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THE COOLING MEDIA INFLUENCE ON SELECTED MECHANICAL PROPERTIES OF STEEL

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The aim of experiment was to analyse the structural transformations and changes in mechanical properties of K720 steel during heat treatment (quenching). Three types of cooling medium were selected. The heating parameters and subsequent delays at the recrystallisation temperature were the same for all samples and were observed in a laboratory furnace. Water with the highest cooling capacity was selected as the benchmark cooling medium. Subsequently, the hardening oil TK – 46 was used. Sunflower oil was selected as the last quenching medium, which can be considered an ecological replacement of quenching oil with possibility of biological disposal. The microstructure and microhardness of individual samples were subjected to a metallographic evaluation and evaluated according to ČSN EN ISO 6507, respectively. The impact toughness analysis was performed according to the ČSN EN ISO 148-1 and a three-point bending test was performed according to ČSN EN ISO 7438. This test specifies a method for determining the ability of metallic materials to undergo plastic deformation in bending. The bend test includes subjection of round, square, rectangular or polygonal cross-section to plastic deformation by bending, without changing the direction of loading, until the specified angle of bend is reached.

Keywords: hardening; structure; microstructure; carbon steel; K720 steel

Steel and iron alloys are the most important contemporary construction materials; they are used for construction purposes in a form of bars, sheets, profiles, etc. The properties of steels are derived according to the content of alloys and heat treatment. The most basic compositions are made of iron and carbon. Alloys are carefully selected in order to adjust the mechanical properties of final product, i.e. toughness, hardness, abrasion resistance, hardenability, etc. (Napoli et al., 2018; Votava et al., 2016).

In addition to the chemical composition, the mechanical properties can be effectively altered by a suitably selected heat treatment. During heat treatment, the crystalline structure of steel changes, what leads to significant changes in its properties (Galindo-Nava and Rivera-Díaz-del-Castillo, 2017). It is also possible to change the mechanical properties of materials by addition of an abrasion-resistant layer to the surface (Ľavodová et al., 2018; Paulíček et al., 2013). Based on the supplied alloying elements, the internal structure may also change. Appropriately selected heat treatment can result in high hardness or toughness. The carbon content in steel significantly changes the sensitivity to the heat treatment. However, in order to achieve high hardness, the carbon content of tool steels ranges from approx. 0.5 to 1.5% C (Haiko et al., 2019). Suitable cooling environment is another aspect with a major impact on resulting mechanical steel properties.

For the research purposes, several types of cooling media were used for hardening the samples of tool carbon supernatant steel. Subsequently, a series of tests

was conducted on these samples: measurement of the hardness, impact toughness and bending tests. Finally, a metallographic analysis of samples was performed, and the microhardness was determined.

Material and methods

For the experiment purposes, test samples were prepared according to Fig. 1. The samples were heated in an MP 05 – 1.1 laboratory furnace with air access and without any protection against decarburization. Prior to heating of samples, the furnace was heated to 810 °C. The continuous rise to this temperature was set for 60 min and was subsequently held at desired temperature for 30 min, since the heating time must ensure austenitization in the entire product cross section. The main parameters include austenitization temperature and delay at this temperature (Gomes et al., 2019). The material sheet calls for a delay of at least 15 minutes at austenitization temperature. Four samples clamped to one quencher were quenched in each cooling bath. Çakir et al. (2011) list three stages of contact between the cooling medium and hardened object surface (vapour phase, nucleate boiling and convective stage). In the first phase, the heat dissipation is low and increases with subsequent phases (Fernandes et al., 2007). After complete immersion below the cooling medium surface, the samples were moved with a bath volume to eliminate the formation of gaseous envelope around the samples (Çakir et al., 2011).

