

# Influence of Carbon Content on the Strengthening Characteristics of Steels During AFSH

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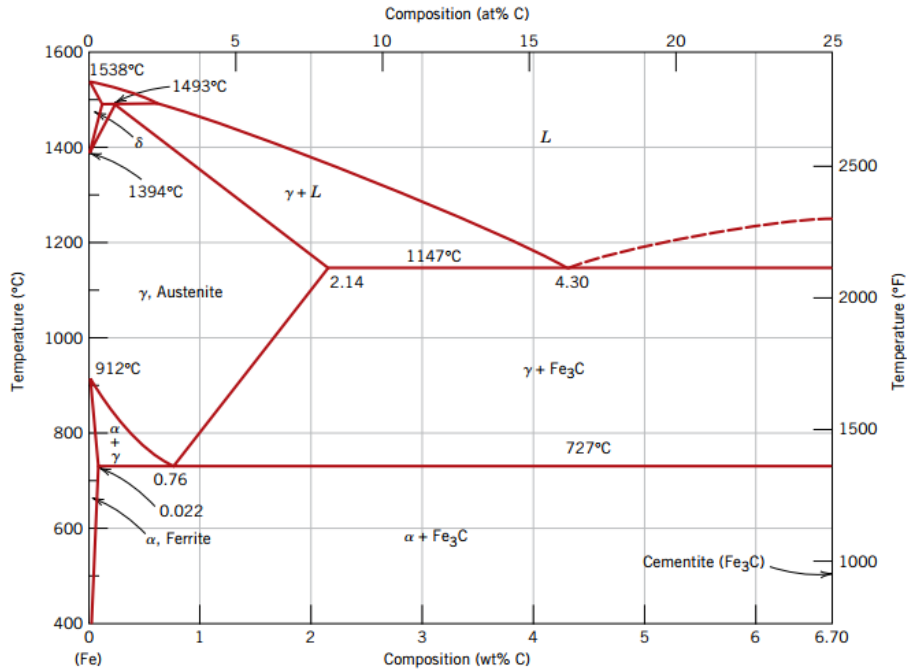
**Keywords:** heat treatment, steel 20, steel 45, steel U7, steel U12, additional friction-strain hardening, AFSH, white surface hardened layer, carbon content, microstructure, deformed martensite.

**Abstract.** The article considers the features of heat treatment of steels, includes quenching, phase transformations and their influence on the structure and properties of the material. The key parameters of heat treatment are described: heating temperature, holding time and cooling rate, as well as their role in forming the required mechanical characteristics of steel. Phase diagrams are considered, in particular for the "iron-carbon" system, and their significance for choosing processing modes. Additional friction-strain hardening (AFSH) of various steel grades (20, 45, U7, U12) after preliminary quenching and low-temperature tempering is studied. An analysis of microstructural changes and microhardness of surface layers after AFSH is carried out, which confirmed the effectiveness of additional hardening. It was found that steels with a higher carbon content, limited to 0.8 %, demonstrate a greater depth of the hardened layer and higher microhardness values, which determines their feasibility for use in conditions of increased wear. The results of the study emphasize the importance of choosing the optimal AFSH mode depending on the carbon content in the steel, which has a significant impact on the formation of the strength characteristics of the material.

## Introduction

It is known that heat treatment (HT), which consists of heating the steel to a selected temperature, holding it for uniform heating of the product and ensuring the completion of phase transformations, and subsequent cooling at a certain speed, is a necessary condition for the material to acquire the necessary properties in a thermal way. In this case, the main parameters of the heat treatment are: heating temperature  $t$ , holding time  $\tau$ , cooling rate  $V_{ox}$ . Accordingly, the goal of heat treatment is to obtain the necessary structure to ensure the necessary properties without changing the chemical composition of the steel [1].

All heat treatment modes are assigned in accordance with the so-called "phase diagrams", which are a graphical representation of the dependence of the balanced phase composition of the alloy on its chemical composition, temperature and, sometimes, pressure. It should be noted that phase diagrams have been experimentally determined for many known materials, and the definition of such diagrams for new alloys is a relevant problem [2]. In particular, for the iron-carbon system, diagrams of the type shown in Fig. 1 are known and widely used in practice. Here, the ordinate axis shows the temperature in degrees Celsius, and the abscissa axis shows the carbon content in the alloy.



