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Preservation conditions of hot work hardening in die steel with regulated austenitic transformation during exploitation

A. A. Kruglyakov[1], **S. O. Rogachev**[2, 3], **P. Yu. Sokolov**[2], **D. V. Priupolin**[2]

[1] **Scientific Production Association WBH** (106 b Friedrichstrasse, Berlin D-10117, Germany)
[2] **National University of Science and Technology "MISIS"** (4 Leninskii Ave., Moscow 119049, Russian Federation)
[3] **Baikov Institute of Metallurgy and Materials Science, Russian Academy of Sciences** (49 Leninskii Ave., Moscow 119334, Russian Federation)

csaap@mail.ru

Abstract. Die steels with regulated austenitic transformation during exploitation (RATE steels) are a new class of tungsten-free steels for hot forming at operating temperatures up to 750 – 800 °C. High durability of the pressing tool and its long service life are ensured by the ability of these steels to preservation of hot work hardening. This circumstance distinguishes RATE steels from traditional alloy steels, which are prone to softening at high temperatures. However, the temperature ranges for the preservation of hot hardening in RATE steels was not systematically studied, which makes it difficult to use a pressing tool more efficiently. In this paper, we study the mechanical behavior of RATE die steel during thermo-mechanical treatment in a wide temperature range, including the stage of preliminary deformation at lower temperatures and the stage of main deformation at higher temperatures corresponding to operating temperatures of the pressing tool. The thermo-mechanical treatment was carried out using a hardening-deformation dilatometer DIL 805 A/D according to the compression mode. We obtained the true stress-strain curves and determined the mechanical characteristics and strain hardening index. Size of the former austenite grain in the steel structure after thermo-mechanical treatment was measured. The temperature-force conditions for enhancing hot hardening or stabilizing hot hardening, or softening, were established. It is shown that the hardening achieved at the stage of preliminary deformation at a temperature of 450 °C is enhanced at the stage of main deformation at temperatures in the range from 550 to 800 °C, while in this temperature range the tendency to increase hot hardening is weakened.

Keywords: RATE steels, die steels, hot deformation, hot work hardening, austenite

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Условия сохранения горячего наклепа в штамповой стали с регулируемым аустенитным превращением при эксплуатации

А. А. Кругляков[1], **С. О. Рогачев**[2, 3], **П. Ю. Соколов**[2], **Д. В. Приуполин**[2]

[1] **Научно-коммерческая фирма WBH** (Германия, D-10117, Берлин, Фридрихштрассе, 106 Б)
[2] **Национальный исследовательский технологический университет «МИСИС»** (Россия, 119049, Москва, Ленинский пр., 4)
[3] **Институт металлургии и материаловедения им. А.А. Байкова РАН** (Россия, 119334, Москва, Ленинский пр., 49)

csaap@mail.ru

Аннотация. Штамповые стали с регулируемым аустенитным превращением при эксплуатации (РАПЭ) – новый класс безвольфрамовых сталей для горячей обработки давлением при рабочих температурах до 750 – 800 °С. Высокая стойкость прессового инструмента и его длительный ресурс обеспечиваются за счет способности этих сталей сохранять горячее деформационное упрочнение (горячий наклеп). Это обстоятельство отличает стали с РАПЭ от традиционных легированных сталей, склонных к разупрочнению при высоких температурах. Однако температурные диапазоны проявления горячего упрочнения в сталях с РАПЭ систематически не изучены, что затрудняет более эффективное использование штампового инструмента. В данной работе изучено механическое поведение штамповой стали с РАПЭ при термомеханической обработке в широком диапазоне температур, включающей этап предварительной деформации при более низких температурах и этап основной деформации при более высоких температурах, соответствующих температурам эксплуатации прессового инструмента. Термомеханическую обработку проводили на закалочно-деформационном дилатометре DIL 805 A/D по схеме сжатия. Получены истинные диаграммы деформации, определены механические характеристики и показатель деформационного упрочнения. Измерен размер бывшего зерна аустенита в структуре стали после термомеханической обработки. Авторы установили температурно-силовые условия, в которых сталь демонстрирует усиление и стабилизацию горячего упрочнения, либо разупрочнение. Показано, что достигнутое на этапе предварительной деформации при температуре 450 °C упрочнение усиливается на этапе основной деформации при температурах в интервале от 550 до 800 °C, при этом в указанном температурном интервале склонность к усилению горячего упрочнения ослабевает.

