INVESTIGATION OF THE MECHANICAL PROPERTIES OF TOOL STEEL 45WCrV7 AFTER RADIAL-SHEAR ROLLING

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ABSTRACT

The work is devoted to the study of the mechanical properties of low carbon tool steel 45WGrV7 after its volume-modification by application of an intensive plastic deformation process. Radial-shear rolling is a proven method of intensive plastic deformation in engineering practice, which produces quality long products with improved structure and properties.

In the present work, rods with different final diameters, obtained by radial-shear rolling were investigated by carrying out three different degrees of relative deformation along the diameter of the rots - 30, 50 and 60 %. Based on tensile and hardness tests, the influence of radial-shear rolling on the mechanical properties of the investigated steel - hardness, tensile strength, conditional yield strength and elongation after failure - was established. The comparative analysis shows that the strength properties after rolling increase by more than 2 times compared to those of the original steel, approaching the properties of expensive high-alloy, high-carbon steels. The findings are a prerequisite for continuing research to study and improve the operational properties of the studied steel.

Keywords: tool steel, radial-shear rolling; mechanical properties, tensile tests, hardness.

INTRODUCTION

Tool steels are a continuously evolving class of materials. To withstand high speeds and enormous stresses resulting from mechanical, thermal, tribological and fatigue loads, tool steels require high performance properties. In recent years, industrially applicable opportunities have been sought to improve their performance properties. Several studies have been carried out on tool steels to study the influence of different surface and/or volume treatment methods on the development of their structure and properties [1 - 8]. Modified in this way, tool steels are finding increasing application as new and promising materials due to their unique mechanical properties.

The production and study of surface and/or volume modified materials with nanoscale structure belongs to one of the priority areas for the development of applied scientific research. A significant increase in the interest of nanostructured metallic materials obtained by plastic deformation and their industrial application has led to an accelerated expansion of research in this field worldwide [9 - 12].

It is known that the refinement of the microstructure of metal alloys to the ultrafine-grained state can be achieved by their volumetric modification with metal forming methods under the following conditions: - achieving high degrees of deformation; - performing deformation at temperatures below the recrystallization temperature of the metal; - ensuring turbulence and non-monotonicity of deformation [13]. Similar conditions can be obtained in metal forming by applying intensive plastic deformation methods [11, 12] such as: cross-screw rolling [14 - 18], high-pressure twisting [19, 20], equal-channel pressing [21, 22], screw extrusion, all-round forging, etc.

The technology of radial-shear rolling is well known and has been successfully applied over the last decades to produce high quality long products from ferrous and non-ferrous metals [16 - 18]. In this technology, compared to the classical cross-screw rolling scheme, a three-roller mill is used in which the feed angle is increased (α = 18° - 20°). In the deformation zone, in the longitudinal direction, the metal experiences compression in two directions and tension in a third, and in the transverse direction, in addition to the compression, the metal is twisted under the action of the roll torque. As a result, favourable conditions are created in the deformation zone for the formation of an ultrafine-grained structure in the volume of the rolled metal. The experience of scientists studying the influence of radial-shear rolling on the structure, properties and behavior of various metals and alloys is summarized by Arbuz et al [14]. The authors experimentally demonstrate the formation of an ultrafine-grained structure and its involvement in the strengthening of the resulting volume-modified materials.

The aim of the work is to study the influence of radial-shear rolling carried out at different degrees of relative deformation on the mechanical properties of the thus obtained volume modified rods with circular cross section of 45WCrV7 steel.

EXPERIMENTAL

Material and specimens

The material used in this study was tools steel DIN 45WCrV7 (1.2542), GOST 5ChV2S in the form of bar with circular cross section. Unlike the most used tool steels, the 45WCrV7 steel studied has a low carbon content (0.45 - 0.50 % C), resulting in higher ductility, and due to the presence of 1.8 - 2.3 % W, 0.9 - 1.2 % Cr, and 0.15 - 0.3 % V, it has high wear resistance, fatigue resistance, and toughness. 45WCrV7 steel is intended for the manufacture of cold machining tools such as cold metal cutting knives, dies for pressing and drawing, punches, and other tools operating under elevated impact loads.

