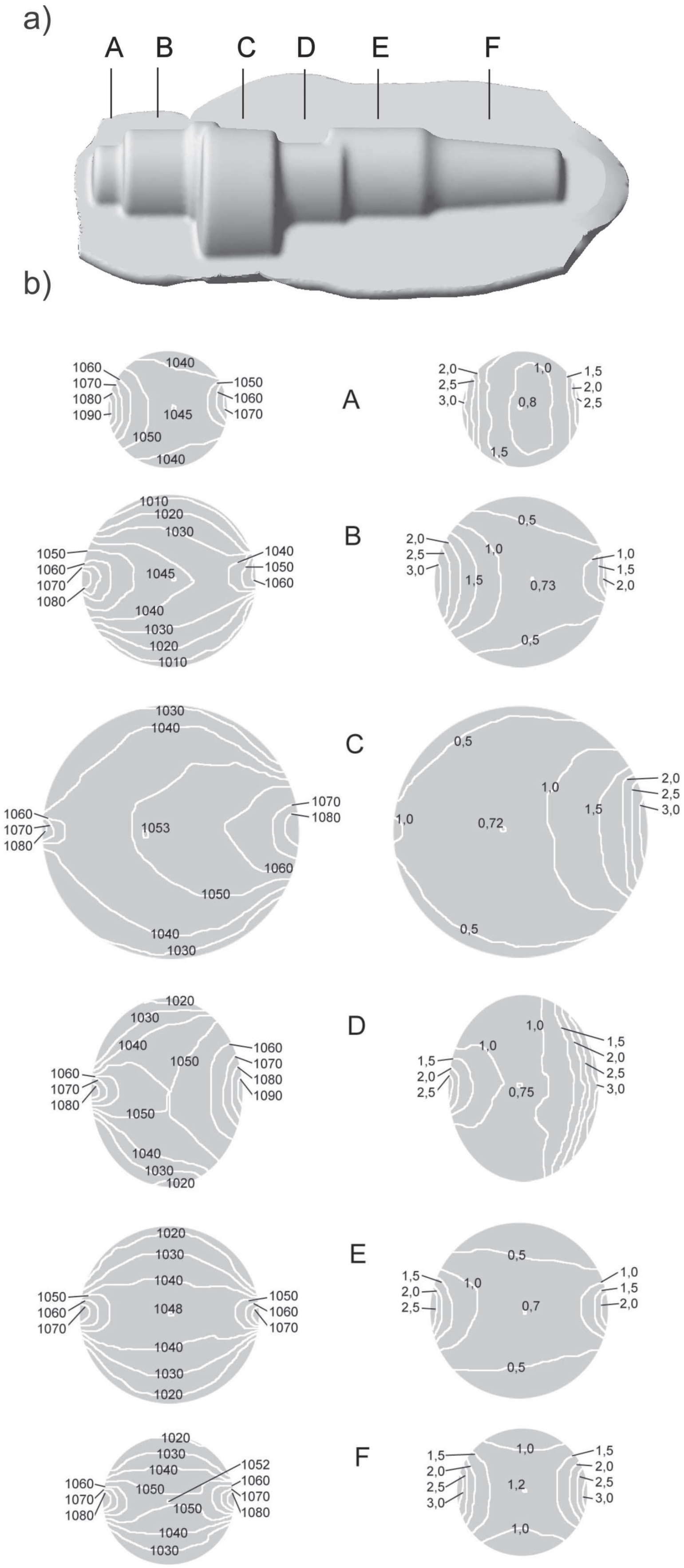


Fig. 2. Temperature (b) and effective strain (c) distribution in characteristic cross-sections A–F of the crankshaft (a) forged in temperature 1050°C

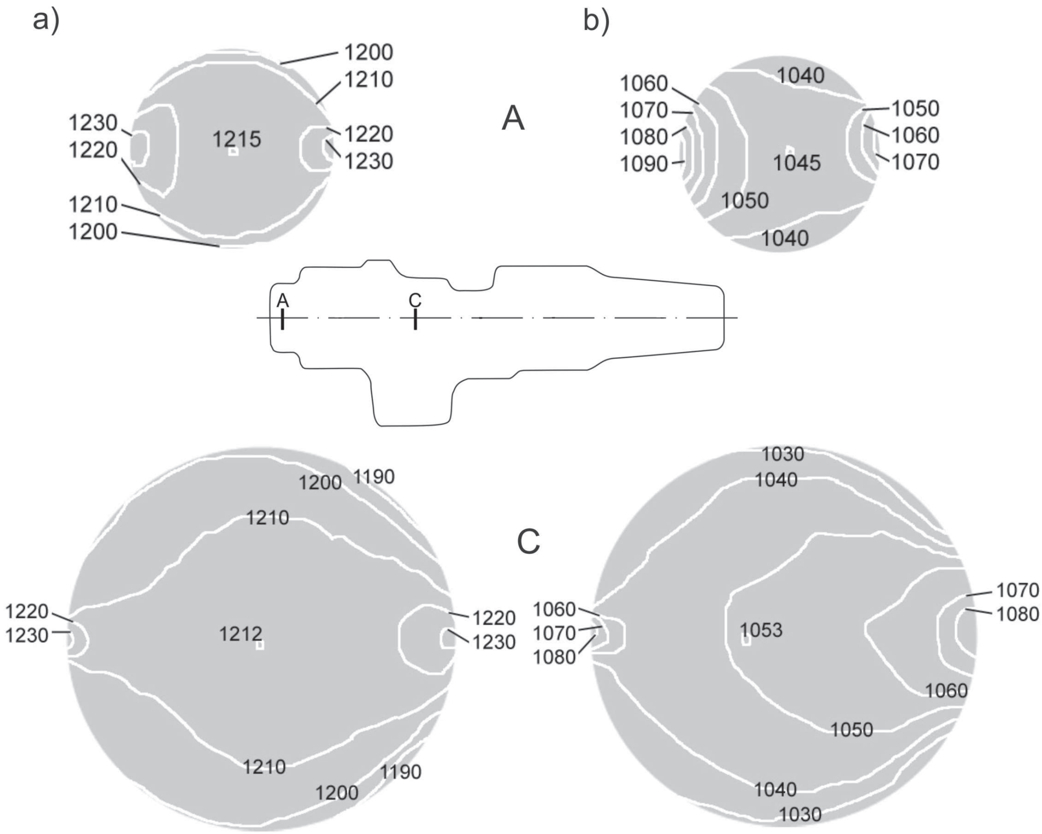


Fig. 3. Transverse temperature profile in selected cross-sections (A and C) of the shaft forged at: a – 1200°C, b – 1050°C

