P. SKUBISZ

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RESULTS OF THERMOMECHANICAL TREATMENT IMPLEMENTATION IN HAMMER DROP FORGING INDUSTRIAL PROCESS

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The study concerns cost-effective realization of Thermomechanical controlled processing (TMCP) in a forging process. The goal of the study was to produce mechanical properties of the steel in as-forged direct-cooled condition equivalent to those of quenched-tempered structural steel with simultaneous energy-savings benefits. The results of satisfactory implementation into hammer forging of a complex-geometry made of microalloyed medium-carbon steel 38MnVS6 in industrial conditions are presented. The use of finite element analysis for estimation of proper run of cooling curves and full-scale simulation for reproducible hot deformation and cooling conditions resulted in producing R_m over 1 120 MPa with elongation reaching 20 %.

Keywords: 38MnVS6, hot forging, thermomechanical controlled processing, mechanical properties, microstructure

INTRODUCTION

Thermomechanical controlled processing (TMCP) has been widely implemented in forging technologies of automotive, truck and civil engineering components for decades now [1, 2]. Utilizing heat attained in a bulk of deformed billet and continuous cooling directly after forging under controlled conditions, good balance of strength and ductility with significant energy savings and overall process economy can be obtained [3, 4]. While TMCP is readily conducted in press-forging technologies, it is more challenging to cope with technical setbacks of hammer forging, as well as with the aftermath of high-strain-rate deformation in direct-cooled material.

Owing to the ease of controlling energy rate within a wide range, numerous plants have been using traditional drop forging hammers or modern high-speed forging equipment which have evolved through decades [5]. Less critical in conventional heat treatment of structural-steel parts side effects of high speed [6, 7] may be detrimental in formation of austenite microstructure to be inherited in direct cooling after hot deformation [8, 9]. Thus, guidelines realization of TMCP for press forging cannot be readily transferred to hammers. The aim of this work is to assess whether the conditions of the latter are suitable for producing microstructure and properties meeting requirements for conventionally heat treated parts, indicating technological limitations and process conditions and to achieve this goal.

MATERIALS AND METHODS

The material used in the study was medium-carbon microalloyed forging steel 38MnVS6 (38MnSiSV5), whose chemical composition is shown in Table 1. Numerous references of implementation of TMCP in press-forged components gives credits for its realization in more demanding forging process conditions [9].

Table 1 **Chemical composition of the steel used in the study/ wt. %**

C	Si	Mn	Mo
0,36	0,56	1,35	0,05
P	S	V	Al
0,01	0,05	0,08	0,012

The research schedule is a combination of physical and numerical modeling meant for comprehensive elucidation of effect of processing conditions on microstructure. As the final properties depend on grain size and fractions of structural components, selection of appropriate forging regime and required cooling rate was a key issue in this effort was. The first aspect was analysed by means of physical modeling in laboratory conditions and the cooling schemes were designed with aid of finite element method (FEM) so as to obtain favourable course of cooling curves.

The response of material subjected to TMCP conditions was analysed in physical modeling tests in laboratory conditions. Forging tests were carried out on hydraulic press 5 MN with use of sample shown in Figure 1. The round hot-rolled bar was heated up to 1 100 °C, soaked up for 400 s and subject to flat-die side upsetting to produce equivalent strain ε_i = 0,48, as estimated by finite element modeling, at ram speed 50 mm/s.

