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Study of the mechanical properties of C45 steel with a ferrite–pearlite microstructure

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ABSTRACT

This paper presents the results of investigations of C45 steel with a ferrite-pearlite microstructure obtained by austenitizing at 850 °C, accelerated cooling in compressed air, and subsequent subcritical heat treatment below Ac_1. The applied route is therefore described as accelerated air cooling followed by subcritical holding, and not as classical quenching and tempering of martensite. The specimens were held at 500, 550, 600, 650, and 700 °C for 15 min, 1 h, 3 h, 9 h, and 23 h. Tensile testing was used to determine the yield strength Re, ultimate tensile strength Rm, and elongation A, while Vickers microhardness HV0.5 and SEM observations were used to characterize the response of the material. The results showed a monotonic decrease in Re, Rm, and HV0.5 with increasing subcritical heat-treatment temperature and holding time, whereas elongation generally increased, although with local non-monotonic variations. The observed trends are interpreted as consistent with softening processes in a ferrite-pearlite structure; however, because the metallographic evidence is qualitative, the mechanistic interpretation is formulated cautiously. The presented data may support the selection of subcritical heat-treatment parameters for C45 steel when specified tensile properties and hardness are required.

Keywords: C45 steel, subcritical heat treatment, ferrite-pearlite microstructure, mechanical properties, microhardness.

INTRODUCTION

Medium-carbon steels constitute one of the important engineering materials and are widely used in many industrial sectors, from automotive engineering to construction and railway applications. They are employed, among others, in the manufacture of crankshafts, axles, gears, and other machine components requiring good toughness under moderate loading conditions. The popularity of medium-carbon steels results from the combination of good mechanical properties and relatively low production costs. In these steels, the ferrite–pearlite microstructure plays a particularly important role, as it provides a balance between strength and ductility that is difficult to obtain in other microstructural states of steel. Among the advantages of medium-carbon steels with a ferrite–pearlite microstructure are a favourable strength-to-ductility ratio, good machinability, and relatively high wear resistance. Their disadvantages include lower weldability compared with low-carbon steels and limited strength compared with steels with martensitic or bainitic microstructures [1, 2].

In the present work, the thermal route used to obtain the investigated ferrite-pearlite microstructure should be distinguished from classical quenching and tempering. Classical quenching from the austenitic region is normally intended to form martensite, which is then tempered to relieve stresses and control carbide precipitation. In this study, however, the specimens were austenitized and then cooled in compressed air in order to limit martensite and bainite formation and to obtain a fine ferrite-pearlite microstructure. The subsequent treatment was performed below Ac_1 and is therefore described in this manuscript as subcritical heat treatment or subcritical holding. This terminology is used consistently below to align the interpretation with the actual thermal cycle.

The literature contains numerous and diverse studies concerning the properties of C45 and other medium-carbon steels. These studies address different microstructures obtained by heat treatment, the most common being martensitic, bainitic, and ferrite-pearlite. The starting microstructure is important because it determines the mechanisms and rate of softening during subsequent thermal exposure.

Investigations of C45 steel with a martensitic microstructure [3–5] and a bainitic microstructure [6–8] are relatively common, and the literature contains numerous studies in various research areas.

In contrast, for C45 steel with a ferrite–pearlite microstructure, the literature provides fewer studies concerning its mechanical and physicochemical properties. In [9], the effect of nitrogen content on the microstructure and mechanical properties of a medium-carbon ferrite–pearlite steel was examined. It was shown that, at the investigated nitrogen levels (0.001 wt.%, 0.009 wt.%, and 0.017 wt.%), nitrogen had no significant influence on the microstructure, whereas the strength (yield strength) decreased with increasing nitrogen content.

The studies described in [10] concerned a medium-carbon steel (0.36 wt.% C) and were focused on the influence of various heat-treatment processes on its mechanical properties. It was found that the strength–ductility relationship after heavy warm deformation and conventional quenching and tempering was more favourable than after continuous cooling or soft annealing.

In [11], steel with a ferrite–pearlite microstructure was investigated with respect to fatigue cracking. It was observed that steel with a dispersed pearlite morphology limited the extent of plastic deformation around the crack compared with a network pearlite structure.

