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# Changes in structure, hardness and crack resistance of plasma-strengthened steel 65G

**I. M. Kossanova**[1], **A. T. Kanayev**[1], **T. A. Tolkynbayev**[2], **M. A. Jaxymbetova**[2], **T. E. Sarsembaeva**[1]

[1] **S. Seifullin Kazakh AgroTechnical University** (62 Zhenis Ave., Astana 010000, Republic of Kazakhstan)
[2] **L.N. Gumilev Eurasian National University** (2 Satpaeva Str., Astana 010008, Republic of Kazakhstan)

ind_jm@mail.ru

***Abstract***. The present paper describes the research of structure, hardness and crack resistance indicators before and after plasma treatment of 65G steel of a ploughshare part. As a result of plasma treatment, we obtained the modified layer with increased hardness in the range of 980 – 3558 HV with increase in 3.6 times. Metallographic studies showed that pearlitic-ferritic structure of the original metal transforms into needle martensite with high hardness and strength due to plasma hardening. It is recommended to determine the impact toughness by the Drozdowski method, in which a fatigue crack is pre-created on a special vibrator. Also, before the fatigue crack was grown, lateral *V*-shaped notches of different depths were made on the sample lateral surface. The relative crack length, λ, varied from 0.27 to 0.65. According to the results of compression tests, it was found that there was a small movement of cracks in the hardened samples in the range from 1.3 to 5.6 mm. The initial unstrengthened samples are in a more brittle state than the quenched ones, and accordingly, significant fracture is observed in the conditions of artificial cracking. The evaluation of 65G steel samples for crack resistance by impact bending tests with subsequent oscillographing showed that plasma hardening inhibits crack growth by increasing impact toughness. Thus, the use of plasma hardening is effective in surface hardening of 65G steel, in particular ploughshares which are constantly exposed to mechanical stresses, friction and wear.

***Keywords:*** steel, hardness, plasma treatment, surface layer, microhardness, crack resistance assessment, impact bending test

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# Исследование изменения структуры, показателей твердости и трещиностойкости плазменно-упрочненной стали 65Г

**И. М. Косанова**[1], **А. Т. Канаев**[1], **Т. А. Толкынбаев**[2], **М. А. Джаксымбетова**[2], **Т. Е. Сарсембаева**[1]

[1] **Казахский агротехнический университет имени Сакена Сейфуллина** (Казахстан, 010000, Астана, пр. Женис, 62)
[2] **Евразийский национальный университет им. Л.Н. Гумилева** (Казахстан, 010008, Астана, ул. Сатпаева, 2)

ind_jm@mail.ru

***Аннотация***. Проведены исследования структуры, показателей твердости и трещиностойкости до и после плазменной обработки стали марки 65Г лемешной части плуга. В результате плазменной обработки получен модифицированный слой с повышенной в 3,6 раза твердостью в интервале 980 – 3558 HV. Металлографические исследования показали, что перлитно-ферритная структура исходного металла вследствие плазменной закалки превращается в игольчатый мартенсит с высокими твердостью и прочностью. Усталостную трещину на образцах создавали на вибраторе Дроздовского. Перед выращиванием усталостной трещины на боковую поверхность образца наносились боковые *V*-образные надрезы различной глубины. Относительная длина трещины λ изменялась в пределах от 0,27 до 0,65. По результатам испытаний на сжатие установлено небольшое перемещение трещин в закаленных образцах в диапазоне 1,3 – 5,6 мм. Исходные неупрочненные образцы находятся в более хрупком состоянии, чем закаленные, соответственно наблюдается значительное разрушение их в условиях нанесения искусственной трещины. Проведенная оценка образцов стали 65Г на трещиностойкость путем испытания на ударный изгиб с последующим осциллографированием показала, что плазменная закалка способствует торможению увеличения трещины за счет роста ударной вязкости. Таким образом, применение плазменной закалки эффективно при поверхностном упрочнении стали марки 65Г, в частности лемехов плуга, которые постоянно подвергаются механическим воздействиям, трению и износу.