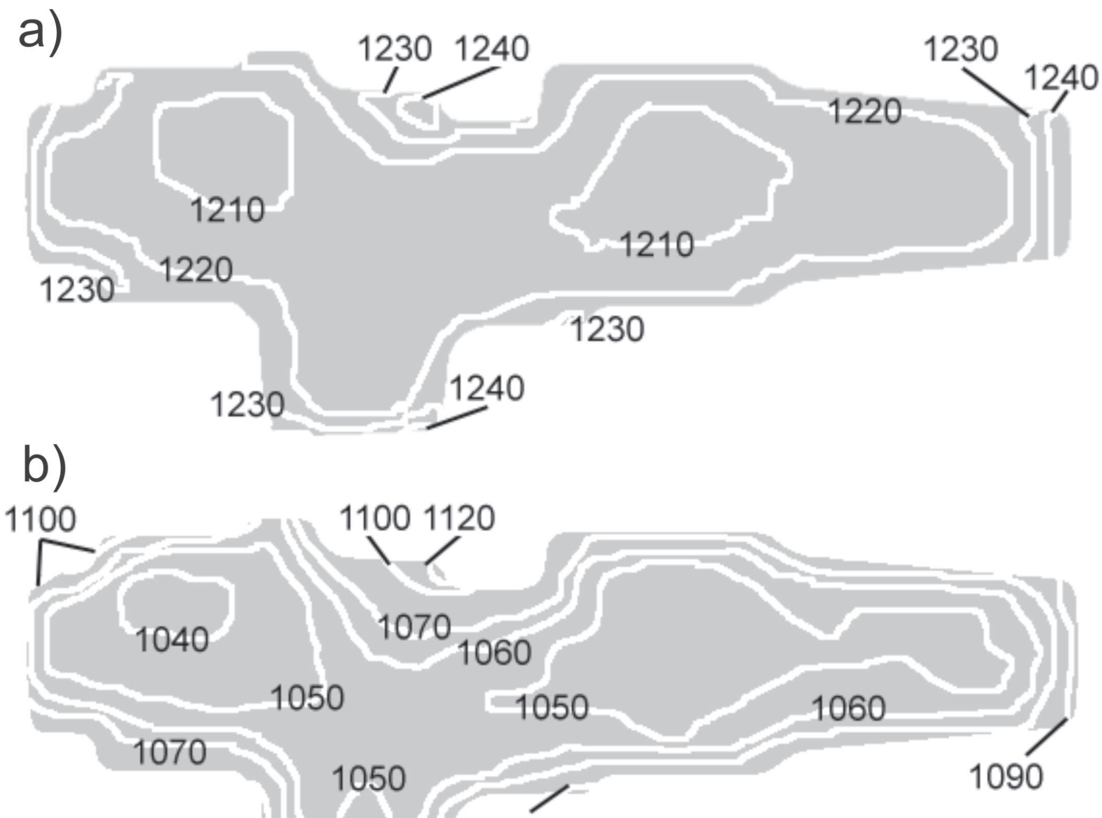


Fig. 4. Temperature profile on longitudinal cross-section of the shaft forged at: a) 1200°C, b)1050°C

It was observed that relatively short dwell time and insignificant differences in deformation degree brought about negligible temperature gradients. The biggest, 20 degrees' deformation-related temperature increase was observed in the vicinity of the flash gutter, and the lowest temperature was noted at the bottom of a cavity, a mere 30 centigrade decrease.

Likewise, the largest deformations (Fig. 2 c), as could be expected, are located in the flash area with small range of extension. Through the whole length practically the same deformation is produced. The lowest value of effective strain is 0,7 (section C, Fig. 2 c).

To investigate the magnitude of temperature gradients and effect of deformation heat dependent on the preheating temperature, numerical calculations of the forging process for variable temperatures at 50 grades intervals were carried out, up to the highest starting temperature 1200 ˚C. The resultant temperature profile changes produced for two distinct cross-sections are depicted in Fig. 3, for two cases, 1200°C (Fig. 3 a) and 1050°C (Fig. 3 b). How the increased initial billet temperature affects the temperature gradients on the lengthwise cross-section in parting plane is shown in Fig. 4, which could predict variation in mechanical properties distribution.

On the basis of numerical computations it was decided, that temperature of 1050°C allows completion of the forging process in finisher-only die impression. On the strength of analysis of equivalent strain and temperature maps it can be concluded that the presented one-stage forging technology provides distributions suitable for utilization of continuous cooling directly after forging. The obtained values of temperature after forging form a guideline for selection of the preheating temperature for further research. Based on this consideration, to determine favourable cooling regime carbonitrides precipitation kinetics was calculated.

3.2. Precipitation kinetics modeling

In high strength low alloy steels in order to control their microstructure and mechanical properties the addition of microalloying elements, V, Nb and Ti is applied. These elements show high chemical affinity for interstitial elements, C and N and form carbides, MC, and nitrides, MN, in austenite and ferrite. Carbides and nitrides are interstitial phases comprising fcc lattices. The similarity of crystal structures enables them to show mutual solubility resulting in the formation of carbonitrides, M(C,N). The chemical composition of carbonitride depends on the temperature. In case of singular addition of microalloying element the chemical formula for carbonitride is MC_yN_{1-y}. In steel the common element is Al, which show the chemical affinity for nitrogen and forms nitride AlN. This compound has hexagonal crystal structure and precipitates independently of carbonitride. Because the parameters of carbonitride precipitations (volume fraction, V_v, average radius, r) play an important role in the controlling of the mechanical properties of steel components after technological processes, such as heat treatment or thermo-mechanical treatment, the knowledge of these parameters is essential.

The mechanical properties of high strength low alloy steels with ferrite microstructure depend on the chemical composition of steel and the microstructure parameters. The yield strength, R_e, of ferrite of high strength low alloy steel is described by equation [11]:

$$R_e = R_{e0} + \sum_1^i k_i c_i + k_y d^{-0.5} + \frac{10.8 V_v^{0.5}}{r} \ln \frac{r}{6.125 \cdot 10^{-4}} \tag{1}$$

where: R_{e0}, k_y are constants, k_i, c_i are strengthening coefficients and concentrations of solute (mass %), d is grain diameter and V_v, r are volume fraction and mean radius of precipitates. Thus the yield strength of microalloyed steel is defined in terms of three strengthening mechanisms: solution strengthening effects by dissolved elements (c_i), grain refinement effect (d) and dispersion strengthening effect in terms of the real particle size, r, and volume fraction,V_v,.