The steel was supplied in the form of bars with a diameter of 36 mm, which are subjected to a preliminary heat treatment - homogenization annealing, including heating up to 700°C, exposure time 35 min and air cooling.

Specimens for tensile and hardness tests were fabricated from the 45WCrV7 steel bar so annealed. These specimens form the first group in our study, namely Group A specimens of original steel.

To achieve the aim of the work, a second group of specimens, group B, was investigated. They are made of bars obtained by volume modification of the original steel. The volume modification of the steel was achieved by applying radial shear rolling. The rolling of the original steel billets was carried out using radial-shear rolling mill, and three different technological regims were applied in terms of the degree of relative deformation - 30, 50 and 60 %. As a result of the conducted rolling, three types of steel rods volume modified at different degrees of deformation were obtained. Specimens were fabricated from these rods for mechanical properties investigation. They form the subgroups B1, B2 and B3, respectively.

Radial shear rolling

Radial shear rolling is a metal forming method in which the workpiece passes through rollers rotating in different directions, deforming under intense pressure. This process of intense plastic deformation allows the creation of round rolled products with advanced structure and improved properties, making it suitable for working with various metal alloys [14, 16, 23, 24]. An analysis of the parameters of the stress-strain state during deformation, as well as of the workpiece shape and damage index of the obtained rolled bars by the radial shear rolling method is made by Arbuz et al. and Lezhnev et al [14, 25].

The laboratory experiments presented in this work were conducted on two radial-shear rolling mills operating at universities in Kazakhstan - laboratory reversible Radial Shear Rolling mill SVP-08, installed at Rudny Industrial University, Rudny and laboratory Radial Shear Rolling mill RSR 10-30, installed at Karaganda Industrial University, Temirtau.

The rolling mills allow the deformation of billets with a circular cross section. Their distinguishing feature is the specially designed feed angles, which significantly reduce defects and waste during deformation, ultimately reducing the cost of metal products.

To carry out the laboratory experiment, workpieces of 200 mm length were cut from the pre-annealed rods with a circular cross-section of 45WGrV7 steel. The workpieces were rolled on a radial cutting rolling mill in three different technological modes, including: - pre-deformation heating; - hot rolling in several passes, reaching different final rod diameters; - cooling of the resulting bars. At each pass through the rolling cell, the diameter of the rod is reduced, the absolute deformation on the rod diameter being ΔD = 3 mm.

Elemental analysis

Elemental analysis is an important part of the research that is carried out in the characterization of metal alloys. To establish the exact chemical composition of the alloy under study, with a view to applying future mechanical, thermal, surface and other treatments to the metal to acquire certain properties, elemental analysis was carried out on the 45WCrV7 steel rods supplied. A mobile arc spark spectrometer for metal analysis SPECTROTEST TXC03 was used for the elemental analysis. The results obtained for the exact chemical composition of the investigated tool steel are presented in Table 1, where the values shown are the average values obtained from 10 chemical composition measurements for each of the two samples tested.

Mechanical tests: tensile and hardness tests

Investigations have been carried out to establish the mechanical characteristics in tensile and hardness tests of 45WCrV7 steel in original and modified condition obtained by radial shear rolling at three different relative deformations along the bar diameter (ε = 30, 50 and 60 %).

The tensile test was carried out on a universal testing machine type P-10 (10 kN, Russia), operating at a test speed based on the loading rate, according to BDS EN ISO 6892-1, method B [27]. The standard specimens were obtained by machining the rods and their shape and dimensions are shown in Fig. 1. As a result of the tensile tests carried out on specimens from the four groups (original specimens - group A and three types of volume modified specimens - groups B1, B2 and B3), the mechanical characteristics of the original and volume modified steel - tensile strength Rm, proof strength $Rp_{0,2}$ and percentage elongation after fracture A - were determined.

In addition, the fractographic analysis of the fractured surfaces obtained after tensile testing of specimens from the four groups was performed. The macroimages of the fractured surfaces were taken with a Dino-Lite AM-413ZT digital microscope at x 50 magnification.