***Ключевые слова:*** сталь, твердость, плазменная обработка, поверхностный слой, микротвердость, оценка трещиностойкости, испытание на ударный изгиб

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## Introduction

In Kazakhstan today, efforts are underway to enhance the quality of machinery and components through studies focused on the strength properties achieved by employing plasma hardening techniques on heavily stressed parts. The use of the promising method of plasma treatment appears rational for enhancing strength parameters, such as hardness, wear resistance, and crack resistance [1; 2]. This method impacts solely on the surface layer of the components, avoiding deformation of the metal and facilitating the creation of a modified layer exhibiting high strength characteristics on the product's surface. Alterations in the structure and properties of the surface layer take place under conditions of ultra-rapid heating and cooling rates (ranging from $10^3$ to $10^5$ K/s) and brief exposure to the processed material [3 – 5].

## Materials and methods

The research focused on studying steel 65G, specifically the ploughshare component of a plough, designed to slice through soil layers and consistently subjected to friction and wear [6; 7].

Templates were cut using a Labotom-3 cutting machine from Struers (Switzerland). Throughout the cutting process, both the sample and cutting disc were cooled using water and a specialized lubricant to prevent oxidation [8; 9]. Following the cutting of appropriately sized samples, the steel's chemical composition was analyzed to determine the presence of additives, utilizing a Niton XL2 *X*-ray fluorescence analyzer (Table 1).

Plasma hardening was performed using a UDGZ-200 plasma hardening facility. This facility operates by employing indirect plasma arc technology, enabling the heating of a 1 – 2 mm surface area without causing internal deformations to the components [10 – 12].

The steel surface was examined using a Carl Zeiss metallographic microscope with a 200× magnification level.

The surface hardness of the samples was measured using a Wilson VH 1150 Vickers hardness macro tester, employing an indenter load of 30 kg.

Impact bending tests were conducted following the guidelines outlined in State Standard GOST 9454–78, incorporating measurements of impact strength. This method involves the deliberate initiation of sample fracture at a point of concentration in the middle by a single strike from a pendulum pile driver. Impact tests were performed using a KM-30 pendulum impact driver, employing impact samples sized at 6.5×11.5×55 mm. To induce fatigue cracks on the samples, a Drozdowsky vibrator was utilized, resulting in a relative crack length $\lambda$ ranging from 0.27 to 0.65 [13 – 15]. Evaluation of impact strength under assured plane deformation conditions was conducted on samples featuring two additional lateral *V*-shaped notches, each with a depth of 1.0 mm. This assessment of impact toughness on notched samples allows for the determination of the specific work involved in crack propagation during fracture under plane-strain state (PSS) conditions [16 – 18].

## Results and discussion

Metallographic examinations have revealed that the mechanical attributes such as strength, hardness, and crack resistance of plasma-hardened components are influenced by the configuration, dimensions, and alignment of subgrains (Fig. 1).

The structural-phase analysis indicated that the initial metal comprises pearlite grains and ferrite. However, through the process of plasma hardening, these structures undergo a transformation into acicular martensite, exhibiting heightened hardness and improved crack resistance [19; 20].

Table 1

**Results of spectral analysis of 65G steel samples**

*Таблица 1.* **Результаты спектрального анализа образцов стали 65Г**

| Sample No. | Content of dopants, wt. % | ±2σ |
|---|---|---|
| *1* | 0.840 Mn | 0.122 Mn |
| *2* | 0.676 Mn | 0.113 Mn |
| *3* | 0.757 Mn; 0.142 Cu | 0.127 Mn; 0.069 Cu |
| *4* | 0.640 Mn; 0.104 Cr | 0.112 Mn; 0.043 Cr |
| *5* | 0.551 Mn | 0.102 Mn |
| *6* | 0.585 Mn | 0.102 Mn |
| *7* | 1.03 Mn | 0.130 Mn |
| *8* | 0.739 Mn; 0.148 Ti | 0.116 Mn; 0.064 Ti |
| *9* | 0.684 Mn | 0.103 Mn |