Ключевые слова: стали с РАПЭ, штамповые стали, горячая деформация, горячий наклеп, аустенит

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Introduction

The heat resistance of α-iron-based steels at temperatures around 690 – 700 °C is considered ultimate. Consequently, the most heat-resistant die steels, such as 5Kh3V3MFS, 3Kh2V8F (also known as DIN: X30WCrV9-3, AISI/SAE: H21 or H21A), 4Kh2V5MF, and 4Kh2V4FS, which boast high tungsten content, are typically limited to operating temperatures during hot pressing up to 660 – 680 °C [1 – 3]. Tungsten-free steels like 70Kh3G2FTR or 4Kh5MGFS have even lower operating temperatures [4; 5]. While the operating temperatures of austenitic steels are somewhat higher, their manufacturability is notably low [6 – 8].

In the 1980s, A.D. Ozerskii and A.A. Kruglyakov pioneered the development of die steels featuring a controlled austenitic transformation during exploitation, (RATE steels). These were tungsten-free steels primarily composed of α-iron, designed for high-pressure hot working at operating temperatures reaching up to 750 – 800 °C [9 – 11]. The exceptional durability of these press tools and their extended service life stem from the steels' capability to maintain hot strain hardening, also known as hot work hardening [12; 13]. This quality distinguishes RATE steels from conventional alloy steels, which are susceptible to softening under high-temperature conditions. The primary cause of this softening lies in the onset of recovery processes and dynamic recrystallization [14 – 16]. As a consequence, there is a notable alteration in the shape of stress-strain curves at elevated temperatures [17; 18].

The inclination towards hot work hardening in RATE steels underwent experimental scrutiny through thermomechanical treatment, involving initial deformation at a lower temperature followed by subsequent deformation at a higher temperature [19 – 21]. The hardening level attained during the preliminary deformation stage was not only sustained but further augmented during the main deformation phase. However, these studies confined the preliminary deformation temperature to 450 °C and the main deformation temperature to 750 °C. Consequently, the temperature ranges conducive to showcasing hot hardening in such steels have not been comprehensively explored. This is a crucial aspect in determining pre-hardening temperatures for the die and operational temperatures that ensure optimal and prolonged die tool performance.

This study aims to investigate the impact of hot deformation temperature on the manifestation of hot hardening in RATE die steel, focusing on a medium-carbon Fe – C – Si – Cr – Ni – Mn – Mo – V – Ti – Nb steel as an illustrative example.

Materials and methods

In this study, RATE die steel, specifically of the 4Kh2N3M2G4FTBS type [22], was utilized subsequent to a softening heat treatment, resulting in an approximate hardness of ~34 HRC.

Thermomechanical treatment (TMT) was conducted using cylindrical samples measuring 10 mm in height and 5 mm in diameter on a DIL 805 A/D hardening-deformation dilatometer. The TMT process comprised the following sequential stages:

– austenitization at 1150 °C for 15 min;

– a 15 min holding period and preliminary plastic deformation at a temperature range of 400 – 500 °C (in intervals of 50 °C);

– a 15 min holding period and main plastic deformation at a temperature range of 550 – 850 °C (in intervals of 50 °C).

After TMT, the samples underwent free cooling (~10 °C/s).

The layout of the TMT protocol is represented in Fig. 1.

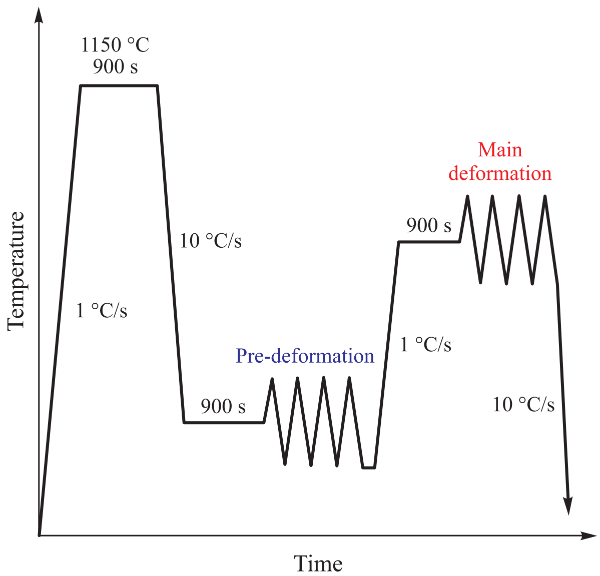

Fig. 1. Thermo-mechanical treatment diagram

Рис. 1. Диаграмма термомеханической обработки

The deformation process was carried out according to a compression sequence involving five cycles, with each cycle involving deformation within the range of 1 – 2 % and a deformation rate set at 1 – 2 %, rate: 0.1 s^{-1}). Process curves capturing "true stress – true deformation" coordinates were recorded throughout the deformation sequences.