Information concerning the content of carbonitride in steel can be obtained using the thermodynamic model [12-15]. The thermodynamic model enables to calculate the chemical composition of austenite or ferrite as well as the content and composition of carbonitride at given temperature, T. In case of steel containing V and Al microalloying additions the thermodynamic equilibrium conditions are described by system of following nonlinear equations system:

$$[Al_a] \cdot [N_a] = K_{AlN} \tag{2}$$

$$\ln \frac{y\, K_{VC}}{[V_a][C_a]} + (1-y)^2 \frac{L_{CN}}{RT} = 0 \tag{3}$$

$$\ln \frac{(1-y)\, K_{VN}}{[V_a][N_a]} + y^2 \frac{L_{CN}}{RT} = 0 \tag{4}$$

$$V_a = \frac{1}{2} f + (1 - f - f_{AlN})[V_a] \tag{5}$$

$$C_a = \frac{y}{2} f + (1 - f - f_{AlN})[C_a] \tag{6}$$

$$N_a = \frac{1-y}{2} f + \frac{f_{AlN}}{2} + (1 - f - f_{AlN})[N_a] \tag{7}$$

$$Al_a = \frac{f_{AlN}}{2} + (1 - f - f_{AlN})[Al_a] \tag{8}$$

where symbols of elements without brackets, X_a, mean their total contents in alloy in atomic fractions, in brackets $[X_a]$ – atomic fraction of element dissolved in austenite, K_{MX} – solubility product for binary compound MX related to composition of austenite expressed in atomic fractions, f, f_{AlN} – molar fraction of undissolved carbonitride, VC_yN_{1-y} and aluminium nitride, AlN, R = gas constant = 8.314 J/mol.K. – 1 and L_{CN} – parameter of interaction of Ti on solution C-N. According to Grieveson, [15] L_{CN} = – 4260 J/mol.

Chemical composition of alloy is presented in mass % and available data for solubility products for binary compounds, MX, are related to mass % of elements M and X. For recalculation of mass % to atomic fractions the following equation was used:

$$X_a = \frac{X}{100(X)\sum n} \tag{9}$$

where: X is mass % of element, (X) – atomic weight of element and Σn – number of moles of element X in mass unit. For recalculation of available common solubility product related to mass % to atomic fractions of elements forming compound MX the following equation was used:

$$K_{MX} = [M_a]\cdot[X_a] = \frac{10^{B-\frac{A}{T}}}{10^4(M)(X\}(\sum n)^2} \tag{10}$$

where A and B are common solubility product constants. To increase the accuracy of calculations, especially at higher alloying elements content it is necessary to consider the effect of austenite composition on chemical activity of dissolved elements. This effect is described by Wagner's equation [16]:

$$\ln(a_i) = \ln([X_i]) + \sum_{j=1}^{n} \varepsilon_i^j \left[X_j\right] \tag{11}$$

where ε_i^j – interaction of j-element dissolved in austenite on activity of i-element. In this case in equation set (1)–(7) instead of atomic fractions, M_i, of element their chemical activity a_i must be used.

For analysis of thermodynamic equilibrium conditions the following solubility product data for binary compounds VC [17], VN [17], AlN [17] were used:

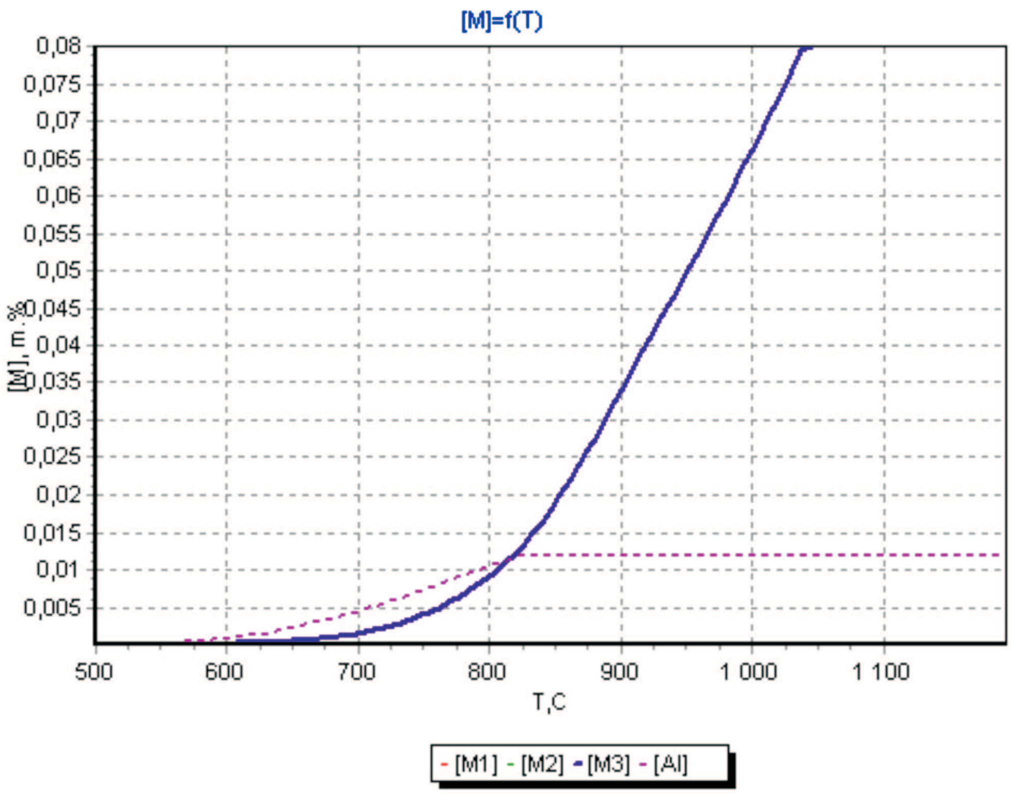
$$\lg([Al]\cdot[N]) = 1.79 - \frac{7184}{T} \tag{12}$$