Paper [12] presents an investigation of ferrite–pearlite SA204 Grade C steel in low-cycle fatigue tests under controlled loading, with regard to microstructural deformation of the material. It was established that grain misorientation in the ferrite–pearlite microstructure resulted from increasing strain accumulation with increasing strain amplitudes and loading cycles.

In [13], the ferritic/pearlitic steel microstructure was modelled, and its mechanical properties were examined in a uniaxial tensile test using the finite element method, followed by verification of the numerically obtained results with experimental strength tests. Good agreement between the results was demonstrated.

In [14], the properties of ferrite–pearlite steel subjected to severe plastic deformation were investigated. It was shown that a significant reduction in grain size and a high dislocation density increase the strength of the investigated steel.

Despite these contributions, the available literature still provides limited systematic data for C45 steel with an initially fine ferrite-pearlite structure subjected to a broad matrix of subcritical temperatures and holding times. In particular, the combined changes in Re, Rm, elongation, and HV0.5 after holding in the range 500–700 °C for times from 15 min to 23 h have not been clearly mapped for this type of initial structure.

The scientific contribution of this work is therefore the experimental mapping of tensile properties and microhardness of C45 steel with a fine ferrite-pearlite microstructure after subcritical heat treatment. The study complements earlier investigations focused mainly on martensitic or bainitic C45 steel and provides a practical data set for selecting thermal parameters when reduced strength and hardness, together with improved plasticity, are required. Because no quantitative metallographic measurements are included, the discussion of microstructural mechanisms is restricted to qualitative interpretation supported by SEM observations and literature comparison.

MATERIAL AND METHODS

The material used in this study was C45 steel supplied as M12 threaded rods of property class 8.8. The specimen geometry and dimensions are presented in Figure 1.

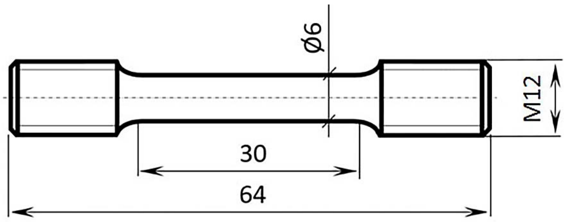

Figure 1. Geometry and dimensions of the tensile test specimens

The chemical composition of the C45 steel was determined and is presented in Table 1.

The microstructure of the initial C45 steel is shown in Figure 2 at 500× and 1000× magnification. The images were obtained using a JEOL JSM-6400 scanning electron microscope (SEM). The microstructure consists of approximately 40% proeutectoid ferrite and 60% pearlite.

After determination of the chemical composition, the material was austenitized and then subjected to accelerated air cooling without the use of a liquid quenching medium. The specimens were removed from the furnace at 850 °C and cooled in a stream of compressed air. The applied cooling conditions were selected to limit the formation of martensite and bainite and to produce a microstructure composed of approximately 8–10% proeutectoid ferrite and 90–92% fine pearlite. For this reason, the cooling step is referred to as accelerated air cooling rather than quenching in the strict metallurgical sense.

The obtained microstructure was subsequently subjected to subcritical heat treatment below the Ac_1 temperature at 500, 550, 600, 650, and 700 °C. The holding times at each temperature were 15 min, 1 h, 3 h, 9 h, and 23 h. Five tensile specimens were tested for each condition. In the tables and figures, the term holding time denotes the duration of this subcritical treatment (Figure 3).

All specimens were subjected to tensile testing and microhardness measurements. The yield strength (Re, MPa), ultimate tensile strength (Rm, MPa), and relative elongation at fracture, A (%), were determined from tensile tests. Vickers microhardness (HV0.5) was measured and the values reported in the tables are mean values for the investigated conditions. The source data available for this revision did not include individual tensile-test or hardness readings; therefore, standard deviations, confidence intervals, and error bars could not be calculated retrospectively, and this limitation is stated explicitly in the Discussion.

RESULTS

The results of the tensile tests in the delivery condition and after austenitizing followed by accelerated cooling to obtain a ferrite–pearlite microstructure are summarized in Table 2.