The strain hardening index *n* was calculated utilizing the equation $S = Ke^n$, where *S* is the true stress; *K* is the coefficient, and *e* is the true deformation.

Microstructural analysis of polished sections involved etching in a 5 % aqueous solution of nitric acid. The resulting microstructure was examined using an NIM-100 optical microscope at a magnification of 200x. The grain size was determined from the microstructure images obtained by employing the secant method.

Microhardness was assessed using the Vickers method with a Micromet 5101 Buehler instrument. The experimental parameters were as follows: a load of 300 g, load application time of 10 s, and microscope magnification set at 500x. Measurements were conducted on transverse polished sections of samples subsequent to TMT in two distinct zones: at the periphery and at the center of the sample.

Results and discussion

The mechanical characteristics of the RATE steel during TMT with varying temperatures for preliminary deformation and a consistent temperature for the main deformation are detailed in Table 1, while the strain curves are visually represented in Fig. 2. Similar to earlier investigations [19; 20], multiple plastic deformations at 450 °C led to a notable strengthening of the steel: the maximum cycle stress (S_{max}) escalated from the initial range of 248 – 263 to 441 – 467 MPa (1.8 times). This achieved level of hardening remained steady during the first cycle of main deformation at 750 °C and further increased across the subsequent four cycles: S_{max} rose to 517 – 523 MPa (1.1 times). Altering the temperature within the preliminary deformation stage from 400 to 500 °C exerted a marginal influ-

Table 1

Mechanical characteristics of RATE steel during TMT with varying pre-deformation temperature

Таблица 1. **Механические характеристики стали с РАПЭ при ТМО с варьированием температуры предварительной деформации**

Deformation	Preliminary					Main				
Temperature	400 °C					750 °C				
Cycle, No.	1	2	3	4	5	6	7	8	9	10
S, MPa	263	326	379	425	467	471	486	498	508	517
e	0.019	0.018	0.018	0.017	0.016	0.016	0.016	0.015	0.015	0.012
n	0.37					0.06				
Temperature	450 °C					750 °C				
S, MPa	250	312	364	409	450	474	493	502	511	518
e	0.019	0.019	0.017	0.017	0.017	0.016	0.016	0.015	0.015	0.014
n	0.38					0.06				
Temperature	500 °C					750 °C				
S, MPa	248	308	358	402	441	486	500	510	517	523
e	0.019	0.018	0.018	0.017	0.017	0.015	0.015	0.015	0.014	0.012
n	0.37					0.04				

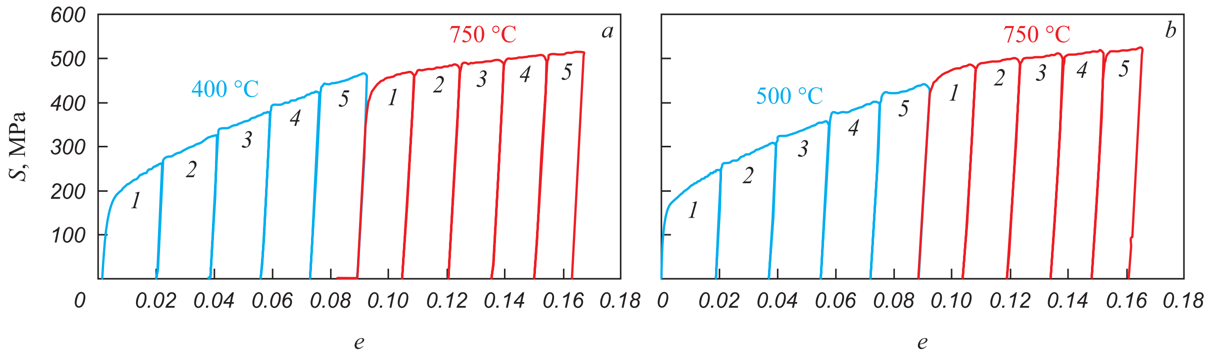

Fig. 2. Stress-strain curves of RATE steel during TMT with varying pre-deformation temperature 400 (*a*) and 500 °C (*b*)

Рис. 2. Кривые деформации стали с РАПЭ при ТМО с варьированием температуры предварительной деформации 400 (*а*) и 500 °С (*b*)

Table 2

Mechanical characteristics of RATE steel during TMT with varying the main deformation temperature