**Fig. 1.** The iron–iron carbide phase diagram [3].

Since the initial state of the material plays a significant role in this research, we focus on some features of the well-known classical types of heat treatment of steels [1, 2].

Quenching – heating steel above the line (912 °C/0 %–727 °C/0.76 %–1147 °C/2.14 %) followed by rapid cooling. During rapid cooling, the decomposition of austenite with the release of cementite and ferrite does not have time to pass, and austenite turns into martensite, which has high hardness. Martensitic transformation is diffusionless in nature. The condition for the formation of martensite is cooling at a rate higher than the critical one. During such cooling, the FCC lattice transforms into BCC lattice, and carbon diffusion, due to the low temperature, is greatly slowed down, i.e. theoretically, the carbon content in martensite remains the same as in austenite. That is, the FCC lattice austenite lattice is rearranged into BCC lattice without the release of carbon from the solution, which leads to a change from a cubic lattice to a tetragonal lattice (BCT).

### Features of the Martensitic Transformation

The martensitic transformation has some characteristic features that distinguish it from transformations in the pearlitic and bainite intervals:

- 1) martensite is formed at a cooling rate greater than the critical one;
- 2) martensitic transformation occurs without an incubation period;
- 3) martensitic transformation practically does not develop during isothermal holding of Mn;
- 4) martensitic transformation is carried out at a speed close to the speed of sound in steel (about 5000 m/s). At any temperature in the Mn-Mk interval, a certain amount of martensite is formed at such a speed (explosively), and the transformation stops. To continue it, it is necessary to lower the temperature;
- 5) the specific volume of martensite is greater than that of austenite, therefore, during martensitic transformation, the volume of the sample (product) increases;

6) the temperatures of the beginning (Mn) and the end (Mk) of the martensitic transformation do not depend on the cooling rate. They depend on the chemical composition of the steel. The higher the carbon content, the lower the Mn and Mk. In a similar way, these temperatures are affected by almost all alloying elements [1].

The thermal operation of hardening is used to give steel strength, hardness, elasticity, i.e. improve its mechanical properties. This is achieved by heating the steel to temperatures exceeding



the strengthening result. Accordingly, the relevance of additional strengthening of such materials using non-standard approaches is obvious both from an operational and economic point of view.

In the classical idea of the correct complex of thermal hardening of steels, there is a need for mandatory tempering after quenching. Low-temperature tempering of steels is carried out with heating to a temperature of 150...250 °C and holding for 3...4 hours. Such treatment reduces internal stresses, converts the structure of quenching martensite into tempering martensite. As a result, strength and partly toughness increase without a noticeable decrease in hardness. Tempered medium and high-carbon steels after low tempering retain hardness within 58...64 HPC, and therefore, high wear resistance. However, products with this level of hardness (unless they have a viscous core) are not designed to withstand dynamic loads [1, 2]. Therefore, cutting and measuring tools made of carbon and low-alloy steels, bearings, as well as parts to which surface hardening, carburizing, and other types of processing are applied are subjected to low-temperature tempering.

The higher the concentration of carbon and alloying elements in the steel, the greater the amount of retained austenite. In carbon steels, retained austenite is fixed in the structure at a carbon content of more than 0.6 %, but its amount is not large, and it practically does not change the properties of the steel. The effect of retained austenite is manifested in steels containing 1 % carbon and above, especially in alloyed ones, in which the amount of austenite can reach 20–30 % [1].

### **Analysis of the Role of Carbon in Steels During AFSH**

The performance of steel products can be improved by changing their surface properties. It is known that the deformation of the material leads to the intensive formation of a finely dispersed microstructure in the surface of the products, in particular the formation of ultrafine and even nano-sized grains, which causes a significant increase in hardness and strength.