Based on the performed tests, the yield strength Re and ultimate tensile strength Rm

Table 1. Chemical composition of the investigated C45 steel

Steel grade	Chemical composition [%]								
	C	Mn	Si	P	S	Cr	Ni	Cu	Al
C45	0.48	0.71	0.25	0.013	0.023	0.10	0.09	0.18	0.023

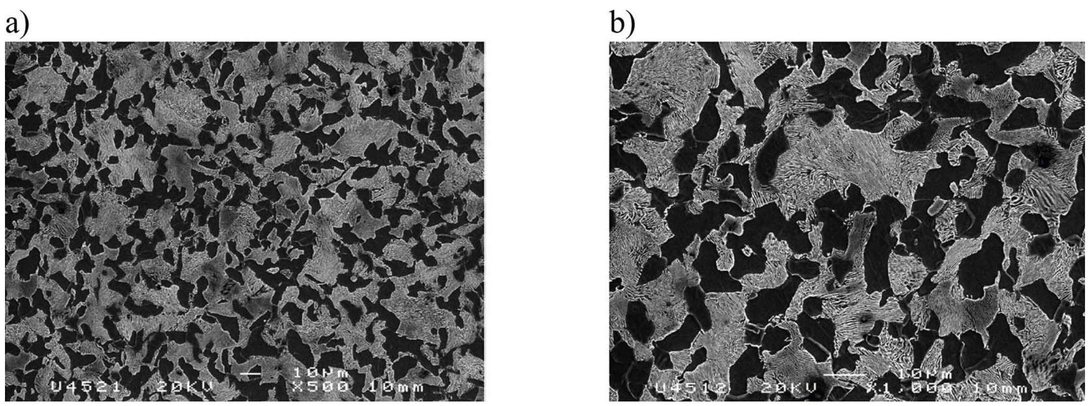

Figure 2. Initial microstructure of C45 steel: (a) magnification ×500, (b) magnification ×1000

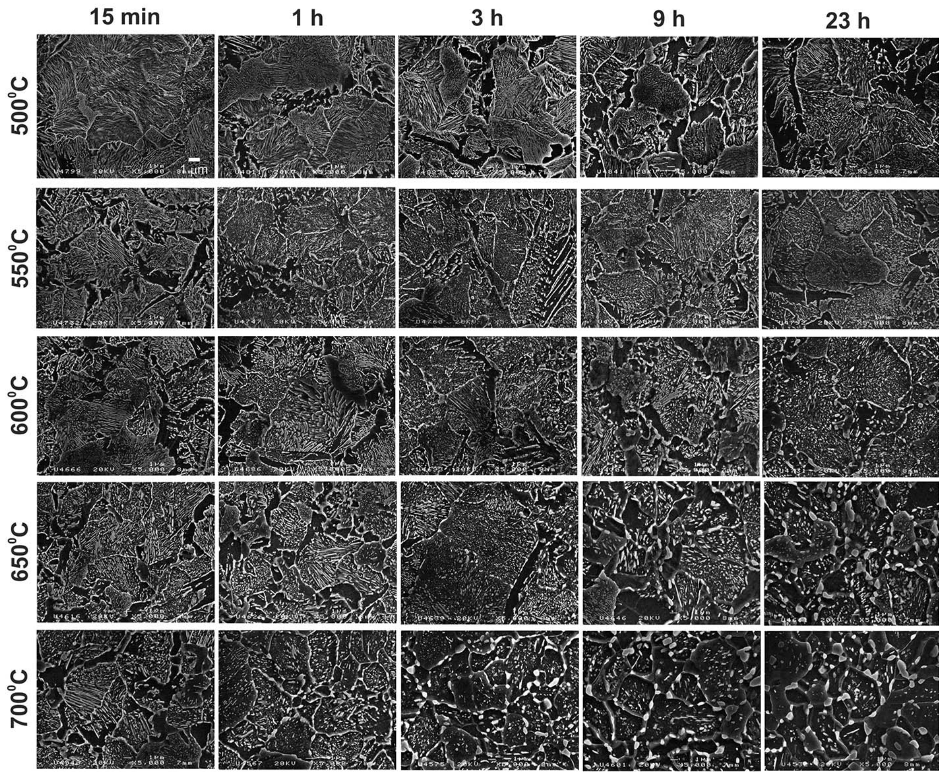

Figure 3. Microstructures of C45 steel after subcritical heat treatment

Table 2. Mechanical properties of C45 steel in the as-received condition and after accelerated cooling to a fine pearlitic (ferrite–pearlite) structure