P. Skubisz: (e-mail pskubisz@metal.agh.edu.pl), AGH University of Science and Technology, Cracow, Poland

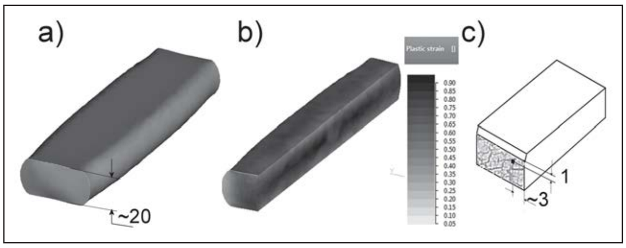

Figure 1 Geometry and dimensions of the processed part: a) contour, b) FEM calculated effective strain, c) location of analysis

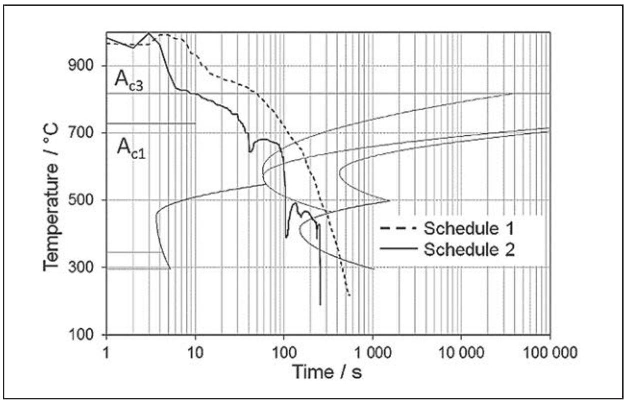

Figure 2 Cooling curves representative of assumed schedules

The as-forged specimens were passed to controlled cooling line, equipped with variable airflow-rate vents and atomizers, described in [10]. The specimens were analysed for tensile properties so as to select the best combination of process parameters.

Processing conditions of the laboratory cognition tests were adapted to industrial forging process of a screw-hook [11], carried out on production line consisting of induction heating, drop forging hammer of blow energy 60 kJ, trimming press and QuenchTube-type continuous cooling line.

Two cooling schemes were assumed in the tests: 1) based on continuous cooling with vents only, and 2) accelerated cooling with atomized spray together with variable airflow rate vents. Schedule 1 was meant for easier control of cooling rate to produce required amount of ferrite and pearlite, as well as to provide conditions for precipitation kinetics of VC and V(C,N), for strengthening through grain boundaries and precipitation. Schedule 2 was designed to fast cool the as-forged material into pearlite range fast enough for preservation of thin spacing [12] and hold it for equalization of temperature, which in combination with recalescence effect should produce an effect of temperature reversion [13]. To increase the cooling time, velocity of the conveyor and thereby, transfer times were changed (Schedule 3).

The process parameters of the tests are set in Table 2.

The estimation of tensile properties of all specimens was carried out on Zwick/Roell Z250 machine at velocity 3 mm/min. on specimens of diameter 3 mm, gauge length 30 mm, with 15 mm extensometer. Impact strength was estimated with Charpy test with 3 kJ energy.

Microstructure evaluation involved two aspects: 1) separation surface on impact-test specimens (Figure 1c), with optical microscope Keyence VHX-7000 using digital composition of field depth, and 2) relieves- with optical microscope Axowert 200MAT Carl Zeiss Jena.

RESULTS AND DISCUSSION

Preliminary test in laboratory stand

The initial tests of forging and controlled cooling in laboratory conditions, in addition to checking the joint effect of selected cooling schedules on hot-forged material, allowed the tracing the cooling curves so as to suggest possible corrections in further industrial tests. The plots of thermocouples are shown in Figure 2.

The obtained mechanical properties (Table 3) indicate reaching ultimate tensile strength (R_m) exceeding 1 100 MPa with elongation beyond 18 %, which is comparable to those required by e.g. automotive industry for high-duty components [9]. It shows that proper forging regime with application of interrupted cooling offers wide possibilities of producing strength and ductility, superior of normalized parts. Analysis of separation surface of impact-strength tested samples illustrates the nature of fracture (Figure 3). All the samples exhibit fine-grained structure with ductile fracture character, which results in better fracture resistance [14], contrary to extensive shiny planes observed on quenched as shown in Figure 3d) for reference.