To determine the hardness, the specimens of the four groups (original and volume modified) were tested by applying three different standardized test methods:

- static tests for hardness determination: Rockwell hardness method scale C, measured with HP-250 device (Germany), using a diamond cone with a tip angle of 120^o, according to BDS EN ISO 6508-1 [28] and Brinell hardness - with TSH-2M device (Russia), using a steel sphere with a diameter of 2.5 mm, according to BDS EN ISO 6506-1 [29];

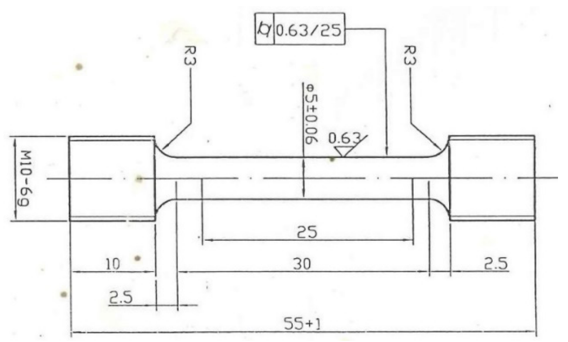


Fig. 1. Shape and dimensions of specimens for tensile test.

Table 1 Chemical composition of the investigated tool steel, wt. %.

	C	Mn	Si	Cr	W	V	Ni	Mo	Cu	Al
Sample 1	0.50	0.25	0.64	1.19	2.07	0.099	0.18	0.051	0.13	0.015
Sample 2	0.52	0.24	0.64	1.16	2.08	0.095	0.18	0.049	0.13	0.015
	Co	Nb	Ti	Ca	Ce	Zn	La	Pb	Zr	Fe
Sample 1	0.018	0.009	0.009	< 0.003	0.031	0.007	0.002	< 0.01	< 0.003	94.8
Sample 2	0.018	0.010	0.008	0.003	0.03	0.006	0.002	< 0.01	< 0.003	94.8

- dynamic hardness tests: Leeb hardness method, determined with a portable combined hardness tester TH 160 (Netherlands), which measures the hardness of the material on different scales by measuring the rebound velocity of a test probe, according to BDS EN ISO 16859-1 [30].

RESULTS AND DISCUSSION

The properties of engineering materials are the result of the the interrelationship between the basic structure, composition of the material and service performance of parts or components manufactured from them. These properties must be considered when selecting a metal for a given application. The present study is aimed at searching for opportunities to improve the service properties of tool steel 45WGrV7, by its volume modification, through the application of radial shear rolling. This will allow the replacement of expensive grades of steels with cheaper ones but produced with improved performance properties.

Volume modification of 45WGrV7 steel by radial shear rolling technology

Radial shear rolling is an intensive plastic deformation method that allows the production of high quality rolled bars with advanced metal structure and improved properties, making it suitable for working with a variety of ferrous and nonferrous metal alloys [14, 16, 24]. Radial shear rolling has several advantages over other metal forming methods. In the process of deformation of the billet, densification and reduction of metal grains takes place, which leads to a significant increase in the physical and mechanical properties of the metal [14]. The results of numerous studies prove that the combination of large feed angles and special calibration of rolls allows reducing the porosity along the center line and the variation of grain size along the cross section of the bars [14, 24].

The laboratory experiments presented in this work were carried out on two Radial Shear Rolling mill - SVP-08 and RSR 10-30. The two radial shear rolling mills have different technical characteristics and different shapes of the working rolls [25, 26]. Thus, while the rolls of the RSP 10-30 mill allow the application of a conventional deformation scheme (direct rolling) [31], the rolls of the SVP-08 mill allow the application of both the conventional deformation scheme and the reversible one [32].

A comparison between these two mills was made using computer modelling of the deformation process of billets in the DEFORM software [25]. The comparative analysis shows that when using the RSP 10 - 30 mill, the forming of the metal occurs more uniformly, both at the surface and in the axial zone of the rod, resulting in a higher quality rolled rod, both in geometry and properties [25]. The authors' findings are the result of the study and analysis of the parameters of the stress-strain state, as well as of the workpiece shape and damage index on the surface of the obtained rolled rods.