In the works of Burakowski T., Wierzchoń T., Dobrzański L.A., Nowotyńska I., Kut S., Dobrzański L.A., Dobrzańska-Danikiewicz A.D., issues related to the strengthening of the surface of metals were studied. Based on these research, Śliwiński P., Węglowski M.S., Kwieciński K., Wieczorek A. in their scientific works note that the upper layers are conventionally divided into coatings and surface layers. A coating is a layer made or applied to a metal surface by a natural or artificial method, while the surface layer is the surface of the material and the near-surface region, the properties of which differ from the properties of the layers located deeper in the material [4–8].

Friction as an energy source for welding and strengthening materials has been theoretically investigated and demonstrated in scientific works [9–14]. Also, various methods of strengthening steels using the friction component have been investigated and demonstrated in scientific articles [15–17].

One of the methods for increasing the surface hardness of steel is additional friction-strain hardening (AFSH). Observation of the features of the relationship between the conditions of this process and the properties of the material will allow for more precise adjustment of the technological parameters of processing, which can help improve the properties of steel products. For this purpose, it makes sense to trace how the carbon content in steel affects its strength characteristics during AFSH.

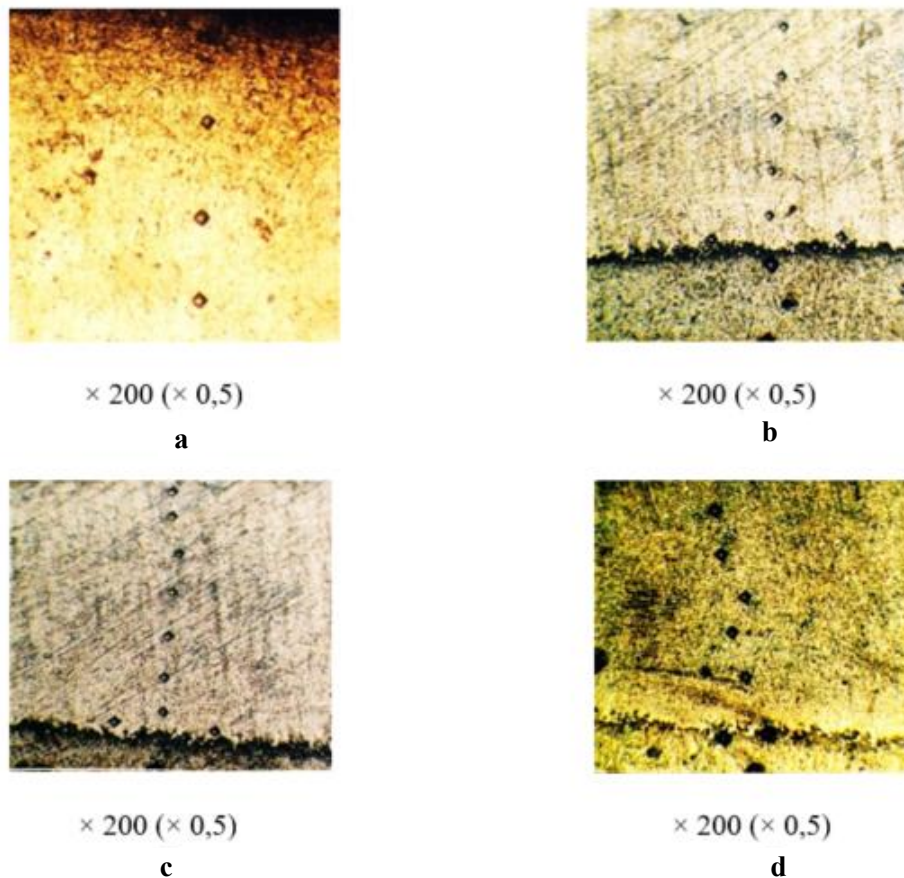
To analyze the role of carbon content in steels with additional friction-deformation strengthening, such brands of carbon group steels as steels 20, 45, U7, U12 (analog, respectively: C22E, C45E, C70W, C110W2) were selected, which were investigated in the previous state after complete quenching and low-temperature release at 180 °C. They cover a wide range of carbon content used to make machine components and tools.