Industrial implementation

The proposed schedules were copied onto the industrial production line at a degree enabled by several rationalizations. First one was forge temperature, which

Table 2 **Process parameters of the realized TMCP schedules**

Conditions/ Machine	TMCP schedule	Process variable							
		Forging temperature /°C	Forge end/°C	Speed/ cm/ min	Airflow rate/ m/s				Atomizer pressure/ bar
					Z1	Z2	Z3	Z4	
Laboratory/ Hydraulic press	1	1 100	1 140	100	15	5	15	15	0,8
	2	1 100	1 145	100	48	48	48	48	-
	3	1 100	1 146	100	48	5	48	48	-
Forge plant / Hammer	1	1 140	1 225	100	25	2	25	25	0,8
	2	1 140	1 225	100	25	2	2	2	0,8
	3	1 140	1 225	80	45	45	45	45	-
	4	1 180	1 240	80	45	5	45	45	0,8

Table 3 **Mechanical properties of preliminary TMCP samples**

Condition	R_e /MPa	R_m /MPa	A_5 /%	K_{VC}/ J/cm^2
Schedule 1	540	1 064	18,1	43
Schedule 2	572	1 137	14,5	16
Schedule 3	605	1 083	19,1	30
Quenched	815	1 560	4,3	11
Normalized	468	733	17,8	27

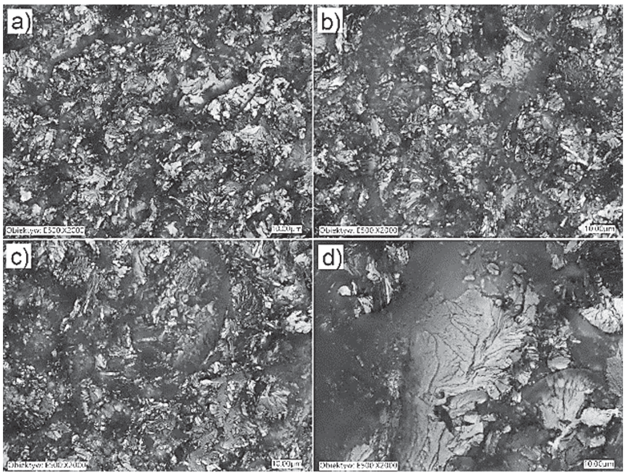

Figure 3 Microstructure of impact-tested material of laboratory samples after cooling schedule: a) 1 , b) 2, c) 3 and d) as-quenched.

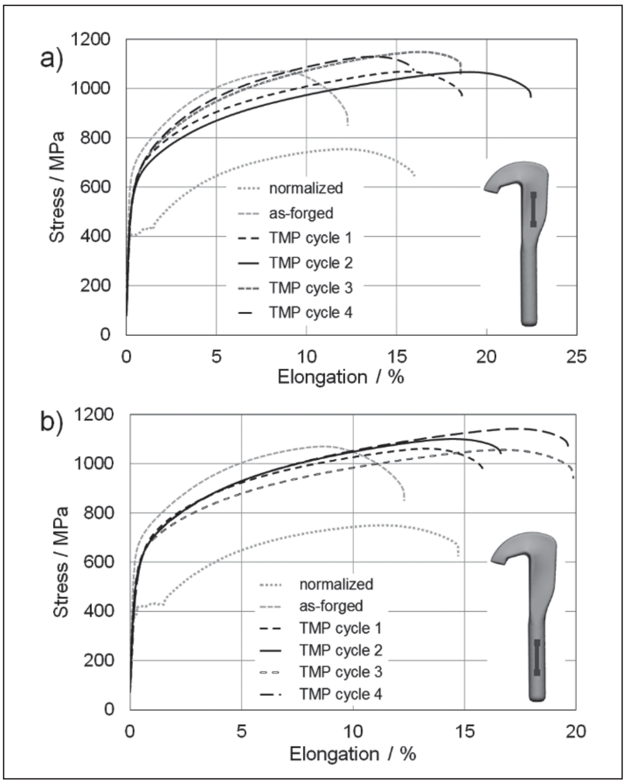

Figure 5 Tensile properties of forged samples TMCP processed under industrial conditions for different cross-sections (a, b)

was higher on account of available energy to produce plastic work. Thus regime 1 140 °C was assumed for realization of the three schedules. For the best schedule, higher temperature was also considered, (to omit supposed instability range [15] it was 1 180 °C) making Schedule 4.