In previous studies, information on the microstructure of the investigated 45WGrV7 steel was obtained by computer simulation after carrying out thermomechanical treatment including pre-homogenization annealing and subsequent radial shear rolling. The authors found an initial grain growth after annealing before workpiece deformation and a subsequent gradient fine grain structure of the workpieces after deformation [23]. Therefore, in the present study, preannealing of the workpieces was carried out (homogenization annealing at 700^{o}C, exposure time 35 min and air cooling). The role of annealing is to remove internal stresses in the metal, eliminate other internal defects that would manifest themselves during further metal forming, and allow the workpieces to be deformed with large relative deformations.

The applied technology of radial shear rolling of 45WGrV7 steel rod workpieces using Radial Shear Rolling SVP-08 mill is described in detail in [25] and the technical characteristics in [26]. The annealed workpieces, with an initial diameter of D_0 = 36 mm and length of L = 200 mm, are subjected to preheating in a Nabertherm R120/1000/13 tube furnace to temperatures of 1100^{o}C and holding at this temperature in order to equilibrate the temperature along the cross section of the workpiece. The heated workpieces were fed into the working cage of the Radial Shear Rolling mill SVP-08 where they were hot rolled with a degree of absolute deformation along the diameter of the workpiece of ΔD = 3 mm. After the workpiece has completely exited the cage, the rolls are arched and the direction of their rotation is switched [26]. The workpiece was then fed to the rolls where it was again reduced in diameter with an absolute deformation of ΔD = 3 mm.

To establish the influence of the degree of deformation on the characteristics of the bars produced, two batches of bars were rolled and compared using the described technology. In the first batch, the initial workpieces were rolled to a final diameter D_1 = 25 mm, in three passes, and the second batch was rolled to a diameter D_1 = 18 mm, in six passes. In this case, after the first 3 passes, the workpieces of the second batch were intermediate heated to a temperature of 1000° C and only then rolled to a diameter of 18 mm. The resulting two batches of rolled bars were air cooled. From the thus obtained rolled bars, by applying different relative deformation along the cross section, respectively ε_1 = 30 % and ε_2 = 50 %, samples for mechanical testing were made, forming the groups of volume modified samples, respectively group B1 and B2.

By radial shear rolling at 60 % relative deformation, volume modified bars with a final diameter of 12 mm were obtained - group B3. Rolling was carried out on a Radial Shear Rolling mill 10 - 30, on which a direct rolling scheme was implemented. In this case, workpieces with initial diameter D_0 = 30 mm and length L = 200 mm were rolled. The applied hot rolling mode is similar, with deformation performed in 6 passes according to the scheme 30 à 27 à 24 à 21 à 18 à 15 à 12 ± 1 mm, with ΔD = 3 mm after each pass. Similarly, after the third pass, the workpieces are returned to the furnace for intermediate heating (1000^{o}C) to improve the ductility of the metal and smoothly realize the severe plastic deformation in the next three passes. The cooling of the resulting bars after rolling was carried out in the off-heating furnace used in the pre-deformation heating, which provided a lower cooling rate compared to that of the cooling process scheme applied to the Radial Shear Rolling mill SVP-08.

Mechanical properties investigation

Tensile test

Tensile strength is a fundamental property that is used to predict the behavior of a material or component under load, which is particularly important to engineers when selecting a material for specific applications. Metallic materials with high tensile strength can withstand significant tensile loads without breaking, making them ideal for severe applications. Additionally, these materials can often resist damage from impact and wear, contributing to a longer lifespan and improved reliability of the systems in which they are used.

In order to determine the effect of radial shear rolling on the mechanical properties of 45WGrV7 steel, tensile tests were carried out on specimens of the volume-modified bars - group B1 (ε_1 = 30 %); group B2 (ε_2 = 50 %) and group B3 (ε_3=60 %) - as well as on specimens of the original bar after its annealing (group A).

