Вестник РУДН. Серия: Инженерные исследования
RUDN Journal of Engineering Research

2022;23(2):140–145

ISSN 2312-8143 (Print); ISSN 2312-8151 (Online)
journals.rudn.ru/engineering-researches

DOI 10.22363/2312-8143-2022-23-2-140-145
UDC 621.78.01:621.785-97

Research article / Научная статья

The influence of heating temperature on coercive force and hardness changes in carbon hypoeutectoid steels

Anna V. Kornilova[a] ✉, **Kyaw Zaya**[b]

[a]Moscow State University of Civil Engineering (National Research University), *Moscow, Russian Federation*
[b]Moscow State Technological University "STANKIN," *Moscow, Russian Federation*
✉ anna44@yandex.ru

Article history
Received: January 25, 2022
Revised: April 17, 2022
Accepted: April 22, 2022

Keywords:
magnetic properties, coercive force, temper colors, cooling in calm air, temperature interval

Abstract. Hypoeutectoid steel with 0,25% carbon without preliminary heat treatment was investigated. The article describes an experimental study of the hardness and coercive force of this steel during heating and subsequent cooling in calm air. The magnetization depth of the device used and the penetration depth of the indenter when measuring hardness are significantly greater than the thickness of the total oxide films, therefore the measurement result is a complex value depending on the properties of the base metal and oxides. The influence on the studied parameters is proved not only of the structure of the base metal, but also of the properties of oxide films that appear on the steel surface in an oxygen-containing medium during heating. As a result, hardness and coercive force do not correlate with each other at all temperature intervals of heating. It is shown that the visual assessment of temperature by temper colors is subjective, and when the temperature threshold exceeds 500ºC (for the research steel in given modes), the visually determined dependence between the temperature and the color of the sample surface after temperature exposure disappears.

For citation
Kornilova AV, Kyaw Zaya. The influence of heating temperature on coercive force and hardness changes in carbon hypoeutectoid steels. *RUDN Journal of Engineering Research*. 2022;23(2):140–145. http://doi.org/10.22363/2312-8143-2022-23-2-140-145

Влияние температуры нагрева на изменение коэрцитивной силы и твердости углеродистых доэвтектоидных сталей

А.В. Корнилова[a] ✉, **Чжо Заяр**[b]

[a]Национальный исследовательский Московский государственный строительный университет, *Москва, Российская Федерация*
[b]Московский государственный технологический университет «СТАНКИН», *Москва, Российская Федерация*
✉ anna44@yandex.ru

История статьи
Поступила в редакцию: 25 января 2022 г.
Доработана: 17 апреля 2022 г.
Принята к публикации: 22 апреля 2022 г.

Аннотация. Исследована доэвтектоидная сталь с содержанием углерода 0,25 % без предварительной термической обработки. Описано экспериментальное исследование твердости и коэрцитивной силы при нагреве и последующем охлаждении на спокойном воздухе. Глубина

Ключевые слова:
магнитные свойства, коэрцитивная сила, цвета побежалости, охлаждение на спокойном воздухе, температурный интервал

намагничивания используемого прибора и глубина проникновения индентора при измерении твердости значительно больше толщины суммарных оксидных пленок, поэтому результат измерения представляет собой комплексную величину, зависящую от свойств основного металла и оксидов. Доказано влияние на исследуемые параметры не только структуры основного металла, но и свойств оксидных пленок, возникающих на поверхности стали в кислородсодержащей среде при нагреве. В результате твердость и коэрцитивная сила не коррелируют друг с другом во всех температурных интервалах нагрева. Показано, что визуальная оценка температуры по цветам побежалости носит субъективный характер и при превышении температурного порога в 500 ºС (для исследуемой стали на заданных режимах) визуально определяемая зависимость между температурой и цветом поверхности образца после температурного воздействия исчезает.