The microstructure of all samples consists of ferrite-bainite structure with some fine pearlite (Figure 4), indicating resemlence to low-carbon acicular/bainitic ferrite, which here might be a results of high sulful. High cooling rates in schedules 1 and 2 seem to promote bainitic structure, hence the lower elongation. Air-cooled samples show more uniaxial grains with more pearlite fraction (Figure 4c), which allows good combination of strength and plasticity. Increasing forge temperature cause goarser grains occurrnce (Figure 4d).

Fine-grained irregular morphology of acicular ferrite featured by high grain boundaries per volume favours good plasticity with simultaneous strength exceeding 1 120 MPa in both analysed sections (Figure 5). Obviously, the thicker section yields highed plasticity, while the other one, higher strength (Figure 5b). However, the differences are sufficiently small so as to infer uniformity in the volume. It shows that both proper forging regime and cooling amends for detrimental hammer-forging effects.

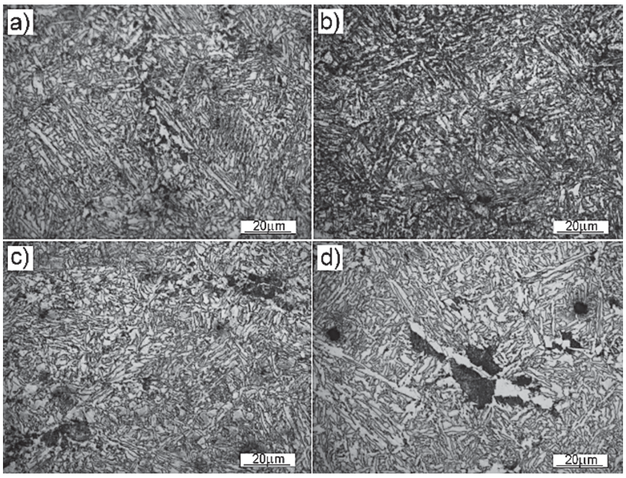

Figure 4 Optical microscope microstructure of forgings after TMCP schedules: a) 1 , b) 2 , c) 3 forged in 1 140 °C and d) schedule 4

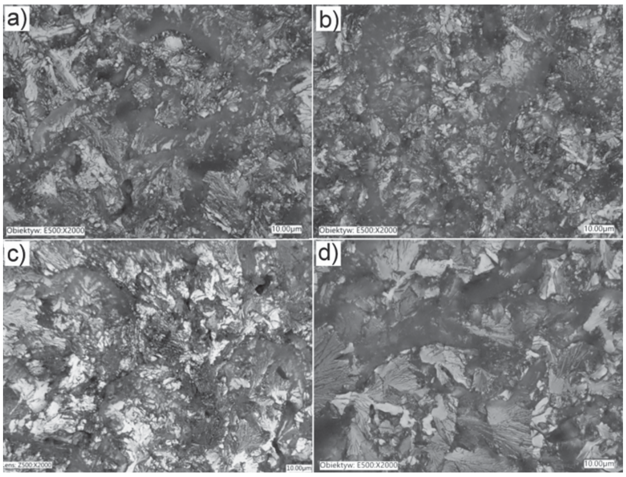

Figure 6 Microstructure of impact-tested forgings after TMCP schedules: a) 1, b) 2 , c) 3 forged in 1 140°Cand d) schedule 1 forged in 1 180 °C

The obtained properties are comparable to those required by e.g. automotive industry for high-duty components [9]. Complex multistage forging chain [11] makes the selected part representative for numerous instances of elongate geometries, and allows for investigation of effect of the process condition on microstructure for straining history varied between locations.