The original bars after annealing (group A) were found to have a tensile strength of 680 MPa, a proof strength of 460 MPa and an elongation after failure of 8 %. The comparative analysis (Fig. 2) performed on the specimens of group A and group B showed that the strength properties of the bars after radial shear rolling

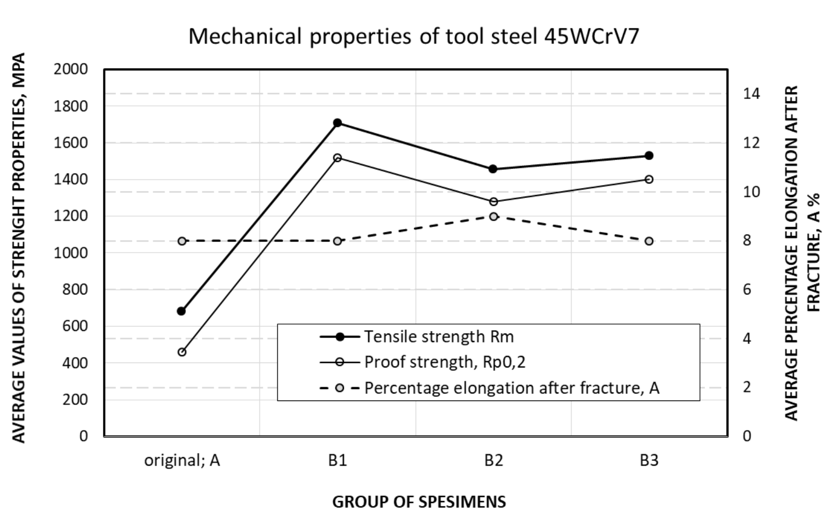


Fig. 2. Mechanical properties of 45WGrV7 steel bars before (group A) and after radial shear rolling with different degrees of relative deformation - 30, 50 and 60 %, respectively groups B1, B2 and B3.

increased compared to those of the original steel. Table 2 presents the results of the tensile tests, where the average of three readings is recorded for additional accuracy. The results obtained prove that the radial shear rolling performed leads to an improvement in the strength properties of the tested steel - the tensile strength has increased by more than 2 times, and the proof strength - by more than 3 times, compared to the established indicators for the original steel.

The observed significant increase in the strength indices is at the expense of the volume modification of the steel microstructure because of the severe plastic deformation of the metal. In radial shear rolling, in the deformation zone, in the longitudinal direction, the metal experiences compression in two directions and tension in a third, and in the transverse direction, in addition to compression, the metal is twisted under the action of the rolling torque [25, 26]. As a result, the structure of the metal after applied radial shear rolling is highly finegrained and heterogeneous in cross section [14]. Previous studies on these deformation processes in the investigated 45WGrV7 steel showed that a non-homogeneous structure was observed in the cross section of the deformed bar with the presence of two regions, a peripheral and a central region, the peripheral region being characterized by a uniform finegrained microstructure and the central region by highly elongated grains in the rolling direction [26]. This non-uniformity in the cross section of the bar structure is also confirmed in radial shear rolling of stainless steel [33].

In addition, increasing the proof strength and bringing it closer to ultimate tensile strength is a desired effect, as it expands the range of working stresses at which the material undergoes only elastic deformations, i.e. without changing its shape and dimensions.

A comparison of the mechanical properties of the volume modified specimens of group B1, B2 and B3 was made, Fig. 2. The analysis shows that when ε = 30 % is realized in three passes (36 à 25 mm) and aircooling, the strength performances are the highest compared to the other applied radial shear rolling modes (50 and 60 % relative strain). With increasing deformation, the strength properties should change monotonically after each pass, as it has been found for corrosion resistant steel [33]. In this case, the relatively higher strength is probably because the bar underwent severe deformation in the first three passes, after which it cooled relatively rapidly under laboratory air conditions. Whereas, in the other two modes of radial shear rolling, after the third pass, an intermediate heating of the metal to 1000^{o}C was conducted to improve its ductility. It is likely that there is a change in the microstructure of the resulting bars under the different deformation modes, which will be the subject of future research and analysis. However, the strength indices of the specimens from group B2 and B3 show a significant increase (more than 2 times) compared to the original bar (group A) but are lower than those of group B1.

The significant increase in the strength properties of the volume modified steel (Fig. 2), while maintaining the initial (of the original steel) elongation values is evidence of the improvement of the operational properties of the steel. This gives us a practical competitive advantage, as it will allow us to manufacture quality tools from the studied modified steel, replacing expensive high-alloy steels.