Для цитирования
Kornilova A.V., Kyaw Zaya. The influence of heating temperature on coercive force and hardness changes in carbon hypoeutectoid steels // Вестник Российского университета дружбы народов. Серия: Инженерные исследования. 2022. Т. 23. № 2. С. 140–145. http://doi.org/10.22363/2312-8143-2022-23-2-140-145

Introduction

When a temperature load is applied and subsequent cooling occurs in metals and alloys, two synergistically affecting each other processes take place simultaneously – a change in the structure and properties of the base metal and the appearance of oxide films on the surface. During the oxidation, the following iron oxides are formed: FeO (wustite), Fe_3O_4 (magnetite) and Fe_2O_3 (hematite). Oxides are arranged in layers according to the decrease in oxygen content from the outer to the inner layer (Figure 1).

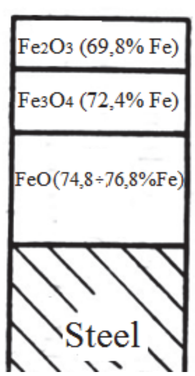

Figure 1. Simplified scheme of oxide films on the surface of carbon steel during heating in an oxygen-containing environment

Wustite (FeO) has face-centered cubic (FCC) and stable at temperatures above 570 °C. Below this temperature, it decomposes. The largest amount of wustiteis formed in the temperature interval 700–900 °C. Wustite is the softest and loosest layer of the oxide film. Magnetite (Fe_3O_4) has a cubic crystal lattice, highly abrasiveness and is insoluble in acids. Hematite (Fe_2O_3) has the highest abrasiveness and practically does not dissolve in acids [1]. With a metal hardness according to Vickers of 140 units, the hardness of FeO is 270–350, Fe_3O_4 420–500, Fe_2O_3 1030 units.

In mechanical engineering, the study of processes that occur during heating and cooling of steel, as an alloy of iron with carbon and other elements, is typically limited to the study and optimization of the base metal's structure. The composition, thickness, and properties of oxide films are dealt with either by specialists in hot rolling [2–5], where scale (a high-temperature oxide film on the surface of steel) is defective, or by specialists in processing scale and restoring iron from it[1] [6–8].

Therefore, the purpose of this research is to determine the effect of temperature loading on the hardness and magnetic properties of hypoeutectoid steel, which depend both on the processes occurring in the base metal and on the properties of surface oxide films.

1. Methods and materials

The work is experimental. For the experiment, cylindrical samples made of carbon steel 25 (carbon content from 0.25–0.33%) were used. The critical points of the researched steel are Ac_1 = 735 ºC,

[1] Degai AS, Zuev MV, Zasukhin AL, Karmanov OB, Mikurova MI, Orekhov OE, Gusev RV. *Method of preparation of oiled scale for processing.* RU2279491C2. 10.07.2006. (In Russ.)

Ac_3 = 835 ºC. To study the coercive force (H_C, A/m), a verified and certified structuroscope (coercimeter) KIM-2M was used. Figure 2 shows a sample and nozzles for measuring coercive force. For hardness, the Rockwell method B scale (HRB, dimension – arbitrary units) was chosen, implemented in a stationary hardness tester TK-14-250. The samples were heated in a laboratory furnace with a PM-16M-V thermostat. The experiment was carried out as follows: the samples were placed in a furnace heated to a given temperature, held for 15 minutes, and cooled in calm air. The temperature ranged from 200 to 1000 ºC. In each sample, before heating and after cooling, the hardness and coercive force were measured several times along the length of the sample, and then the values were averaged. Before heating, for all samples – the average value of hardness is 89 units of the Rockwell B scale, the average value of the coercive force is 1023 A/m.