AFSH steel data was performed according to  $S = 30$  mm/s;  $t = 0.7$  mm, which showed the highest efficiency in the processing of 65G steel (analog 66Mn4) by different modes, during research that was performed [18] and provided the highest values of micro-hardness and depth of strengthening, which was recognized as optimal mode, including for these conditions of the AFSH. The relevance of the study of this issue is caused by the need to determine the most optimal carbon content in steel in terms of the efficiency of its additional friction-deformation strengthening.

Thus, the analysis of microstructures and microhardness data after AFSH showed the presence of changes in the surface layer of these steels (Fig. 3), i.e. in all the steels considered, the structure of “white surface hardened layers” was revealed, similar to that described earlier [18].

Steel 20 (Fig. 3, a) is characterized by the appearance of a not significantly hardened “white layer” with some traces of plastic deformation to a depth of approximately 200  $\mu\text{m}$ , with a microhardness of about 9,000 MPa. Under it is a weakening layer, which consists of the structures: trostite, sorbite, pearlite and ferrite. The third layer corresponds to the structure of tempering martensite and has a microhardness of up to 3,500 MPa.

Steel 45 (Fig. 3, b) has, due to its finely dispersed white structure, a sufficiently high level of microhardness – about 12,500 MPa at a depth of up to 370 microns. Another important factor is that this steel has a very small weakening zone. The third zone consists of tempering martensite and has a microhardness of about 8,000 MPa.



**Fig. 3.** The effect of AFSH on the structure of carbon steels with different carbon contents after pre-hardening (AFSH mode:  $S = 30 \text{ mm/s}$ ;  $t = 0.7 \text{ mm}$ ): a – steel 20; b – steel 45; c – steel U7; d – steel U12.

The structure of steel U7 (Fig. 3, c) is similar to the structure of steel 45, but is characterized by significantly higher microhardness and layer depth, which determine the maximum efficiency of strengthening. The microhardness of the strengthened zone is about 16,000 MPa at a depth of 550  $\mu\text{m}$ . The weakening zone is also not clearly expressed. The third zone has a microhardness of about 6,000 MPa.

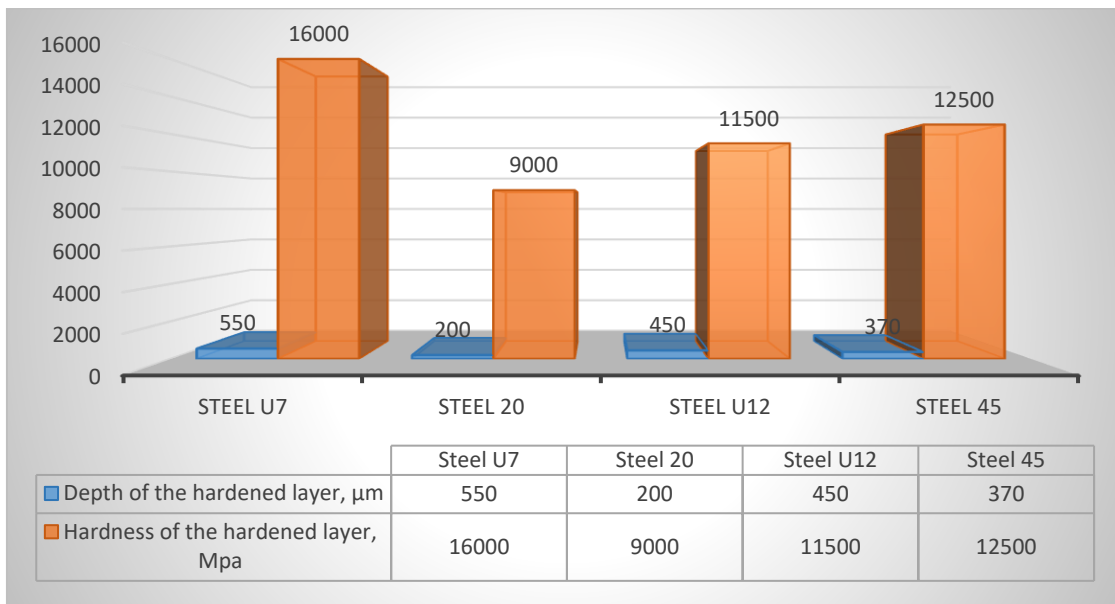
The microhardness of the surface of steel U12 (Fig. 3, d) is also lower than the microhardness of steel U7 and is about 11,500–12,000 MPa. The thickness of the white surface layer is also lower and is 450  $\mu\text{m}$  (Fig. 3, d). In this steel, the weakening zone is more noticeable. However, the hardness of the core, i.e. the base metal zone, is quite high – 6,800 MPa. This can be explained by the fact that the high carbon content somewhat changes its physical properties and the heat released during AFSH, in a certain way contributes to the redistribution of the structure-formation across the cross-section of the sample.