In this work, investigations of the fractured surfaces after the tensile tests of specimens of the four groups - A, B1, B2 and B3, using a digital microscope were carried out. The macro images taken are presented in Fig. 3. The fractographic analysis shows the presence of a visible narrowing or "necking" of the material

Table 2. Tensile test results of tool steel in original and volume modified condition obtained by radial shear rolling with different degree of relative deformation.

	Tensile strength, Rm, MPa	Proof strength, $Rp_{0,2}$, MPa	Percentage elongation after fracture, A, %
Original specimens (after annealing) - group A	680	460	8
Volume modified specimens - group B1 (ε = 30%)	1710	1520	8
Volume modified specimens - group B2 (ε = 50%)	1456	1280	9
Volume modified specimens - group B3 (ε = 60%)	1528	1400	8

before its ultimate failure, the fracture being typical of steels with reduced ductility. The central part of the fractured surfaces is characterized by brittle fracture - the fractured surfaces is granular with flat, shiny zones. In the specimens of group B (Fig. 3), it is seen that the structure is heterogeneous, with the presence of a peripheral zone with a fine-grained structure and a central one with a rough deformation structure. Future research will be directed towards a more detailed fractographic study using SEM to establish the fracture processes that occurred.

Hardness test

To determine the hardness, static and dynamic hardness tests were conducted on original (group A) and volume modified specimens by radial-shear rolling (group B1, B2 and B3). The hardness measurements were made in the cross and longitudinal surfaces of the bars, and the results are presented in Table 3. The hardness in the cross section of the bars was measured in the central part, at 0.5 of the bar radius and in the peripheral region, close to the surface.

Based on the results obtained from the hardness tests carried out, it was found that the Brinell hardness of the original specimens (group A) in the cross-section of the bar was about 200 HB and 214 HB on the longitudinal surface. The measured hardness in the transverse and longitudinal surface of the different volume modified steel bars (group B specimens) was significantly increased compared to that of the original steel (more than 2.5 times), Table 3. The obtained results correspond with the achieved increase in the mechanical properties of the volume modified steel.

Comparing the measured hardness across the bars, it was found that the hardness increases from the centre to the surface (Fig. 4a). The available gradient is an

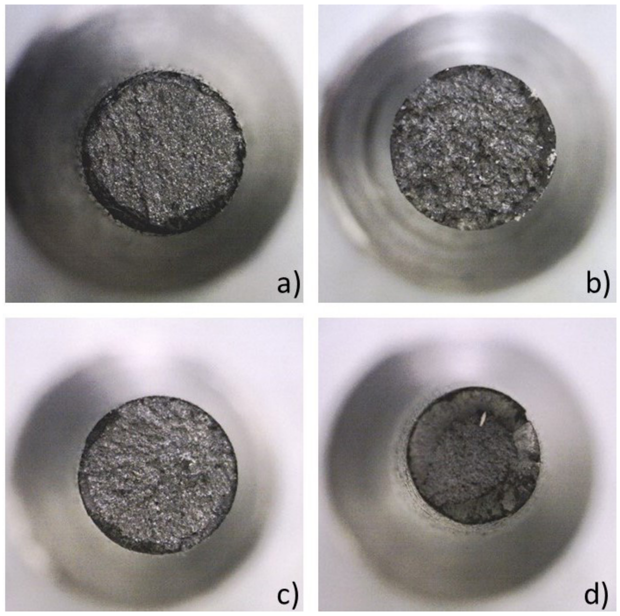
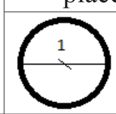
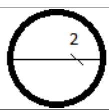
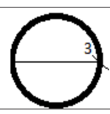
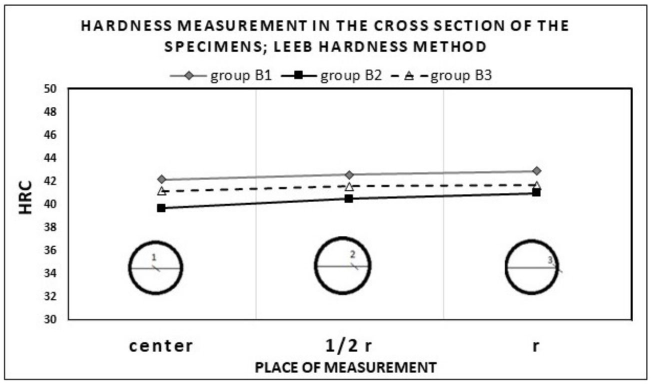