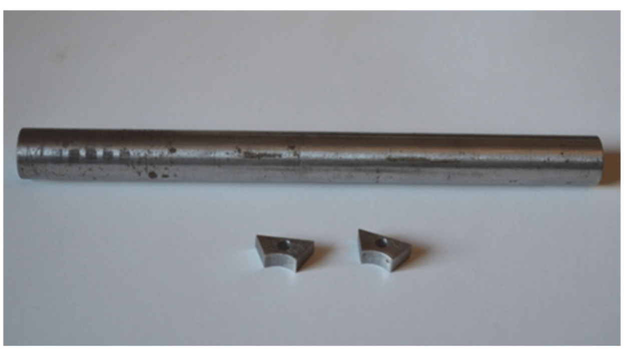

Figure 2. Sample and nozzles for measuring coercive force

2. Results and discussion

On Figure 3, numbers from 1 to 9 show the heating temperatures of the samples under study, plotted on the steel corner of the Fe–Fe_3C diagram. Samples 1–6 were heated to temperatures below the critical point Ac_1, sample 7 – between Ac_1 and Ac_3, samples 8 and 9 were completely austenitized during heating. All samples, except the first, were heated above the Curie point of cementite (210 °C). Research the behavior of the coercive force during thermal cycling near the Curie point of cementite (210 ºC) is the subject of works [9–13]. However, the study of the complex influence of processes in the base metal and in the zone of formation of oxide films on engineering characteristics – hardness and magnetic properties during single heating has not been carried out.

Figures 4 and 5 are show graphical dependences of the experimental results. Numbers 1–9 correspond to the temperatures of the experiment in Figure 3.

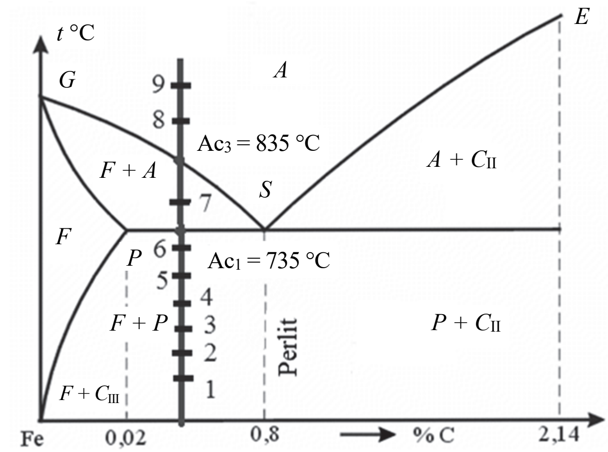

Figure 3. The steel angle of the Fe–Fe3C diagram, with points (1–9) corresponding to experiment temperatures

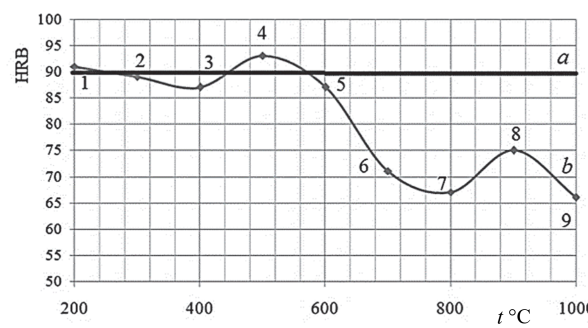

Figure 4. Dependence of the change in hardness after heating and cooling on the heating temperature:
a – average hardness before heating; *b* – after heating and cooling

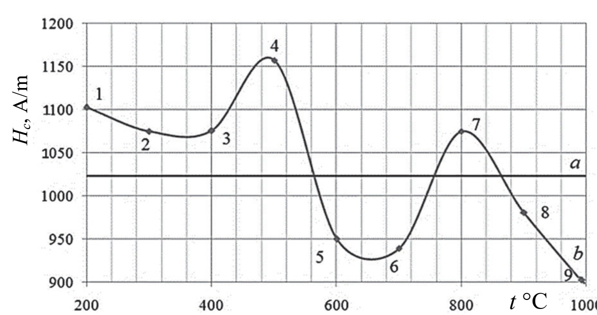

Figure 5. Dependence of the change in the coercive force after heating and cooling on the heating temperature:
a – the average value of the coercive force before heating;
b – after heating and cooling

Figure 6 shows the temper colors of the samples after heating and cooling. Sample 0 is one of the samples at the same experimental series, not participating in the experiment. Obviously, the visual assessment of temperature by temper colors is subjective, when the temperature threshold of 500 ºC is exceeded (in this work), the visually determined dependence between the temperature and the color of the sample surface after exposure to temperature disappears.

In this experiment, both the coercive force and hardness were determined taking into account the properties of the base metal and surface oxide films. The depth of magnetization of the device used and the depth of penetration of the indenter when measuring hardness are significantly greater than the thickness of the total oxide films, therefore, the measurement result is a complex value depending on the properties of the base metal and oxides. Description of the processes occurring in steel during experimental studies is given in Table.