$$\lg([V]\cdot[C]) = 6.72 - \frac{9500}{T} \tag{13}$$

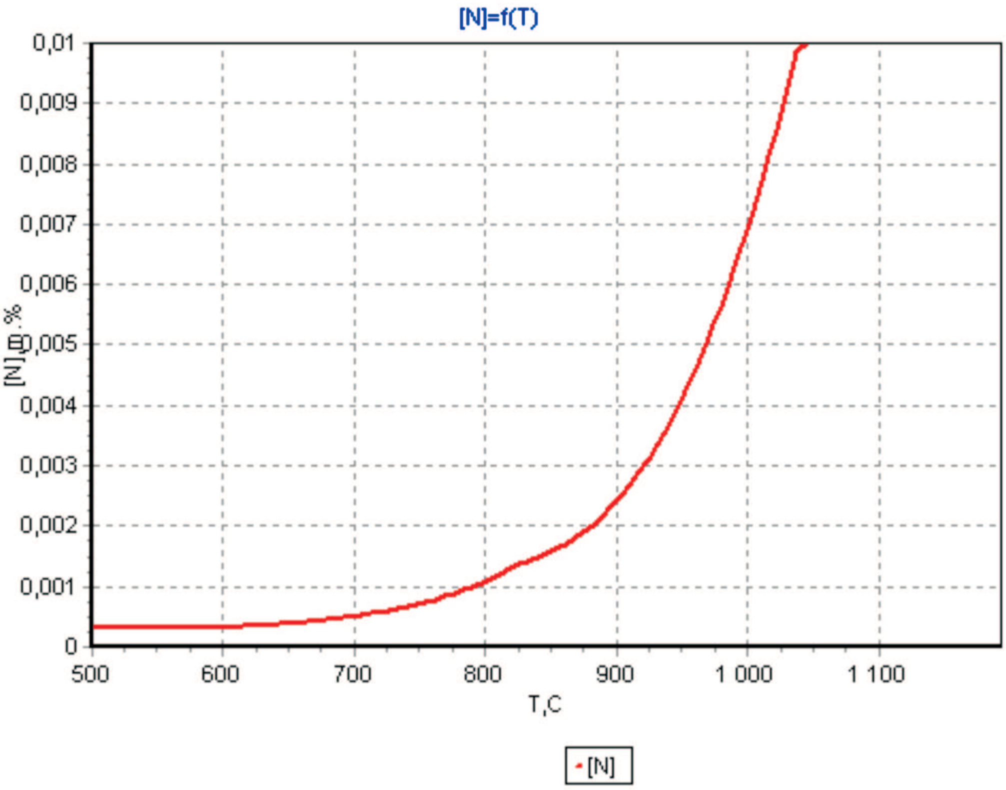
$$\lg([V]\cdot[N]) = 3.63 - \frac{8700}{T} \tag{14}$$

The Wagner's interaction parameters were used according to [14]. Results of calculations, using presented thermodynamic model, of austenite composition ([V], [Al], [N]) as well as AlN and V(C,N) contents as functions of temperature are presented in Fig. 5.

a)



b)



c)

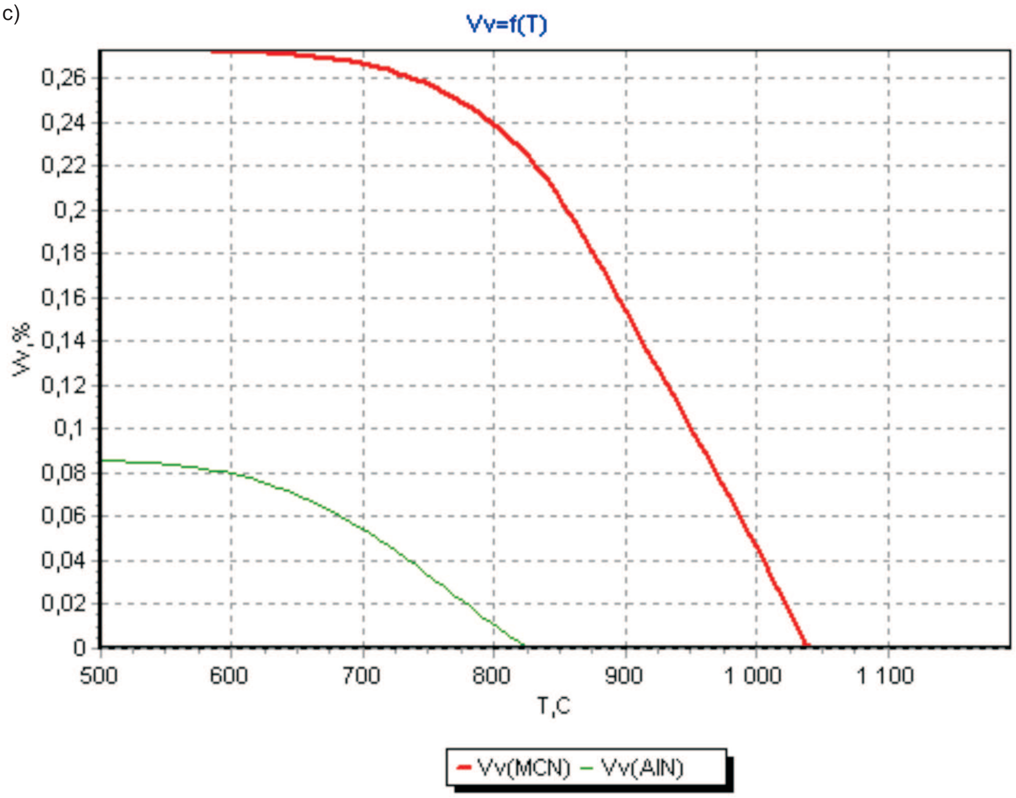


Fig. 5. The relationships between: a) [V], [A]=f(T), [N]=f(T), c) V_v(AlN), V_v(V(C,N))=f(T)