Fig. 1 Sample dimensions

Fig. 2 Testing areas

Table 1 Chemical composition of K720 steel

K 720	C	Si	Mn	Cr	V
	0.90	0.20	2.00	0.40	0.10

In order to make the maximum use out of the individual samples and in order to achieve the highest possible accuracy of measurement results, 5 measurements were conducted on each sample (Fig. 2). Firstly, the hardness tests were performed (according to the ČSN EN ISO 6508); subsequently, the three-point bending break tests were conducted using a single-axis tensile testing machine, and finally, impact tests were performed using a Charpy hammer. According to ČSN EN ISO 148-1, this test consists of breaking a notched test piece with a single blow from swinging pendulum under specified conditions. The notch of test piece has a specified geometry and is placed in between two supports – opposite to the location, which is impacted in a test. The energy absorbed in the impact test, the lateral expansion, and the shear fracture appearance are normally determined.

The microhardness measurement was performed on a set of 3 samples from each cooling bath using a Hannemann microhardness tester according to ČSN EN ISO 6507-1, which is a part of the Neophot 21 metallographic microscope. A diamond pyramid with an apex angle of 136 ° and a force of 0.9806 N was pressed into the material. The

microhardness HV is subsequently read according to the length of the diagonals. This method is suitable for heat-treated material and coatings with a thickness over 10 µm (Votava et al., 2020).

Heat treatment parameters

Production company provided free downloadable materials for the heat treatment and subsequent use of steel K 720; its chemical composition is given in Table 1. Its quenching temperature ranges from 790 to 820 °C; delay at the quenching temperature ranges from 15 to 30 min; tempering temperature is 250 °C; and delay at the tempering temperature is 120 min. Such a low tempering temperature was selected in order to achieve the required hardness of future product.

Results and discussion

Experiment evaluation

The first aspect taken into account was the surface of samples. The samples were heated with access to oxygen, resulting in coverage of their surface with a layer of oxides with different cohesiveness during heating (Brito et al., 2019). Fig. 3 shows representatives from each bath: the purest samples

are produced by the water bath. Furthermore, hardening oil also showed very good results in terms of the surface cleanliness – scales are still visible on the samples, but the surface is completely clean in certain places. In addition to this, the hardening process was not accompanied by flames and there was little smoke during the process. The samples hardened in vegetable oil showed a continuous layer of partially removed scale and thermally degraded oil on their surface. The process was accompanied by occasional formation of flames and considerable smoke. There was a lot of scale released in the vegetable oil used.

a) WATER sample no. 3, bath temperature: 23.7 °C

The samples hardened in water showed an average hardness of 62.6 HRC after quenching, the highest value shown from among the baths used. The average hardness dropped to 58.9 HRC by tempering. A similar loss of hardness caused by tempering can be observed in steel DIN 1.3359, which is very similar to K720 steel in terms of carbon content (Amini et al., 2019). After breaking the samples by three-point bending test, all specimens showed a brittle fracture (Fig. 4). The fracture consists of the main fracture surface and there is an additional fracture surface after the fragment separation in the upper part. The fracture surface is uneven, pitted with hints of a shell-like fracture. The highest measured force value for the water bath was 3,179.5 N. The average breaking force of the 5 × 10 mm samples was approx. 3,002 N, which is less by approx. 600 N than breaking force necessary for samples quenched in hardening oil. The three-point

Fig. 3 Surfaces of the hardened samples

Fig. 4 Fracture surface appearance – water (impact test)

Fig. 6 Microhardness test of K720 steel – water-hardened

Fig. 5 Fracture surface appearance – water (bending test)

Fig. 7 Microstructure of K720 steel – water-hardened

bending test procedures are almost linear for all samples with no apparent yield strength differences (Fig. 16). The influence of the neighbouring samples on the measured values is not obvious. The fracture surface created after the impact work test is shown in Fig. 5. The fracture consists of the main fracture surface and surface after the fragment separation. There is a well-drawn fan-shaped drawing on the fracture surface. The average value of impact toughness was 9.43 J for the samples hardened in the water, which is the smallest value shown by all the cooling environments. The microstructure and pitting after the microhardness measurement after hardening are shown in Figs. 6 and 7.