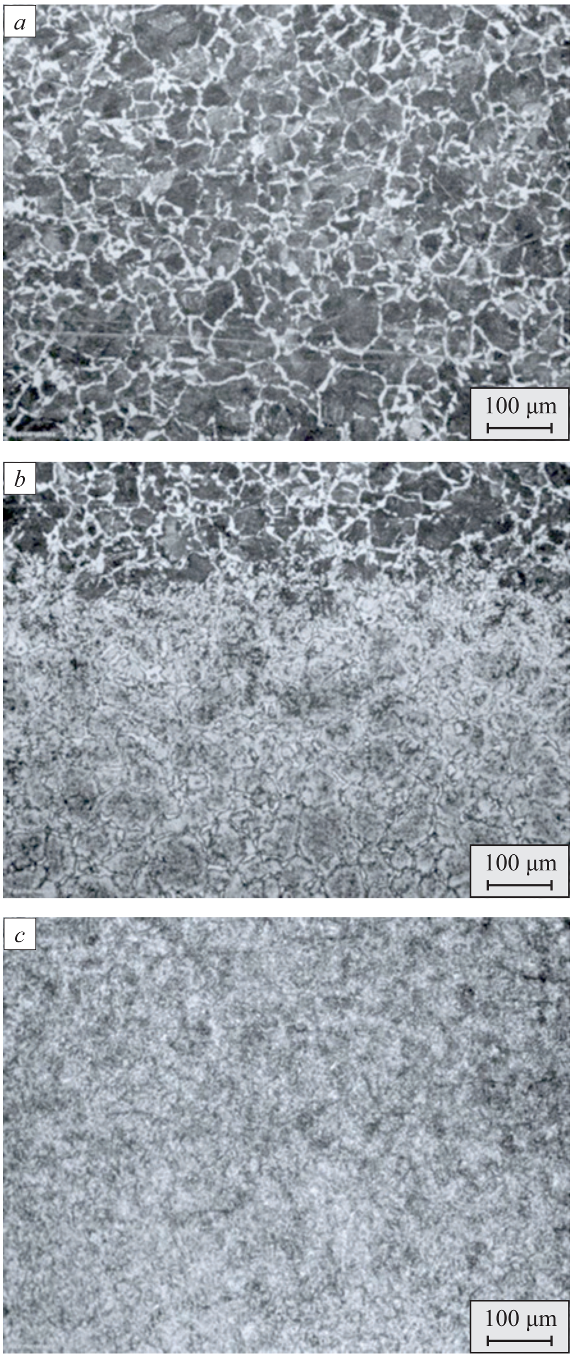


Fig. 1. Metallographic structure of 65G steel after surface plasma hardening:
*a* – base metal; *b* – transition layer; *c* – hardened layer

Рис. 1. Металлографическая структура стали 65Г после поверхностной плазменной закалки:
*a* – основной металл; *b* – переходной слой; *c* – закаленный слой

## Material hardness measurement

Table 2 outlines the outcomes of hardness measurements conducted both before and after the plasma treatment of 65G steel.

The data presented demonstrate a notable elevation in the hardness of 65G steel resulting from plasma quenching. The average hardness value before and after hardening was derived from three measurements for each sample, showcasing an approximate 3.6-fold increase in hardness.