Condition	Re [MPa]	Rm [MPa]	A [%]	HV 0.5
Delivery condition	1012	1029	5.2	298
After accelerated cooling	688	919	12.8	282

in the investigated ferrite–pearlite structure decreased relative to the C45 steel in the delivery condition by approximately 32% and 11%, respectively, while the elongation A increased by about 145%. The Vickers microhardness HV0.5 decreased slightly, by approximately 5%.

The tensile test results for yield strength (Re), ultimate tensile strength (Rm), and elongation (A) for the material after accelerated cooling and subsequent subcritical holding are presented in Tables 3–5, respectively.

As shown in Table 3 and Figure 4, the yield strength Re decreased monotonically with increasing subcritical heat-treatment temperature and holding time, from 668 MPa at 500 °C/15 min to 447 MPa at 700 °C/23 h; detailed values and percentage changes are provided in Table 3 and Figure 4.

As shown in Table 4 and Figure 5, the ultimate tensile strength Rm decreased monotonically with increasing temperature and holding time, from 896 MPa at 500 °C/15 min to 573 MPa at 700 °C/23 h; the complete data set is given in Table 4 and Figure 5.

As shown in Table 5 and Figure 6, elongation A exhibited local non-monotonic variations but generally shifted toward higher values at longer holding times and higher temperatures, ranging from 11.1% to 17.8%; the detailed behaviour is presented in Table 5 and Figure 6.

The results of the microhardness measurements for the ferrite-pearlite structure with very fine pearlite after subcritical heat treatment are presented in Table 6.

As shown in Table 6 and Figure 7, the Vickers microhardness HV0.5 generally decreased with increasing subcritical heat-treatment temperature and holding time, from 286 HV0.5 at 500 °C/15 min to 176 HV0.5 at 700 °C/23 h; detailed values are given in Table 6 and Figure 7.

Table 3. Yield strength (Re) obtained from tensile tests

Parameter	Temp °C	Holding time				
		15 min	1 h	3 h	9 h	23 h
Re [MPa]	500	668	648	622	608	592
	550	648	629	597	563	535
	600	607	587	541	518	500
	650	558	539	513	488	472
	700	515	497	472	467	447

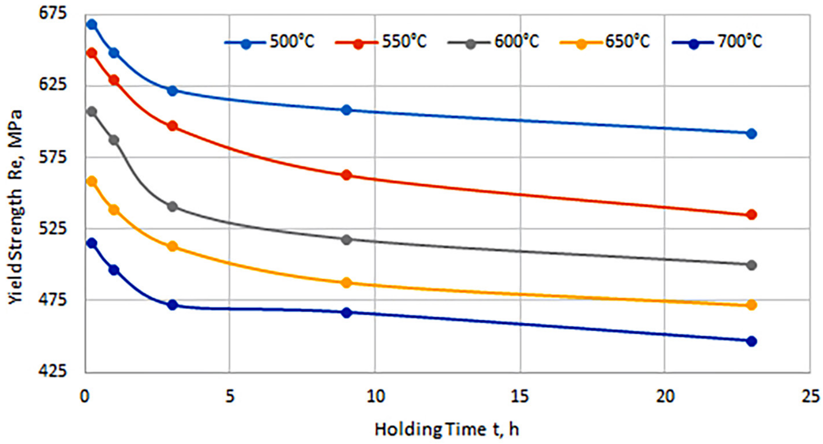

Figure 4. Yield strength (Re) as a function of subcritical heat-treatment temperature and holding time for C45 steel

Table 4. Ultimate tensile strength (Rm) obtained from tensile tests

Parameter	Temp °C	Holding time				
		15 min	1 h	3 h	9 h	23 h
R_m [MPa]	500	896	858	838	830	810
	550	860	857	817	786	751
	600	843	803	762	732	696
	650	775	751	718	671	658
	700	723	682	627	622	573