Таблица 2. **Механические характеристики стали с РАПЭ при ТМО с варьированием температуры основной деформации**

Deformation	Preliminary					Main				
Temperature	450 °C					550 °C				
Cycle, No.	1	2	3	4	5	6	7	8	9	10
S, MPa	252	313	363	408	449	445	478	512	541	569
e	0.019	0.019	0.018	0.017	0.017	0.016	0.016	0.015	0.015	0.014
n	0.37					0.16				
Temperature	450 °C					600 °C				
S, MPa	242	303	354	398	438	420	445	485	513	537
e	0.019	0.018	0.018	0.017	0.017	0.016	0.015	0.015	0.014	0.012
n	0.38					0.16				
Temperature	450 °C					650 °C				
S, MPa	254	316	368	414	452	439	474	504	530	552
e	0.019	0.019	0.018	0.018	0.017	0.016	0.016	0.015	0.015	0.013
n	0.37					0.15				
Temperature	450 °C					700 °C				
S, MPa	245	305	355	398	438	454	477	501	521	537
e	0.019	0.019	0.019	0.019	0.018	0.017	0.017	0.017	0.016	0.014
n	0.36					0.11				
Temperature	450 °C					750 °C				
S, MPa	250	312	364	409	450	474	493	502	511	518
e	0.019	0.019	0.017	0.017	0.017	0.016	0.016	0.015	0.015	0.014
n	0.38					0.06				
Temperature	450 °C					800 °C				
S, MPa	254	315	367	410	449	442	449	449	451	451
e	0.019	0.018	0.017	0.017	0.017	0.015	0.015	0.015	0.014	0.013
n	0.37					0.01				
Temperature	450 °C					850 °C				
S, MPa	246	303	352	395	436	368	373	375	377	378
e	0.019	0.018	0.017	0.017	0.017	0.017	0.017	0.016	0.016	0.014
n	0.37					0.02				

ence on the hardening level, both during preliminary and main deformations. At equivalent degrees of deformation, the maximum stress disparity was no more than 6 %. However, this difference diminished as the degree of primary deformation increased. The heightened hardening observed in the first cycle of main deformation, compared to the fifth cycle of preliminary deformation, was most pronounced (10 %) when the preliminary deformation temperature was set at 500 °C.

The mechanical characteristics of the RATE steel during TMT at a constant temperature for preliminary deformation while varying the temperature of the primary deformation are summarized in Table 2, with corresponding strain curves presented in Fig. 3.

The achieved level of hardening during the preliminary deformation stage at a temperature of 450 °C demonstrates intensification during the main deformation phase at temperatures ranging from 550 to 750 °C. Specifically, at 550 °C, S_{max} increases to 569 MPa (a 27 % increase), while at 750 °C, it reaches 518 MPa (a 15 % rise). Notably, as the temperature of the main deformation escalates from 550 to 750 °C, the propensity for hot