Analysis of the results of the study of the structure and microhardness of steels 20, 45, U7, U12, indicates that the surface hardened layer of steels, for example, has a martensite structure that has undergone deformation and has a higher microhardness. The results of the studies of the microhardness and depth of the hardened layer of steels after AFSH are presented in Table 1.

The graph in Fig.4 shows that among the conditions for additional strengthening is the optimal carbon content, which according to the results of these studies is 0.65–0.8 %. Such a content allows the martensitic transformation to occur as completely as possible when cooling from the heating temperature during hardening. An increase in the carbon content above 0.8 % provokes the appearance of residual austenite structure in the steel structure during hardening, which reduces the overall hardness of the material, although it has a certain potential for hardening during further deformation. Therefore, the graph clearly shows a decrease in the effectiveness of additional strengthening using the example of steel U12.

**Table 1.** Effect of AFSH on the properties of steels.

| Steel grade                  | Processing scheme | Hardening depth, [μm]                        | Hardness of the reinforced layer, [MPa] | Base metal hardness, [MPa] | Degree of additional reinforcement |      |
|------------------------------|-------------------|--|---|----------------------------|------------------------------------|------|
| HARD MODE S=30 MM/c, t=0.7MM |                   |  |   |                            |                                    |      |
| Test sample material         | 20                | Quenching + low-temperature tempering + AFSH | 200                                     | 9000                       | 3500                               | 2.57 |
|                              | 45                |  | 370                                     | 12500                      | 5000                               | 2.50 |
|                              | U7                |  | 550                                     | 16000                      | 6000                               | 2.66 |
|                              | U12               |  | 450                                     | 11500                      | 6800                               | 1.69 |



**Fig. 4.** The influence of additional frictional strain hardening on the properties of steels.

Fig. 4 provides graphic confirmation that in terms of microhardness and depth of the “white” layer, steel U7 has the best performance. This result can be explained by a better tendency to quenching under standard conditions, i.e. a sufficiently high carbon content in these steels provides intensive hardening of the surface layers. A further increase in the carbon content, such as in steel U12, leads to a decrease in the temperature of the end of martensitic transformations (below 0 °C), as a result of which a significant amount of the retained austenite structure may appear [1]. This fact negatively affects the strength characteristics of steels with a high carbon concentration. At the same time, a significantly lower level of surface hardness of steel 20 after AFSH can be explained

by an insufficient amount of carbon at the level of  $\sim 0.2\%$ , which does not allow to obtain a martensite structure at the main stage of heat treatment, as a result of supersaturation of the solid solution with carbon, with a correspondingly high level of hardness.

## Conclusions

So, according to the results of the research, it is shown that the carbon content significantly affects the hardening characteristics of steels during AFSH. An important condition for additional strengthening is the optimal carbon content, which is  $0.65\text{--}0.8\%$ . This content allows the martensitic transformation to occur as completely as possible when cooling from the heating temperature during quenching. Therefore, the most effective among the steels presented in this study in terms of microhardness and depth of the “white” layer is steel U7. An increase in the carbon content above  $0.8\%$  provokes the appearance of residual austenite in the steel structure during quenching, which reduces the overall hardness of the material, although it has a certain potential for strain hardening during further deformation.

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