CONCLUSIONS

Application of TMCP for hammer forging allows producing Rm 1 120 MPa with 19 % elongation. Although these levels are second to press-forged parts, still meet requirements typical of steel 38MnVS6 for civil or automotive industry.

The use of atomized air spray and forced air enables controlling properties of hammer die-forgings, reducing detrimental effects of unfavourable straining conditions. Local intensification of cooling rate may result in overcooling promoting strength enhancement or equalization of cooling between locations in the bulk.

It allows take advantage of several strengthening mechanisms, both typical of microalloyed steels (grain refinement and precipitation) and those present in conventional heat treatment based solely on transformation hardening.

Acknowledgements

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REFERENCES

[1] M. Cohen, W. S. Owen, Thermo-Mechanical Processing of Microalloying‘75 International Conference on Microalloyed Steels, 1975, 2-8

[2] H. Hara, M. Kobayashi, The Use of Hot Forged Microalloyed Steel on Automobile Components, The Institute of Metals, 1987, pp. 5-15

[3] Thermomechanical Processing of High Strength Low Alloy Steels, Tamura I.(ed.), Ouchi C., Tanaka T., Sekini H., Butterworths, 1988

[4] J. Adamczyk, M. Opiela, Engineering of Forged Products of Microalloyed Constructional Steels, J. Arch. Mater. Manuf. Eng. 15 (2006) 153–158

[5] T. G. Byrer, S. L. Semiatin, D. C. Vollmer, Forging Handbook, Forging Industry Association, American Society of Metals, Cleveland, 1985

[6] B. Garbarz, T. Bołd, Influence of austenite substructure on structure and properties of low alloy steels quenched directly from hot deformation temperature, Met. Sci., 18 (1984) 357-361

[7] P. Skubisz, Ł. Lisiecki, Warm-forging characteristics and microstructural response of medium carbon high-strength steels for high-duty components, Key Engineering Materials 611-612 (2014) 167-172

[8] T. Sakai, A. Belyakov, R. Kaibyshev, H. Miura, J. J. Jonas, Dynamic and post-dynamic recrystallization under hot, cold and severe plastic deformation conditions, Progr. Mater. Sci. 60 (2014) 130-207

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

[10] P. Skubisz, Ł. Lisiecki, T. Skowronek, A. Żak, W. Zalecki, Effect of direct cooling conditions on the microstructure and properties of hot-forged HSLA steels for mining applications, Mater. Tehnol. 50 (2016) 5, 783-789

[11] P. Skubisz, A. Żak, M. Burdek, Ł. Lisiecki, P. Micek, Design of controlled processing conditions for drop forgings made of microalloy steel grades for mining industry,Arch. Metall. Mater. 60 (2015) 1, 445-453

[12] O.P. Modia et al., Effect of Interlamellar Spacing on the Mechanical Properties of 0,65% C Steel, Mater. Charact. 46 (2001) 347-352

[13] Guo L., Roelofs H., Lembke M. I., Bhadeshia H. K. D. H. Modelling of recalescence effect on austenite decomposition. Mat. Sci. Tech. 33 (2017) 10, 1258-1267

[14] Petch N. J., The cleavage strength of polycrystals, J. Iron Steel Inst., 1953, 174, 25-28

[15] R. D. Septimio, S. T. Button, C. J. Van Tyne, Processing maps for the analysis of hot workability of microalloyed steels 38MnSiVS5 and 0.39C1.47Mn, J. Mat. Sci. 51 (2016) 5, 2512-2528

Note: The responsible professional translator: Karolina Bousiou-Czeppe, E-polyglots Language School, Thessaloniki, Greece