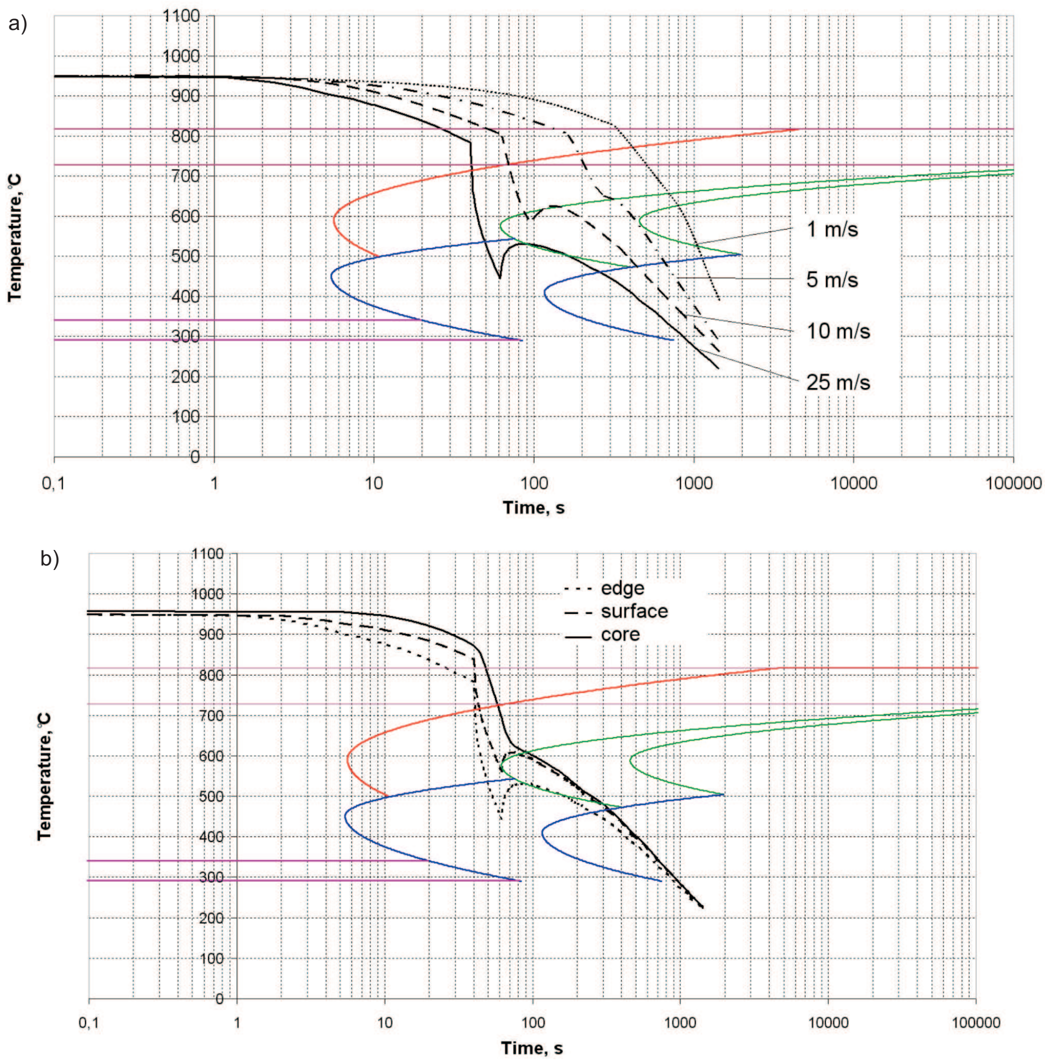


Fig. 6. Numerically estimated cooling curves for: a) various air flow rates: 1- 0 m/s, 2 – 5 m/s, 3 – 10 m/s, 4 – 25 m/s, b) different transverse location in section A

From Fig. 6c we can conclude, that in investigated steel during cooling from austenitising temperature precipitation of carbonitride V(C,N) an aluminum nitride occur. The start precipitation temperature for V(C,N) is 1030°C and for AlN – is 820°C. During slow cooling all carbonitride will be precipitated in austenite at 600°C, giving volume fraction equal 0.27%. But in the temperature range of 800÷600°C will precipitate only 0.03% of carbinitride. The precipitations of AlN content will increase with decreasing temperature to value of 0.082%. In order to increase the dispersion strengthening effect by carbonitride particles the higher cooling rate is required in order to decrease the temperature of carbonitrides precipitation and thus to decrease the size of particles. For sufficient cooling rate the precipitation will occur in ferrite and these particles give strengthening effect depending on the particle size, r, according to equation (1).

Applied thermodynamic model enables to calculate some parameters which can be used for prediction of mechanical properties of steel after technological process: chemical composition of austenite, volume fraction of precipitates. One of important parameter, size of particles giving dispersion strengthening effect, r, is not available. For calculation of r as a function of cooling rate from austenitising temperature the kinetic model of precipitation process has to be used, which is under development.

3.3. Numerical modelling of continuous cooling

Numerical modelling was performed with commercial code TTSteel. On the basis of chemical composition, grain size and accumulated strain, Temperature-Transformation-Time diagram for analysed steel was plotted. To define transformation points corresponding to various cross-sectional locations, temperature changes in the volume was calculated with a use of FEM. For selected locations of greater importance, such as edge, surfaces or the core, cooling curves were plotted. To attain the history of temperature changes, as an austenizing temperature, average temperature of end of forging was assumed.

As the direct cooling was to be carried out in continuous cooling line, consisting of six cooling zones, the concept of assumed time-temperature regime was to simulate 40 sec cooling on air, standing for trimming operation, and subsequent accelerated cooling with forced air to the range 600÷700°C, followed by 120 sec interval, to hold isothermally at established temperature for precipitation to occur and obtain fine-grained ferrite-pearlite. High cooling rate in ferrite range should prevent from excessive grain growth, which may result in Widmansteatten plates [18] and also brings finer perlite. On the other hand, high fraction of pearlite strongly influences impact toughness [19]. Rapid cooling simulation involved determination of favourable cooling rate by calculation of appropriate air flow rate. Analysis involved variable air flow rate: 0, 3, 10 and 25 m/s. After preliminary calculations it was concluded that for the geometry concerned it suffices to use two cooling zones, the remaining switched off to cool the part slowly to ambient temperature.

Cooling curves of the whole cooling cycle for variable cooling rate with forced air in respect to transition points are shown in figure 6 a), variations in cooling rate due to differences of heat transfer plotted for edge, surface and core of the shaft are presented in figure 6 b).

4. Industrial verification

To verify the attitude of theoretical determination of cooling conditions industrial trials were carried out. The industrial trials of controlled cooling was realized in a special tunnel-alike cooling line containing six cooling zones (S1÷S6), which made it possible for independently controlled cooling intensity in each of them in order to obtain unique temperature regime in consecutive cooling stages. Temperature measurement was done with pyrometers mounted in each of the cooling station. In result of initial trials of eight computationally determined treatment cycles, three combinations of fan settings were selected, producing required course of temperature changes in consecutive zones (Fig. 7). For these variants specimens from the forgings were taken out and mechanical testing performed. The results of mechanical testing are presented in figures 8 and 9.