**b) HARDENING OIL sample no. 1,
bath temperature: 23.8 °C**

The samples quenched in hardening oil were expected to show the best results and were used for comparison with other cooling media. The average hardness after quenching reached value of 62.08 HRC. By tempering, the resulting hardness decreased to an average of 57.75 HRC. The breaking force average value of samples was 3,685.25 N, which was more by approx. 680 N than breaking force necessary for samples hardened in water bath. All of these samples showed a brittle fracture. Selected representative sample is shown in Fig. 8. The fracture surface is conch-shaped and is smoother in contrast to samples hardened in water. The surface of samples is very good – with almost clean surface in certain places. The hardening oil has an

Fig. 8 Fracture surface appearance – hardening oil (bending test)

Fig. 9 Fracture surface appearance – hardening oil (impact test)

Fig. 10 Microhardness test of K720 steel – cooled in hardening oil

Fig. 11 Microstructure of K720 steel – cooled in hardening oil

excellent temperature resistance, therefore, there was almost no residual degraded oil visible on the samples. Fig. 9 shows the fracture surface after the Charpy hammer impact test; it consists of the main fracture surface and the surface after fragment separation. A fan-shaped drawing is

clearly visible on the main surface area. The average value of impact toughness of samples quenched in hardening oil was 17.77 J, which was almost twice the value shown by samples quenched in water, as well as the highest value from among all cooling environments. The microstructure and pitting after measuring the microhardness after quenching in hardening oil are shown in Figs. 10 and 11.

**c) SUNFLOWER OIL sample no. 2,
bath temperature: 23.8 °C**

The samples quenched in sunflower oil showed an average hardness of 58.25 HRC; subsequent tempering reduced the hardness to an average of 55.16 HRC. After a subsequent three-point bending test, it was observed that the breaking force necessary for successful execution of the test was 2,843.02 N in average. The graphs of individual tests are shown in Fig. 16. All samples showed a brittle fracture. The fracture surface appearance of samples quenched in sunflower oil was less shell-like and generally more direct in contrast to samples cooled in hardening oil. The fracture surface showed a slight grain size (Fig. 12). The average impact toughness value was 16.54 J; higher values were achieved only by samples quenched in hardening oil.

Fig. 12 Fracture surface appearance – vegetable oil (impact test)

Fig. 13 Fracture surface appearance – vegetable oil (bending test)

Fig. 14 Microhardness test of K720 steel – cooled in vegetable oil

The fracture surface shape is shown in Fig. 13. All samples showed a brittle fracture. The fracture surface is almost perpendicular to the sample axis and shows a hint of a fan-shaped pattern on its surface. Samples quenched in vegetable oil were covered with a layer of unseparated scale and a layer of degraded oil, which could cause significantly lower hardness in comparison to the samples quenched in other cooling media. The microstructure and pitting after measuring the microhardness after hardening in olive oil are shown in Figs. 14 and 15.

Resulting values of the mechanical properties recorded in individual tests are given in Table 2. In terms of hardness, the water bath appears to be the most suitable cooling environment. In this cooling medium, the highest average hardness – 62.58 HRC – was achieved. Similar values were observed in samples quenched in hardening oil – 62.08 HRC. Brito et al. (2019) conducted an experimental comparison of different vegetable oils and mineral hardening oil. Their results showed that vegetable oil (sunflower oil) reduces the internal stress of samples compared to mineral hardening oil thanks to its cooling properties. This fact was also reflected, since there was recorded a significantly lower hardness – the projectable hardness after quenching was 58.25 HRC. However, a significant advantage of vegetable oil lies in its easy and ecological production, as well as possibility of ecological disposal. Moreover, research realized by Prathviraj

Fig. 15 Microstructure of K720 steel – cooled in vegetable oil

et al. (2020) showed that sunflower oil can be used in form of both new or degraded after filtration and chemical purifying. Prathviraj et al. (2020) compared the cooling rates of both types and proved that both are suitable for heat treatment of high carbon steel.

Subsequent tempering was adapted for the purposes of production of cutting tools made of heat-treated steel with high edge retention usable in agricultural production.