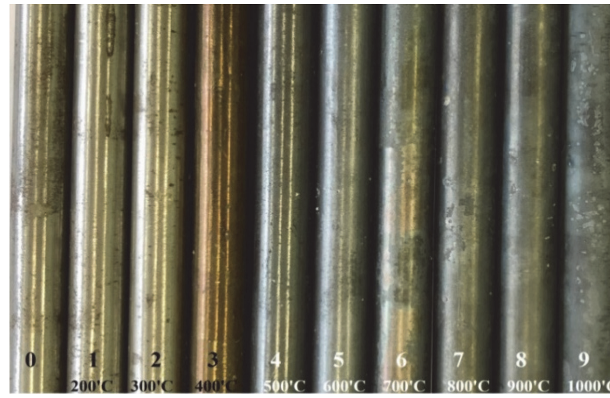

Figure 6. Temper colors of samples after heating and cooling

Description of the occurring processes in the research samples during heating and cooling

Temperature interval	Reaction of hardness and coercive force	Steel changes
200–300 °C	Slight drop from unloaded temperature state	Residual stresses decrease in the base metal, a thin single-layer oxide film appears on the surface
300–400 °C	Hardness reduction continues. Coercive force decreases slightly	Deformed crystal lattice begins to align in the base metal; hematite predominates in the structure of surface oxides (sample 3, Figure 6)
400–500 °C	Increased hardness and coercive force	There is a similarity of incomplete annealing in the structure of the base metal, but the thickness of a particularly hard layer (hematite) increases on the surface
500–600 °C 600–700 °C	Hardness drop. Avalanche-like drop in coercive force due to the appearance of non-ferromagnetic elements in the structure of surface oxide films	Incomplete annealing of the base metal occurs, loose wustite predominates in the structure of the surface layers (appeared at a temperature of 570 °C)
700–800 °C	Hardness drop. Growth of the coercive force due to the predominance of the wustite ferromagnetic component in the oxide structure, the phenomenon of scale detachment from the base metal	The transition during heating to the GSF region of the Fe–Fe3C diagram (Figure 2), an increase in the thickness of oxide films on the surface
800–900 °C	Hardness increase. Sharp drop in coercive force	Complete austenization of the base metal, hardening takes place in it due to a process of similar normalization, partial removal of oxides from the surface occurs
900–1000 °C	Sharp drop in hardness and coercive force	There is an overheating of the base metal, uncontrolled growth of austenite grains, self-removal of scale from the surface (Figure 7)

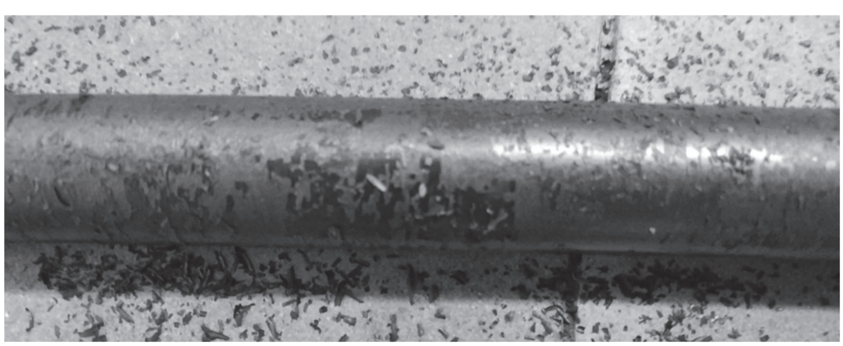

Figure 7. High temperature scale on the sample surface

Conclusion

When applying a temperature load and subsequent cooling in carbon steel, two synergistically influencing processes occur simultaneously – a change in the structure and properties of the base metal and the appearance of oxide films on the surface. Hardness and coercive force (the most structurally sensitive magnetic characteristic of a ferromagnet) are not correlated with each other at all temperature intervals of heating.