Table 2

**Results of hardness measurements on the surface of 65G steel samples**

*Таблица 2.* **Результаты измерений твердости на поверхности образцов стали 65Г**

| Sample No. | Plasma treatment at the measurement site | $HV_{30}$ | | | Average $HV_{30}$ |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | |
| *1* | W/o treatment | 484.7 | 422.7 | 653.6 | 520.3 |
| | With treatment | 1519.7 | 1780.2 | 2398.5 | 1899.5 |
| *2* | W/o treatment | 764.6 | 762.9 | 698.3 | 741.9 |
| | With treatment | 3423.5 | 2476.8 | 1931.1 | 2610.5 |
| *3* | W/o treatment | 609.0 | 640.0 | 621.0 | 623.3 |
| | With treatment | 2348.0 | 1483.9 | 1766.8 | 1866.2 |
| *4* | W/o treatment | 553.4 | 354.4 | 855.3 | 587.7 |
| | With treatment | 3554.3 | 4589.2 | 3467.7 | 3870.4 |
| *5* | W/o treatment | 368.5 | 345.1 | 368.2 | 360.6 |
| | With treatment | 554.1 | 686.0 | 900.5 | 713.5 |
| *6* | W/o treatment | 418.6 | 355.3 | 344.4 | 372.8 |
| | With treatment | 980.8 | 2418.5 | 2832.3 | 2077.2 |
| *7* | W/o treatment | 404.5 | 370.4 | 361.7 | 378.9 |
| | With treatment | 1407.2 | 960.5 | 860.7 | 1076.1 |
| *8* | W/o treatment | 998.3 | 453.1 | 1287.9 | 913.1 |
| | With treatment | 1133.4 | 1317.6 | 2302.8 | 1584.6 |

Following the plasma hardening process, the crack resistance of the steel was evaluated via impact bending tests accompanied by oscillography. The impact strength of the hardened samples was recorded as 127, 116, 110, 104, 98, 106, 94 and 102 J/cm$^2$.

Fig. 2 illustrates the findings of impact strength studies correlating with crack length. Notably, a gradual escalation in impact toughness is observed as the initiator crack length increases.

Using the outcomes from fracture analyses, the primary dynamic test characteristic, impact strength *KCT*, was calculated.

Fig. 3 displays the assessment results of impact toughness for 65G steel samples before and after plasma hardening. A dynamic growth of *KCT* following plasma quenching is evident, signifying its role in impeding further crack propagation by elevating the *KCT*. Consequently, the original samples exhibit a comparatively more brittle state than the quenched ones, highlighting a

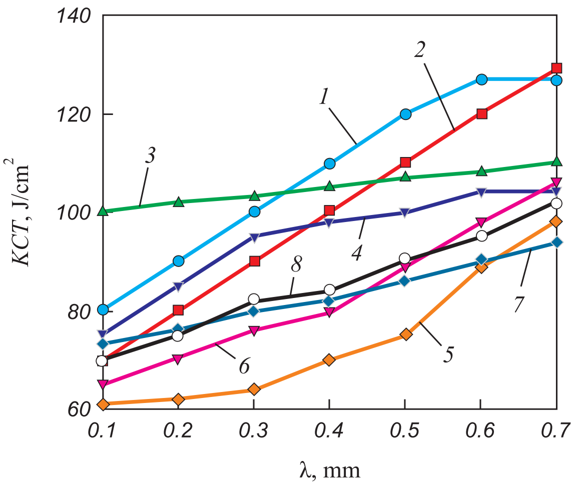


Fig. 2. Dependence of impact strength on crack length (samples *1* – *8*)

Рис. 2. Зависимость ударной вязкости от длины трещины (образцы *1* – *8*)