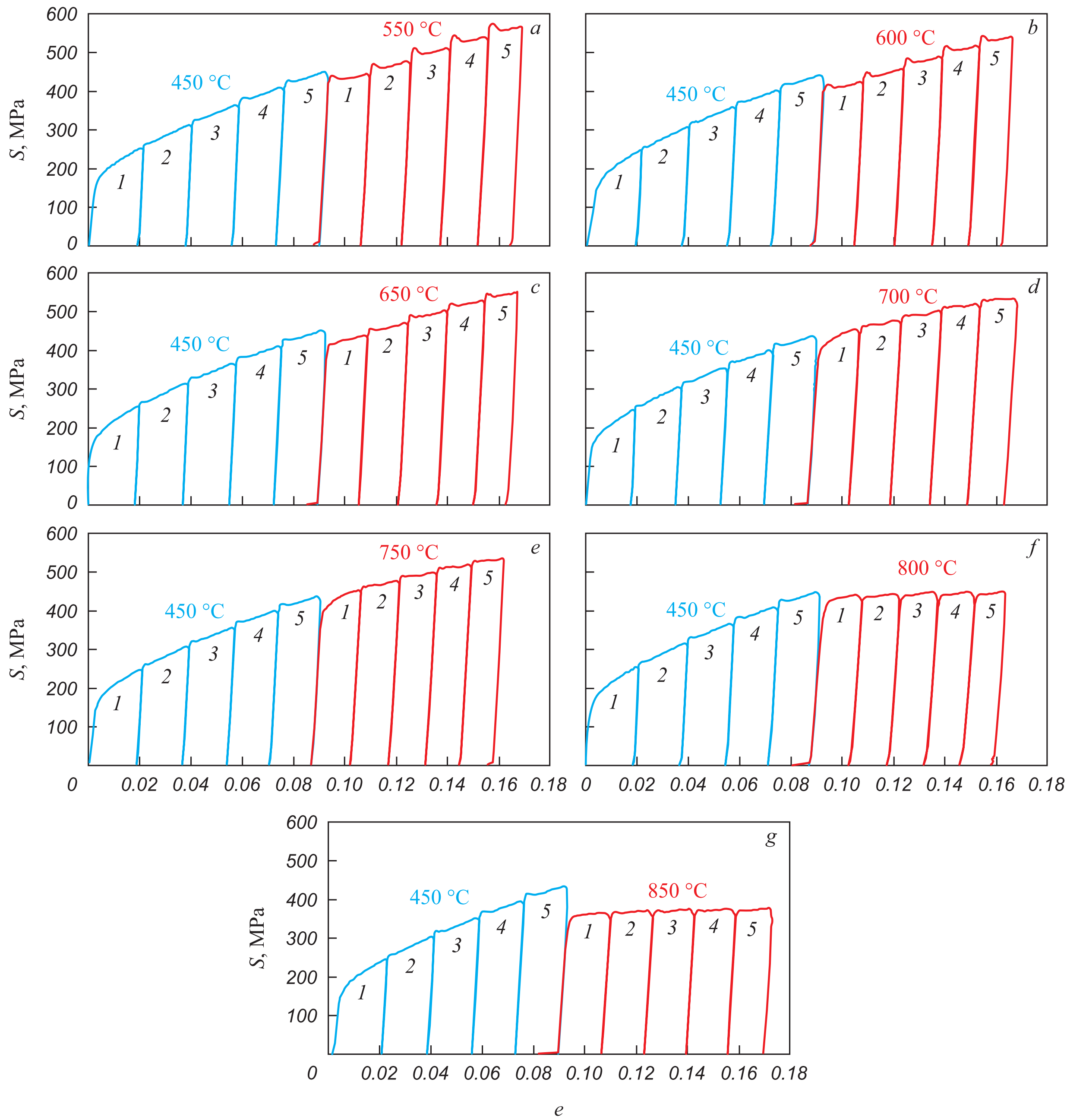

Fig. 3. Stress-strain curves of RATE steel during TMT with varying the main deformation temperature, °C:
a – 550; *b* – 600; *c* – 650; *d* – 700; *e* – 750; *f* – 800; *g* – 850

Рис. 3. Кривые деформации стали с РАПЭ при ТМО с варьированием температуры основной деформации, °С:
a – 550; *b* – 600; *c* – 650; *d* – 700; *e* – 750; *f* – 800; *g* – 850

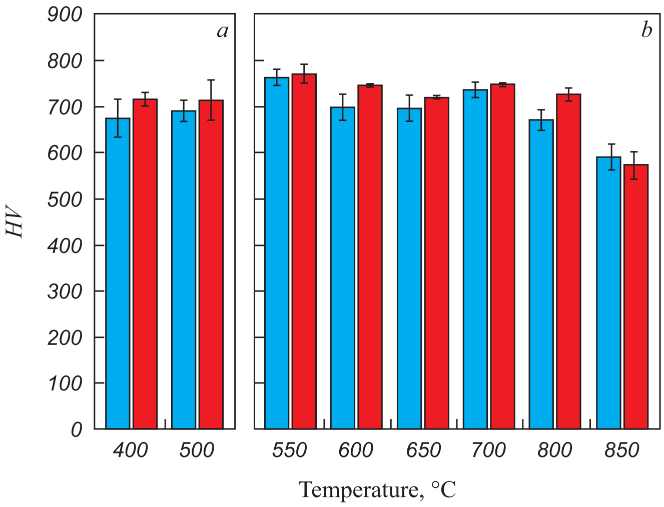

Fig. 4. Dependence of RATE steel microhardness on temperature of preliminary (*a*) and main (*b*) deformation: ■ – periphery; ■ – center

Рис. 4. Зависимость микротвердости стали с РАПЭ от температуры предварительной (*а*) и основной (*b*) деформации: ■ – периферия; ■ – центр

hardening diminishes, indicated by a decrease in the strain hardening index ‘*n*’ from 0.16 to 0.06. Further elevating the temperature of the main deformation to 800 °C does not yield an additional increase in hot hardening; instead, it stabilizes at S_{max} levels of around 450 MPa ($n = 0.01$). Eventually, with a subsequent increase in the temperature of the main deformation to 850 °C, some softening of the steel becomes apparent: S_{max} in the initial deformation cycle drops to 368 MPa (a 20 % decrease), maintaining this level across the subsequent four deformation cycles ($n = 0.02$). It's crucial to highlight that even at 850 °C, the S_{max} values surpass those observed during the initial hardening cycles at 450 °C. Remarkably, the strength level of the RATE steel at 850 °C exceeds that of high-alloy 10Cr–10Ni–5Mo–2Cu steel (under comparable degrees of deformation and loading rates) [23].