It is obvious that the visual assessment of temperature by temper colors is subjective, when the temperature threshold of 500 ºC is exceeded (for the research steel in given modes); the visually determined dependence between the temperature and the color of the sample surface after temperature exposure disappears. Therefore, recommendations for determining the temperature of the fire effect on metal structures by the temper colors of steel structures (for example, after a fire) cannot be recognized as sufficiently reliable.

References

1. Panchenko VS, Merezhinskaya EV, Kardailskaya EV, Gera DN. Study of etchability of steel scale in hydrochloric acid. *Steel.* 2013;10:42–44. (In Russ.)

2. Garber EA, Gatiyatullin DZ. Factors that cause residual scale surface defects in hot-rolled wide strips and methods of their elimination. *Mechanical Equipment of Metallurgical Plants.* 2017;(2(9)):18–21. (In Russ.)

3. Pokachalov VV. Phase composition of scale and defects arising during wire drawing. *Hardware*. 2006; (3(13)): 30–33. (In Russ.)

4. Sychkov AB, Kopceva NV, Efimova YY, Zhloba AV, Kamalova GY. Identification of the surface defects of sheet “Rolled scale.” *Modeling and Development of Metal Forming Processes.* 2018;(24):12–18. (In Russ.)

5. Merkulov AA, Efimov SA, Korolev AV. Mathematical modeling of the process of rotary cleaning of rolled metal from scale. *Mathematical Methods in Engineering and Technologies – MMET*. 2014;(5(64)):133–137. (In Russ.)

6. Druz ON, NikitinYuN. Improvement of technology for processing scale into powder material. *Resource Saving Technologies for Production and Pressure Shaping of Materials in Machine-Building.* 2020;(4(33)):28–39. (In Russ.)

7. Kortz T, Wulfert H. Cost-effective process of processing and use of oil-containing rolling scale. *Ferrous Metals*. 2012;(2):25–30. (In Russ.)

8. Lipatkina TN. Receiving an iron-rich product from scale. *Litiyo i Metallurgiya (Foundry Production and Metallurgy).* 2016;(1(82)):72–75. (In Russ.)

9. Kornilova AV, Idarmachev IM, Zayar C, Paing T. A method of determination of the service life of a die tool with application of magnetic methods of nondestructive control and diagnostics. *Journal of Machinery Manufacture and Reliability.* 2014;43(5):439–444. https://doi.org/10.3103/S1052618814050082

10. Zaya K, Paing T, Kornilova AV. The effects of operational thermal cycling on mechanical and magnetic properties of structural steels. *IOP Conference Series: Materials Science and Engineering.*2019;675(1):012041. https://doi.org/10.1088/1757-899X/675/1/012041

11. Kornilova AV, Toptygin KP, Krasnovskii AN, Zaya K. Features of the destruction of tool steels in technical processes in aerospace industry. *Advances in the Astronautical Sciences. 2nd IAA/AAS Conference on Space Flight Mechanics and Space Structures and Materials, SciTech Forum 2019.* Moscow; 2021. p. 689–702.

12. Kornilova AV, Nabiullina LK, Paing T, Zayar K, Selishchev AI. Study of damage stamps for hot forging magnetic methods. *Vestnik MSTU “STANKIN.”* 2014; (2(29)):40–43. (In Russ.)

13. Kornilova AV, Idarmachev IM, Ping T, Zayar K. Some practical aspects of the application of magnetic methods of non-destructive testing and diagnostics. *Occupational Safety in Industry.* 2014;(3):50–53. (In Russ.)

Список литературы

1. *Панченко В.С., Мержинская Е.В., Кардаильская Е.В., Згера Д.Н.* Повышение температуры воздуха горения в методических печах // Сталь. 2013. № 10. С. 42–44.

2. *Гарбер Э.А., Гатиятуллин Д.З.* Причины образования на поверхности горячекатаных стальных широких полос дефекта «остаточная окалина» и методы его устранения // Механическое оборудование металлургических заводов. 2017. № 2(9). С. 18–21.

3. *Покачалов В.В.* Фазовый состав окалины и дефекты, возникающие при волочении проволоки // Метизы. 2006. № 3 (13). С. 30–33.