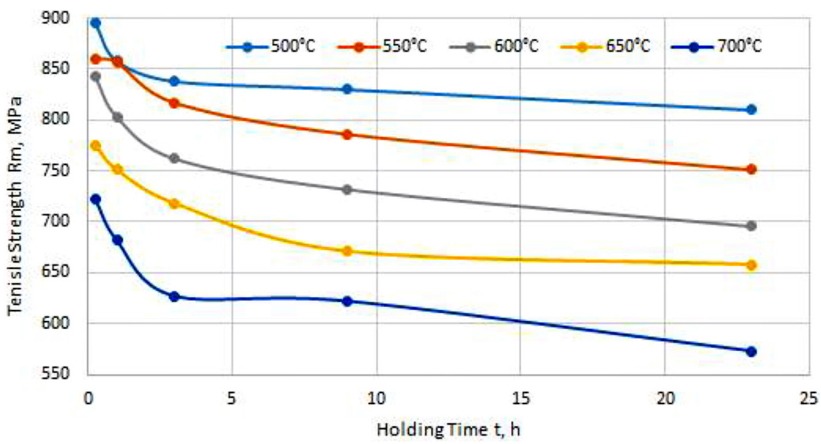

Figure 5. Ultimate tensile strength (Rm) as a function of subcritical heat-treatment temperature and holding time for C45 steel

Table 5. Elongation at fracture (A, %) obtained from tensile tests

Parameter	Temp °C	Holding time				
		15 min	1 h	3 h	9 h	23 h
A [%]	500	11.7	11.1	13.2	14.0	15.5
	550	11.5	11.4	14.1	14.2	16.0
	600	12.3	12.7	14.5	16.9	17.0
	650	13.6	13.2	14.9	17.1	17.3
	700	15.4	14.6	16.2	17.5	17.8

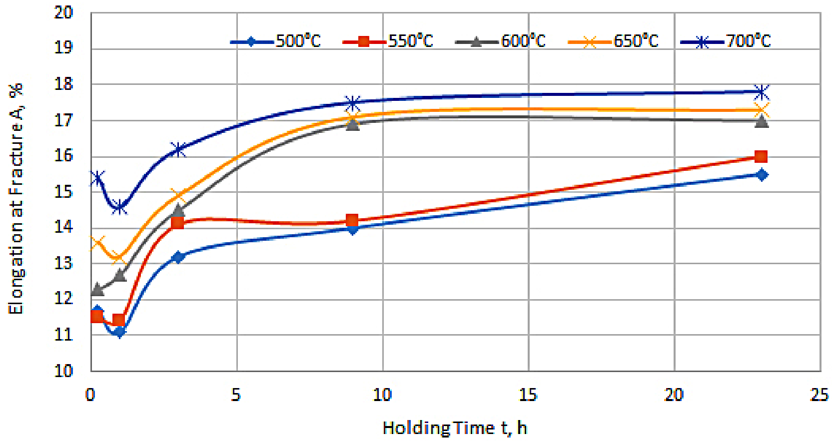

Figure 6. Effect of subcritical heat-treatment temperature and holding time on the elongation at fracture A (%) of C45 steel

The engineering significance of these trends is evaluated in the Discussion, with attention to the limitations resulting from qualitative metallography and the absence of statistical scatter data.

DISCUSSION

The present results show that subcritical heat treatment below Ac_1 of C45 steel with a fine ferrite-pearlite microstructure leads to systematic softening: Re, Rm, and HV0.5 decrease as temperature and holding time increase, while elongation generally improves. This behaviour is consistent with the general principles of heat treatment of carbon steels [1,2], but the interpretation differs from classical quenching and tempering because the investigated starting structure was ferrite-pearlite rather than martensite.