The microhardness of the RATE steel after TMT and cooling to room temperature mainly correlates with the level of hot hardening after the main deformation (Fig. 4). Consequently, following preliminary deformation within the range of 400 – 500 °C and subsequent cooling, the microhardness remains constant at approximately 700 HV. After cooling from main deformation temperatures spanning 550 – 800 °C, a minor decreasing trend in microhardness is observed, ranging from 770 to 700 HV. After main deformation at a temperature of 850 °C, the microhardness sharply drops to 580 HV. The disparity in microhardness between the sample's center and its periphery is negligible.

Fig. 5 illustrates the microstructure, specifically the former austenite grain of the RATE steel after TMT, varying the temperature of preliminary deformation,

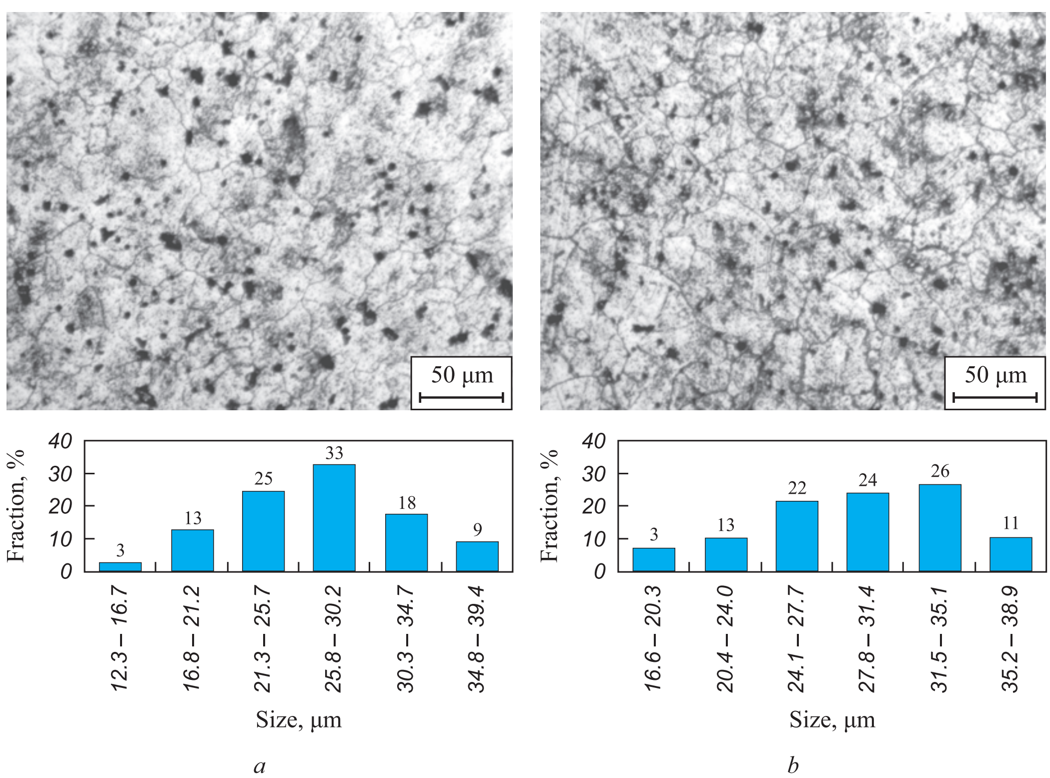

Fig. 5. Former austenite grain in the structure of RATE steel after TMT with varying pre-deformation temperature 400 (*a*) and 500 °C (*b*)

Рис. 5. Бывшее зерно аустенита в структуре стали с РАПЭ после ТМО с варьированием температуры предварительной деформации 400 (*a*) и 500 °C (*b*)