The other mechanical properties considered were: deformation; force required to break the samples; and impact toughness. In terms of strength, the best results were shown by the samples quenched in the hardening oil and the lowest in the vegetable oil. The highest values of impact toughness were achieved in the samples cooled in hardening oil; the lowest values were achieved in samples cooled in water bath.

From the overall point of view, the hardness was considered to be a measure indicating the resistance to blunting of cutting part. Furthermore, strength and toughness are indicators of tool cutting part's resistance to damage.

The quenched steel structure shows presence of residual austenite. Due to the insufficient cooling rate in vegetable

Table 2 Mechanical properties of hardened samples

Cooling environment		Hardness after quenching (HRC)	Hardness after tempering (HRC)	Force (N)	Impact toughness (J)
Water	average	62.58	58.91	3,002.62	9.43
	variance	0.57	0.40	30,079.84	0.70
	standard deviation	0.79	0.66	173.44	0.89
Hardening oil	average	62.08	57.75	3,685.25	17.77
	variance	0.40	0.35	16,370.94	1.06
	standard deviation	0.66	0.62	127.95	1.10
Vegetable oil	average	58.25	55.16	2,843.02	16.54
	variance	1.02	0.63	14,639.04	0.34
	standard deviation	1.05	0.83	120.90	0.62

Table 3 Microhardness values of samples

Tested materials	Microhardness values HV ₁₀							
	1	2	3	4	5	average HV ₁₀	dir. deviation HV ₁₀	var. coefficient (%)
Sample 1	644	613	658	658	672	649	20.1	3.1
Sample 2	548	508	570	573	561	552	23.7	4.3
Sample 3	865	844	850	824	833	843.2	14.1	1.7

oil bath, there is a higher proportion of residual austenite in hardened steel. Due to the rate of transformation and its non-diffusive character, the samples hardened in water bath have the smallest proportion of residual austenite. Measured values of the microhardness fully correspond with the rest of measured mechanical properties. The measured values are shown in Table 3.

Fig. 16 shows course of the bending force curves for all cooling environments. The curves are intersected by linear regression with R^2 .

Deformation of samples

Martensite is a common end product of enormous industrial importance for the most heat-treated commercial low-carbon and medium-carbon steels, and is inevitably accompanied by deformation (Sun et al., 2020). It can be exacerbated by certain significant factors, including chemical composition; material purity; and heat treatment factors (e.g. uneven cooling, unsuitable cooling media, etc.). Significant importance of deformation due to martensitic structure lies in the application of carbide welds for

abrasively stressed components. Due to internal stress, the entire weld may break (Votava and Kumbár, 2014). The samples used in this work showed deformation 1 mm at maximum from Fig. 17. Frequently, their deformation was almost negligible. The samples quenched in vegetable oil showed the smallest deformation, the largest deformation occurred in samples hardened in water.

Conclusion

The work presented deals with the heat treatment of tool steel K 720, namely hardening and tempering. The aim was to determine the influence of individual cooling media (hardening oil, sunflower oil and water) on mechanical properties of this steel. Three types of tests were conducted in order to characterise the loading of machine parts under conditions of agricultural production. The samples were subjected to hardness tests, Charpy impact toughness test and three-point bending test. All tests among individual cooling media were of a comparative nature. Measurement results showed that the most suitable cooling medium for the K 720 steel is the hardening oil TK – 46, since it provided the best results in terms of strength and toughness. The least beneficial results were showed by samples quenched in sunflower oil – these samples showed low hardness and strength in comparison to samples hardened in other types of cooling media. The highest hardness was achieved in water-hardened samples at the expense of the toughness and strength.

Considering all three cooling media used, water clearly provides the most environmentally friendly cooling bath, since it does not require any industrial disposal and can be disposed of safely after its utilization. The situation is very similar for vegetable oil – its production is not difficult and it also

Fig. 16 Bending test results of hardened samples **Fig. 17** Sample deformation statistics

can be easily disposed of in an ecological manner. Since several parameters of tested samples quenched in vegetable oil were similar to properties shown by samples cooled in hardening oil, this cooling medium can be used in specific cases. Although the hardening oil represents the most durable cooling media observed, its ecological disposal is the most difficult.

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