4. *Сычков А.Б., Копцева Н.В., Ефимова Ю.Ю., Жлоба А.В., Камалова Г.Я.* Идентификация дефекта поверхности листового проката типа «Вкатанная окалина» // Моделирование и развитие процессов обработки металлов давлением. 2018. № 24. С. 12–18.

5. *Меркулов А.А., Ефимов С.А., Королев А.В.* Математическое моделирование процесса роторной очистки металлического проката от окалины // Математические методы в технике и технологиях – ММТТ. 2014. № 5 (64). С. 133–137.

6. *Друзь О.Н., Никитин Ю.Н.* Совершенствование технологии переработки окалины в порошковый материал // Ресурсосберегающие технологии производства и обработки давлением материалов в машиностроении. 2020. № 4 (33). С. 28–39.

7. *Корц Т., Вульферт Х.* Экономически эффективный процесс переработки и использования маслосодержащей прокатной окалины // Черные металлы. 2012. № 2. С. 25–30.

8. *Липаткина Т.Н.* Получение металлизованного продукта из окалины // Литье и металлургия. 2016. № 1(82). С. 72-75.

9. *Kornilova A.V., Idarmachev I.M., Zayar C., Paing T.* A method of determination of the service life of a die tool with application of magnetic methods of nondestructive control and diagnostics // Journal of Machine-

ry Manufacture and Reliability. 2014. Vol. 43. No 5. Pp. 439–444. https://doi.org/10.3103/S1052618814050082

10. *Zaya K., Paing T., Kornilova A.V.* The effects of operational thermal cycling on mechanical and magnetic properties of structural steels // IOP Conference Series: Materials Science and Engineering. 2019. Vol. 675. No 1. https://doi.org/10.1088/1757-899X/675/1/012041

11. *Kornilova A.V., Toptygin K.P., Krasnovskii A.N., Zaya K.* Features of the destruction of tool steels in technical processes in aerospace industry // Advances in the Astronautical Sciences. 2nd IAA/AAS Conference on Space Flight Mechanics and Space Structures and Materials, SciTech Forum 2019. Moscow, 2021. Pp. 689–702.

12. *Корнилова А.В., Набиуллина Л.К., Тет П., Чжо З., Селищев А.И.* Исследование магнитными методами повреждаемости штампов для горячей объемной штамповки // Вестник МГТУ «СТАНКИН». 2014. № 2 (29). С. 40–43.

13. *Корнилова А.В., Идармачев И.М., Паинг Т., Заяр Чжо.* Некоторые практические аспекты применения магнитных методов неразрушающего контроля и диагностики // Безопасность труда в промышленности. 2014. № 3. С. 50–53.

About the authors

Anna V. Kornilova, Doctor of Technical Sciences, Professor of the Department of Testing of Structures, Moscow State University of Civil Engineering (National Research University), 26 Yaroslavskoye Shosse, Moscow, 129337, Russian Federation; ORCID: 0000-0001-5569-9320, Scopus Author ID: 7004499009, Researcher ID: U-3353-2017, eLIBRARY SPIN-code: 6569-6240; anna44@yandex.ru

Kyaw Zaya, postgraduate student, Department of Composite Materials, Moscow State Technological University "STANKIN," 1 Vadkovskiy Pereulok, Moscow, 127055, Russian Federation; ORCID: 0000-0003-0131-1399, Scopus Author ID: 56416430100; k.kyawzaya@yandex.ru

Сведения об авторах

Корнилова Анна Владимировна, доктор технических наук, профессор кафедры испытания сооружений, Национальный исследовательский Московский государственный строительный университет, Российская Федерация, 129337, Москва, Ярославское шоссе, д. 26; ORCID: 0000-0001-5569-9320, Scopus Author ID: 7004499009, Researcher ID: U-3353-2017, eLIBRARY SPIN-код: 6569-6240; anna44@yandex.ru

Чжо Заяр, аспирант, кафедра композиционных материалов, Московский государственный технологический университет «СТАНКИН», Российская Федерация, 127055, Москва, Вадковский пер., д. 1; ORCID: 0000-0003-0131-1399, Scopus Author ID: 56416430100; k.kyawzaya@yandex.ru