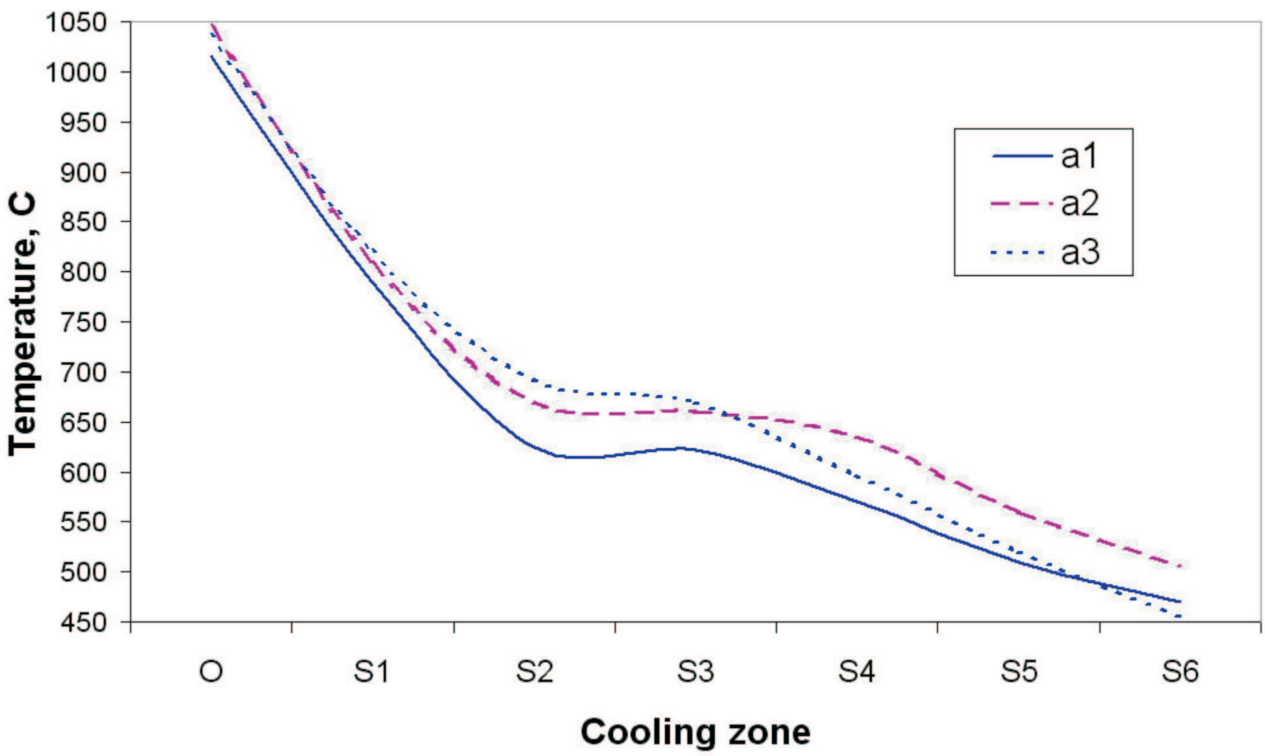


Fig. 7. Temperature of the surface in consecutive zones: a1, a2, a3 – treatment cycles, O – start-of-cooling temperature, S1 ÷ S6 – cooling zones

In the two starting efforts (cooling variants a1 and a2, shown in Fig. 8 a), unsatisfactory mechanical properties were obtained. Despite impressive surplus of plasticity, reported strength properties indicators were far too low. With changes in fan-speed controlled cooling intensity, third variant of cooling produced required minimum of both strength and plasticity indices, were meeting the imposed minimum for both strength and plasticity indices. Ultimate tensile strength 822 MPa and tensile yield stress 560 MPa were reported, while the minimum values (Min) were 820 MPa and 550 MPa, respectively (Fig. 8 a).

a)

b)