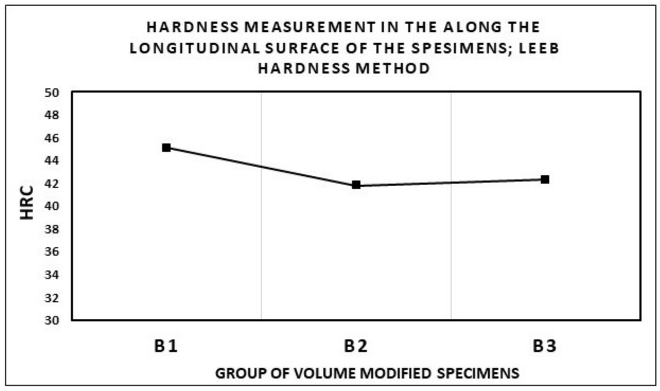
Fig. 3. Macroimage of the fractured surfaces of the specimens (after tencile test) of the four groups; x 50 magnification: (a) group A; (b) group B1; (c) group B2; (d) group B3.

Table 3. Hardness of tool steel in original and volume-modified condition obtained by radial-shear rolling with different degrees of relative deformation, determined by dynamic and static tests.

Spesimens	Dynamic tests					Static tests	
	Hardness scale	Hardness measured in the cross-section of the samples; place of measurement			Hardness measured on the longitudinal surface of the specimens	Test metod	Hardness measured on the longitudinal surface of the specimens
							
Original specimens - group A	HB	192	202	209	203	Brinell hardness test, HB	214
group B1	HRC	42.2	42.6	42.9	45.1	Rockwell hardness test, HRC	45.0
group B2	HRC	39.7	40.5	41.0	41.8		41.0
group B3	HRC	41.2	41.6	41.7	42.3		42.0



a)



b)

Fig. 4. Leeb hardness measured in (a) the cross section and (b) the longitudinal surface of the volume modified spesimens (group B1, B2 and B3).

indicator that a heterogeneous structure is present in the cross section, with two main layers, central and peripheral. In previous studies on the investigated steel, results of microhardness measurements along the cross section of the bars have been presented, where a difference in microhardness values between the peripheral (265 HV) and the central zone (224 HV) of the bars was found i.e. the microhardness in the peripheral layers of the bar was on average 1.17 times higher than that in the central part of the bar [26].

Comparison of the hardness of specimens from groups B1, B2 and B3 in the transverse (Fig. 4a) and longitudinal (Fig. 4b) surfaces shows that the hardness is is comparable, and the trend in the change in hardness confirms the observed tendency in the change in tensile strength. Similar results were obtained in static tests using the Rockwell method.

CONCLUSIONS

During the study carried out on original and volume modified by radial-shear rolling at different degrees of relative deformation specimens of 45WGrV7 steel, the influence of rolling on the mechanical properties - tensile strength, proof strength, elongation after failure and hardness was established. The possibility of obtaining volume modified bars with enhanced mechanical properties by radial shear rolling has been demonstrated. The strength properties increased by more than 2 times compared to those of the original steel. The findings are a prerequisite for further research on 45WCrV7 steel to study the microstructure, wear resistance and fatigue life of the steel after radial shear rolling. The improvement in the performance characteristics of the steel makes it possible, to replace the costly high alloy tool steels with the cheaper low carbon grades, while maintaining the high quality and desirable properties of the tools produced.

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Authors' contributions

R.Y.: conceptualization, methodology, investigation, writing, project administration, funding acquisition; E.P. and S.L.: rolling - technology and experiments, methodology, investigation; S.Y.: mechanical testing, methodology, investigation; I.O. and D.G.: investigation, literary review, data processing, visualization

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