A useful comparison can be made with previous ASTRJ work on C45 steel with a martensitic structure subjected to high tempering [5]. In that study, increasing temperature and time also reduced tensile strength and microhardness, but the initial martensitic state resulted in higher hardness and strength, especially at the lower end of the investigated temperature range. The present ferrite-pearlite material starts from a softer structural state

Table 6. Average Vickers microhardness (HV0.5) of C45 steel with a ferrite-pearlite microstructure after subcritical heat treatment

Temp °C	Holding time				
	15 min	1 h	3 h	9 h	23 h
500	286	272	261	242	235
550	270	265	254	235	225
600	245	238	235	218	210
650	234	223	219	198	193
700	211	204	186	178	176

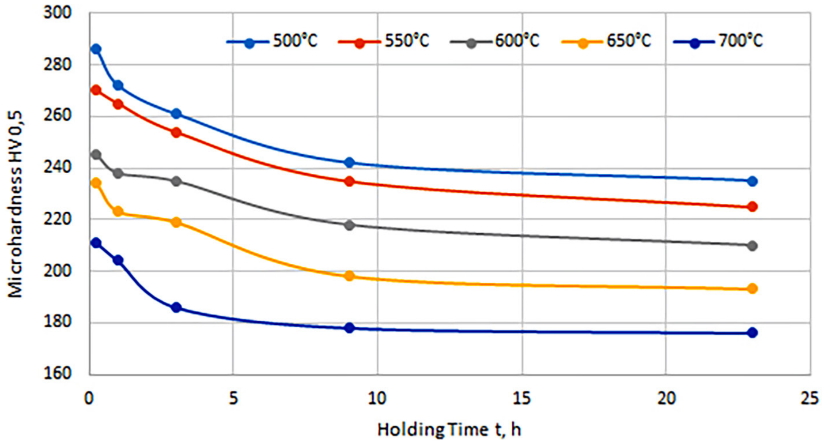

Figure 7. Effect of subcritical heat-treatment temperature and holding time on the Vickers microhardness HV0.5 of C45 steel

and therefore shows lower HV0.5 values under comparable high-temperature holding conditions, confirming that the initial microstructure strongly influences the final property level.

The trends observed here are also consistent with broader studies of ferrite-pearlite steels, which show that strength and ductility are sensitive to ferrite-pearlite morphology, pearlite dispersion, deformation history, and microstructural heterogeneity [9–14]. The present work extends this context by providing a systematic matrix of tensile and microhardness data for C45 steel after 25 combinations of subcritical temperature and holding time.

The microstructural explanation should nevertheless be treated cautiously. The SEM observations confirm the ferrite-pearlite character of the material, but no quantitative metallographic measurements were performed, such as ferrite fraction after each condition, ferrite grain size, pearlite colony size, interlamellar spacing, or carbide morphology descriptors. Therefore, the decreases in Re, Rm, and HV0.5 are interpreted only as being consistent with ferrite recovery and with possible fragmentation, spheroidization, and coarsening of cementite in pearlite, rather than as direct quantitative proof of these mechanisms.

The practical relevance of controlling hardness and microstructure in C45 steel is supported by recent ASTRJ work on abrasive wear mechanisms of several steels, including C45, where hardness, microstructure, and the abrasive environment were shown to influence service behaviour [16]. However, the present study did not include wear or impact tests; therefore, its conclusions are limited to tensile properties and Vickers microhardness.

The statistical treatment is also a limitation of the present data set. Five tensile specimens were tested for each heat-treatment condition, and the tables report mean values available for the investigated conditions. In the published version, the article is based on previously developed mean values, which limits the presentation of statistical quantities such as confidence intervals or error bars. Consequently, small differences between neighbouring conditions should be interpreted with caution, whereas the overall monotonic trends in Re, Rm, and HV0.5 are supported by the full temperature-time matrix.

Finally, some combinations of temperature and holding time led to similar values of Re, Rm, or HV0.5. This observation may be useful for preliminary engineering selection of heat-treatment parameters, but it should not be described as rigorous time-temperature equivalence. A quantitative equivalence would require a kinetic model, activation-energy analysis, or additional experiments designed specifically for that purpose.

CONCLUSIONS

1. The thermal route used in this study is best described as austenitizing at 850 °C, accelerated cooling in compressed air to obtain a fine ferrite-pearlite microstructure, and subsequent subcritical heat treatment below Ac_1, rather than classical quenching and tempering of martensite.
2. For all investigated holding times, the yield strength, ultimate tensile strength, and microhardness decreased as the subcritical heat-treatment temperature increased from 500 to 700 °C.