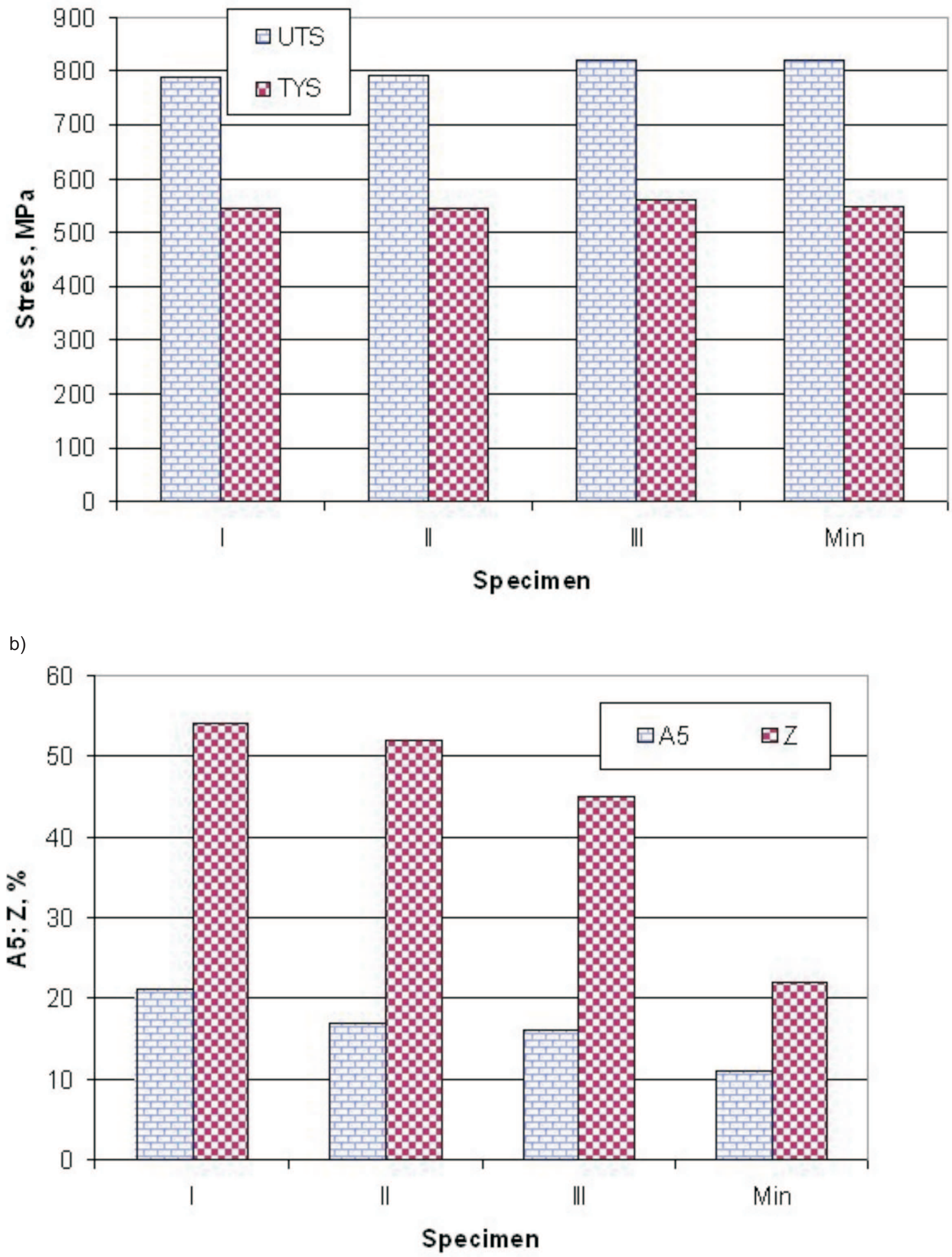


Fig. 8. Mechanical properties of the forged shaft made of 38MnSiVS6 microalloyed steel with controlled direct cooling: a) ultimate tensile strength (UTS) and tensile yield stress (TYS), b) elongation (A5) and reduction at fracture (Z)

Plasticity indices – area reduction at fracture and elongation at fracture for all of the variants were significantly higher than the required minimum. For the first and the second try it was threefold higher, reaching 52÷54% (Fig. 8 b, a1 and a2). Next attempt brought about slight decrease in plasticity, nevertheless it still formed a generous surplus over required level of 12% for elongation and 22% for reduction at fracture (Fig. 8 b, Min) reaching 16% and 24%, respectively (Fig. 8 b, a3). As such, it offers wide possibilities of further strength improvement for this chemistry.

Due to the tensile test specimen dimensions, tensile testing resulted in a sort of an average through differing in diameter sections of the forged part. As the tensile testing involved A5 specimens taken out from the core zone of the forged part, the final strength properties resulted from overall condition of the material in the axis. To investigate how uniform the distribution of mechanical properties really was, verifying numerically calculated distribution of effective strain and temperature, hardness measurements for selected locations in a lengthwise cross-section were made. The measurements were carried out for two parts, representing conventional Q&T treatment and a3 cycle of TMT treatment, that is, one with insufficient strength and the one that reached required strength level. Measurements in five characteristic locations, designated in Fig. 9 with numbers from 1 to 5, indicate several to a dozen percent discrepancies. As can be concluded from the maps of temperature profiles in corresponding cross-sections (Fig. 5), those differences in hardness go along with cooling-rate related local temperature differences. For case "a" higher hardness in locations close to ends can be observed, whereas for case "b" – in locations which represent the largest cross-sections.

Both strength properties and ductility are inextricably related to obtained microstructure, therefore quantitative effects of controlled continuous cooling must be seen in grain size and morphology of structure components. Microstructure observed in the region of location 1 is shown is shown in Fig. 10. Although differences between particular cooling variants require more precise analysis, difference between grain structure after conventional Q&T (Fig. 10 a) and thermo-mechanical treatment (Fig. 10 b) are obvious. Both pearlite grains as well as ferrite network developed in grain boundaries during direct cooling process are finely refined.

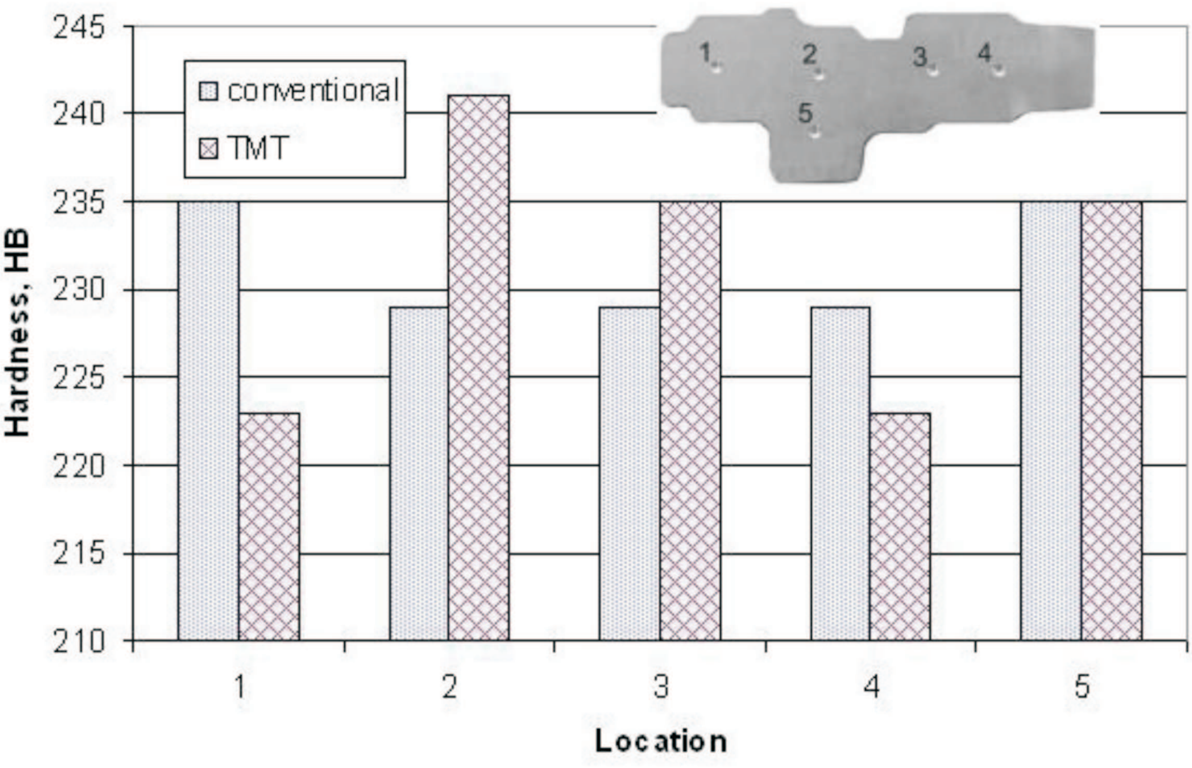


Fig. 9. Hardness measurement in locations 1÷5 in longitudinal cross-section of the crankshaft