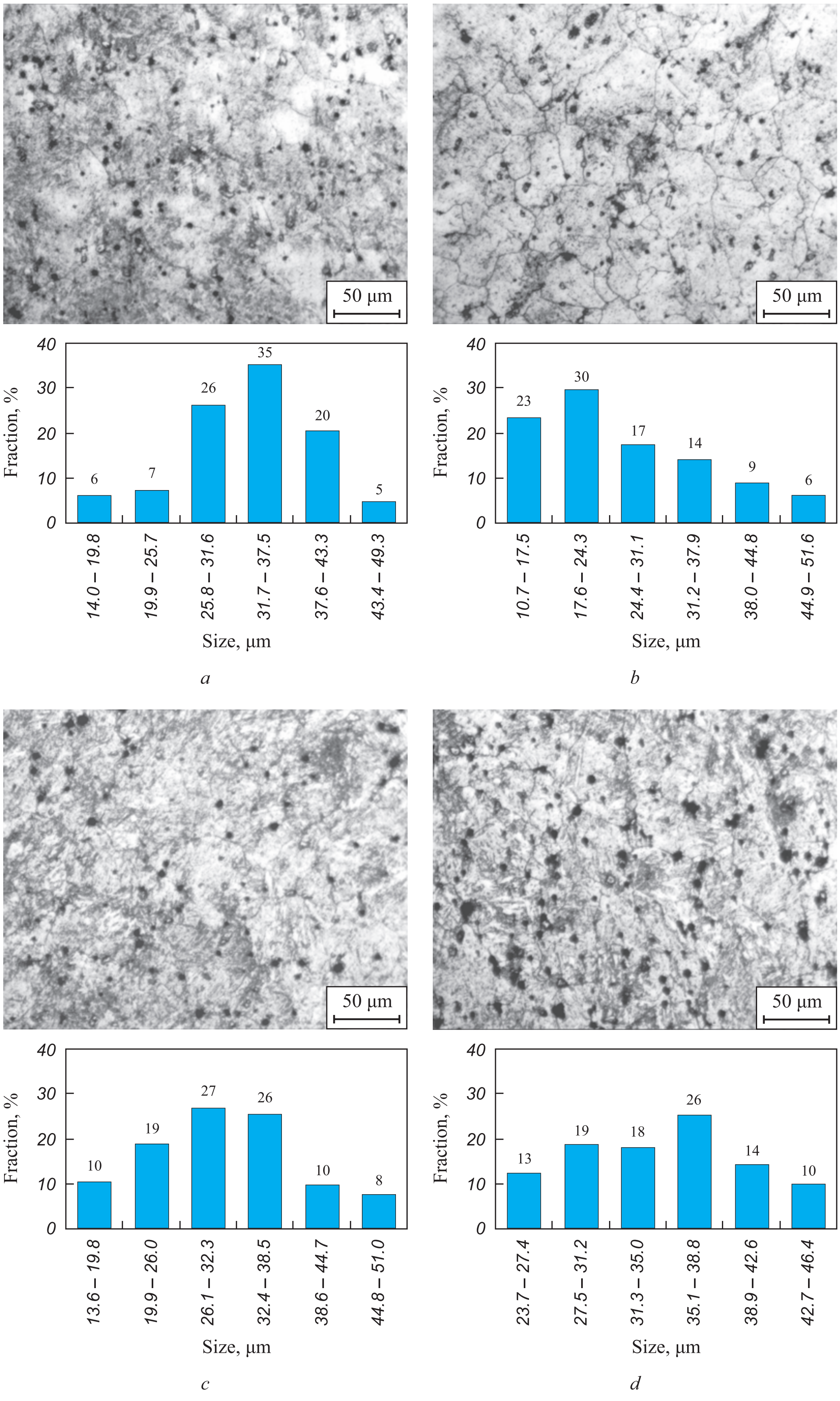

Fig. 6. Former austenite grain in the structure of RATE steel after TMT with varying the main deformation temperature, °C:
a – 550; *b* – 750; *c* – 800; *d* – 850

Рис. 6. Бывшее зерно аустенита в структуре стали с РАПЭ после ТМО с варьированием температуры основной деформации, °C:
a – 550; *b* – 750; *c* – 800; *d* – 850

Table 3

Size of the former austenite grain in the structure of RATE steel after TMT with varying pre-deformation temperature

Таблица 3. **Размер бывшего зерна аустенита в структуре стали с РАПЭ после ТМО с варьированием температуры предварительной деформации**

Pre-deformation temperature, °C	400	500
Minimum grain size, μm	12	17
Maximum grain size, μm	39	39
Average grain size, μm	27 ± 6	29 ± 5

Table 4

Size of the former austenite grain in the structure of RATE steel after TMT with varying the main deformation temperature

Таблица 4. **Размер бывшего зерна аустенита в структуре стали с РАПЭ после ТМО с варьированием температуры основной деформации**

Main deformation temperature, °C	550	600	650	700	750	800	850
Minimum grain size, μm	17	16	12	11	14	14	16
Maximum grain size, μm	38	36	34	52	49	51	48
Average grain size, μm	29 ± 5	25 ± 5	22 ± 5	26 ± 8	33 ± 7	31 ± 8	35 ± 6

and cooling to room temperature, alongside histograms depicting grain size distribution.