3. The lowest values measured in the investigated matrix were 447 MPa for Re, 573 MPa for Rm, and 176 HV0.5, obtained after holding at 700 °C for 23 h.
4. Elongation showed local non-monotonic variations but generally increased at longer holding times and higher temperatures, reaching a maximum of 17.8% in the investigated conditions.
5. The observed property changes are consistent with softening of the ferrite-pearlite microstructure, but the specific microstructural mechanisms remain qualitative because no quantitative metallographic analysis was performed.
6. The results may support selection of subcritical heat-treatment parameters for C45 steel when specified tensile properties and microhardness are required; no conclusions are drawn regarding impact toughness, wear resistance, or strict time-temperature equivalence.

REFERENCES

1. Muhlbauer A., Von Starck A., Kramer C. Handbook of Thermoprocessing Technologies. Vulkan-Verlag GmbH; 2007.
2. Ashby M.F., Shercliff H., Cebon D. Materials: Engineering, Science, Processing and Design. Butterworth-Heinemann; 2018.
3. Wang W., Liu S., Xu G., Zhang B., Huang Q. Effect of thermal aging on microstructure and mechanical properties of China low-activation martensitic steel at 550 °C. Nuclear Engineering and Technology. 2016;48(2):518-524.
4. Rashidi M., Johansson L., Andrén H.O., Liu F. Microstructure and mechanical properties of two Z-phase strengthened 12% Cr martensitic steels: the effects of Cu and C. Materials Science and Engineering: A. 2017;694:57–65.
5. Woźniak W., Sąsiadek M., Jachowicz T., Edl M., Zając P. Studies on the mechanical properties of C45 steel with martensitic structure after a high tempering process. Advances in Science and Technology Research Journal. 2022;16(3):306–315. https://doi.org/10.12913/22998624/150564
6. Sąsiadek M., Woźniak W., Melichar M. Testing and evaluation of mechanical properties of C45 steel with bainitic structure. Journal of Achievements in Materials and Manufacturing Engineering. 2024;125(2):49–55.
7. Kumar A., Singh A. Mechanical properties of nanostructured bainitic steels. Materialia. 2021;15:101034.
8. Hsu C.Y., Stodolna J., Todeschini P., Delabrouille F., Christien F. Effect of bainitic or martensitic microstructure of a pressure vessel steel on grain boundary segregation induced by step cooling simulating thermal aging. Journal of Nuclear Materials. 2023;584:154554.
9. Zhao F., Liu X., Zhang Z., Xie J. Effect of nitrogen content on the mechanical properties and deformation behaviors of ferritic-pearlitic steels. Materials Science and Engineering: A. 2022;855:143918. https://doi.org/10.1016/j.msea.2022.143918
10. Storojeva L., Ponge D., Raabe D., Kaspar R. On the influence of heavy warm reduction on the microstructure and mechanical properties of a medium-carbon ferritic-pearlitic steel. International Journal of Materials Research. 2004;95(12):1108–1114.
11. Korda A.A., Miyashita Y., Mutoh Y., Sadasue T. Fatigue crack growth behavior in ferritic-pearlitic steels with networked and distributed pearlite structures. International Journal of Fatigue. 2007;29(6):1140–1148.
12. Zhang S., Romo S., Giorjao R.A., Leao P.B., Ramirez A.J. EBSD analysis of strain distribution and evolution in ferritic-pearlitic steel under cyclic deformation at intermediate temperature. Materials Characterization. 2022;193:112293.
13. Nygårds M., Gudmundson P. Micromechanical modeling of ferritic/pearlitic steels. Materials Science and Engineering: A. 2002;325(1–2):435–443. https://doi.org/10.1016/S0921-5093(01)01509-X
14. Muñoz J.A., Khelfa T., Komissarov A., Cabrera J.M. Ductility and plasticity of ferritic-pearlitic steel after severe plastic deformation. Materials Science and Engineering: A. 2021;805:140624.
15. PN-EN ISO 6892-1:2016-09. Metallic materials – Tensile testing – Part 1: Method of test at room temperature.
16. Szala M., Szafran M., Matijošius J., Drozd K. Abrasive wear mechanisms of S235JR, S355J2, C45, AISI 304, and Hardox 500 steels tested using garnet, corundum and carborundum abrasives. Advances in Science and Technology Research Journal. 2023;17(2):147–160. https://doi.org/10.12913/22998624/161277