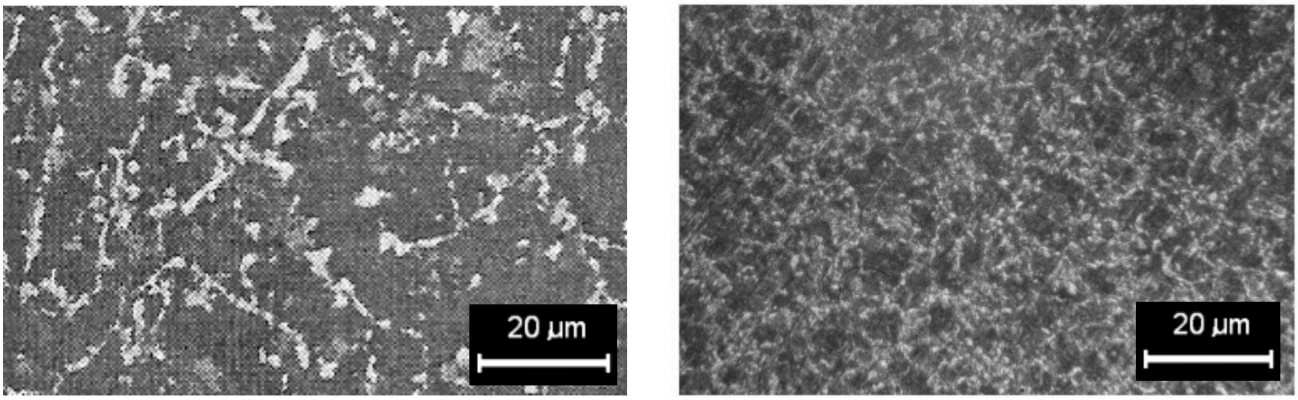


Fig. 10. Microstructure of crankshaft produced in: a) forging and Q&T treatment, b) thermomechanical treatment with application of direct cooling

5. Summary and conclusions

The results of presented study show large possibilities of control of final properties of forgings by means of thermo-mechanical treatment in industrial practice. Key issues in accomplishment of required level of final mechanical properties of drop forgings are temperature and deformation and their profiles at the end of forging operation, as well as, subsequent cycle of direct cooling with appropriate cooling curves courses in particular. Both of them must fulfill unique requirements of precipitation kinetics for a given composition of steel.

Thermo-mechanical parameters of forging operations, which are starting conditions for subsequent direct cooling can be precisely determined with finite element method modelling. As an output of the modelling the billet temperature, reduction, times and forging equipment kinematics, which allow proper profiles of temperature in forged part, are obtained. As far as cooling curves are considered, to obtain their optimal course in every cross-section six cooling zones with independently controlled cooling rate were employed. Appropriate settings ensured required time-temperature regime during continuous cooling directly after forging.

It can be concluded that air cooling with forced air of about 20 m/s suffices to provide microstructure and mechanical properties typical of high-duty automotive forged parts. Despite differences in cooling curves flow in the surface and the core of the shaft, as well as those caused by varying cross-sectional dimensions, which brought about up to 18 HB hardness variation, it produced UTS higher than 820 MPa and TYS 550 MPa.

Acknowledgements

Financial assistance of MNiSzW in the framework of 17.17.110.963 agreement is acknowledged.

REFERENCES

[1] J. Adamczyk, Inżynieria wyrobów kutych ze stali konstrukcyjnych mikrostopowych. Hutnik – Wiadomości Hutnicze. 11, 529-538 (1999).

[2] A.B. Cota, F.E.G. Oliveira, A.L. Barbosa [et al.], Microstructure and Mechanical Properties of a Microalloyed Steel After Thermal Treatments. Materials Research **6**, 2, 116-121 (2003).

[3] K.W. Wegner, Werkstoffentwicklung fur Schmiedeteile im Automobilbau. ATZ Automobiltechnische Zeitschrift 100, 12, 918-927 (1998).

[4] J. Kneller [et al.], Steel's Technical and Economical Progress in the Production of Lighter and Smaller Engine Components. American Iron and Steel Institute, 25 (2003).

[5] V. Ollilainen, W. Kasprzak, L. Holappa, The effect of silicon, vanadium and nitrogen on the microstructure and hardness of air cooled medium carbon low alloy steels. Journal of Materials Processing Technology, 134, 405-412 (2003).

[6] D.K. Matlock, G. Krauss, J.G. Speer, Microstructure and properties of direct-cooled microalloy forming steels. Journal of Materials Processing Technology **117**, 324-328 (2001).

[7] A. Niechajowicz, A. Tobota, Warm deformation of carbon steel. Journal of Materials Processing Technology **106**, 123-130 (2000).

[8] M. Jahazi, B. Eghbali, The influence of hot forging conditions on the microstructure and mechanical properties of two microalloyed steels. Journal of Materials Processing Technology **113**, 594-598 (2001).

[9] J. Sińczak, A. Łukaszek-Sołek, P. Skubisz, S. Bednarek, Kucie matrycowe odkuwki kołnierza z zastosowaniem obróbki cieplnoplastycznej. Hutnik – Wiadomości Hutnicze **3**, 187-191 (2007).

[10] B.K. Panigrahi, Bull. Mater. Sci. **24**, 4, 361-371 August 2001.

[11] T. Gladman, The Physical Metallurgy of Microalloyed Steels, The Institute of Materials, 1997.

[12] H. A d r i a n, Materials Science and Technology **8**, 406-420 (1992).
[13] H. A d r i a n, Proceedings of the International Conference "Microalloying'95", ed. by M. Korchynsky, A.J. DeArdo, P. Repas i G. Tither, Pittsburgh, 285-307 (1995).
[14] H. A d r i a n, Thermodynamic model for precipitation of carbonitrides in HSLA steels with an application to hardenability investigations, Ed. AGH, Kraków, 1995 (in Polish).
[15] P. G r i e v e s o n, Proc.Brit.Ceram. Soc. **8**, 137 (1967).
[16] C. W a g n e r, Thermodynamics of alloys, 1952, Reading, MA Addison-Wesley.
[17] K. N a r i t a, Physical Chemistry of the Groups IVa (Ti,Zt), Va (V,Nb,Ta), Trans ISIJ **15**, 145-152 (1975).
[18] K. C h a k r a b o r t y, A.B. C h a t t o p a d h y a y, A.K. C h a k r a b a r t i, A study on the grindability of niobum microalloyed forging quality HSLA steels. Journal of Materials Processing Technology **141**, 404-410 (2003).
[19] R. K u z i a k, T. B o l d, Y.W. C h e n g, Mictrostructure Control of Ferrite-Pearlite High Strength Low Alloy Steel Microalloy Additions. Journal of Materials Processing Technology **53**, 255-262 (1995).

Received: 20 August 2010.