Table 3 provides the former austenite grain size after TMT, showcasing that an increase in the preliminary deformation temperature from 400 to 500 °C doesn't influence the former austenite grain's size, which averages around 28 μm, aligning with 7 points according to State Standard GOST 5639–82.

Fig. 6 illustrates the microstructure, particularly the former austenite grain of the RATE steel after TMT, while varying the temperature of the main deformation and subsequent cooling to room temperature. Additionally, histograms representing grain size distribution are provided.

Table 4 presents the former austenite grain size following TMT at various main deformation temperatures. The data reveals a slight inclination towards an increase in the former austenite grain size from 29 to 35 μm as the main deformation temperature escalates from 550 to 850 °C. This progression aligns with 7 points according to State Standard GOST 5639–82.

Conclusions

The rise in preliminary deformation temperature from 400 to 500 °C minimally impacts the strengthening of steel with RATE at both the preliminary and main deformation stages at a constant temperature of 750 °C.

At a constant preliminary deformation temperature of 450 °C, the level of hardening achieved intensifies during the main deformation stage within the range of 550 to 750 °C. However, this strain hardening tendency weakens with rising temperatures. Further elevation of the main deformation temperature to 800 °C results in a stabilized strengthened state. Subsequently, a marginal softening is observed up to 850 °C.

Increasing the preliminary deformation temperature from 400 to 500 °C at a constant main deformation temperature of 750 °C does not significantly alter the size of the former austenite grain, which averages around 28 μm. Conversely, a subtle increase in the former austenite grain size from 29 to 35 μm is noted when the main deformation temperature rises from 550 to 850 °C, while maintaining a constant preliminary deformation temperature of 450 °C.

The findings suggest that RATE steel demonstrates efficient performance across a broad range of tool heating temperatures, spanning from 550 to 800 °C. Notably, even at a heating temperature of 850 °C, the steel retains a considerably high strength margin of 380 MPa.

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Information about the Authors / Сведения об авторах

Aleksandr A. Kruglyakov*, Cand. Sci. (Eng.), General Director,* Scientific Production Association WBH
E-mail: dr.a.krugljakow@t-online.de

Stanislav O. Rogachev*, Cand. Sci. (Eng.), Assist. Prof. of the Chair “Metallography and Physics of Strength”*, National University of Science and Technology “MISIS”; *Research Associate*, Baikov Institute of Metallurgy and Materials Science, Russian Academy of Sciences
ORCID: 0000-0001-7769-7748
E-mail: csaap@mail.ru

Pavel Yu. Sokolov*, Senior Lecturer*, National University of Science and Technology “MISIS”
E-mail: sokolov@misis.ru

Denis V. Priupolin*, Student*, National University of Science and Technology “MISIS”
E-mail: dpriupolin@gmail.com

Александр Аркадьевич Кругляков*, к.т.н., генеральный директор,* Научно-коммерческая фирма WBH
E-mail: dr.a.krugljakow@t-online.de

Станислав Олегович Рогачев*, к.т.н., доцент кафедры металловедения и физики прочности*, Национальный исследовательский технологический университет «МИСИС»; *научный сотрудник,* Институт металлургии и материаловедения им. А.А. Байкова РАН
ORCID: 0000-0001-7769-7748
E-mail: csaap@mail.ru

Павел Юрьевич Соколов*, старший преподаватель,* Национальный исследовательский технологический университет «МИСИС»
E-mail: sokolov@misis.ru

Денис Викторович Приуполин*, студент*, Национальный исследовательский технологический университет «МИСИС»
E-mail: dpriupolin@gmail.com

Contribution of the Authors / Вклад авторов

A. A. Kruglyakov – conceptualization, formulation of conclusions.

S. O. Rogachev – scientific guidance, writing the text.
P. Yu. Sokolov – investigation, calculations.
D. V. Priupolin – investigation, calculations.

А. А. Кругляков – формирование основной концепции, формулирование выводов.
С. О. Рогачев – научное руководство, подготовка текста статьи.
П. Ю. Соколов – проведение расчетов.
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