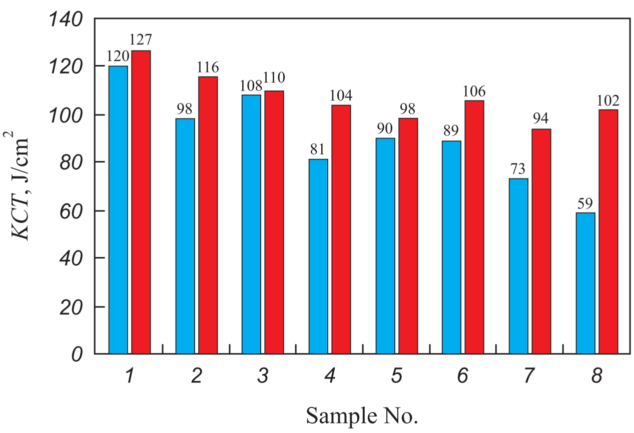


Fig. 3. Diagram of dynamic crack resistance of initial (■) and hardened (■) samples

Рис. 3. Диаграмма динамической трещиностойкости исходных (■) и закаленных (■) образцов

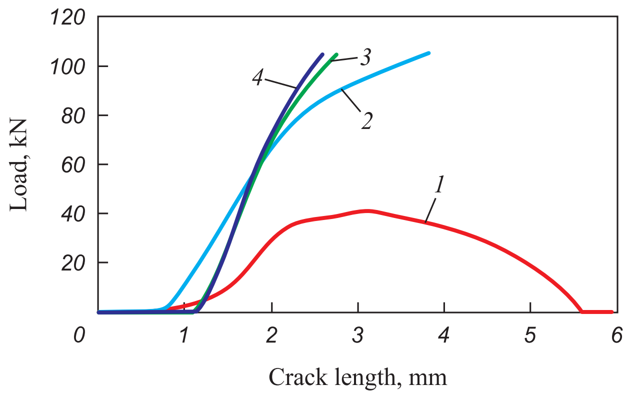


Fig. 4. Cracks' length at linear load (hardened samples *1* – *4*)

Рис. 4. Длина трещин при линейной нагрузке (закаленные образцы *1* – *4*)

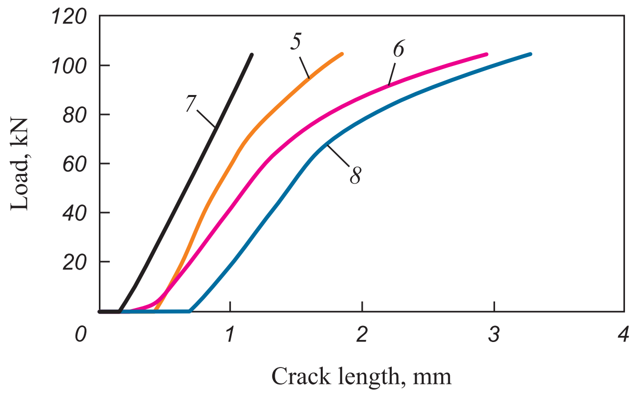


Fig. 5. Cracks' length at linear load (hardened samples *5* – *8*)

Рис. 5. Длина трещин при линейной нагрузке (закаленные образцы *5* – *8*)

substantial vulnerability to failure under plane deformation conditions [21; 22].

During the compression testing of samples under a linear load of up to 120 kN, crack displacement within the range of 1.3 – 5.6 mm was observed (Figs. 4, 5).

The observed crack movement led to a slight reduction in the live cross-sectional area of the sample. Consequently, an increase in the work of fracture ($A_p$) is evident (Fig. 4, 5).

## Conclusions

Metallographic examinations conducted on 65G steel revealed that upon plasma hardening of its surface within a hardened zone of 2 mm thickness, a gradient-layer structure with varying hardness spanning from 980 to 3558 HV is formed. This process induces a notable increase in microhardness, reaching up to 3.6 times, a significantly higher enhancement compared to other hardening methods. For example, electric plasma hardening resulted in an increase in hardness by 2.16 times.

Investigations into impact toughness and the behavior of impact-induced cracks indicated that plasma arc hardening effectively impedes the dynamic expansion of cracks within the surface layer.

Thus, the study outcomes affirm the viability and effectiveness of employing plasma arc hardening as a means to fortify the surface layer of heavily stressed components, specifically exemplified in the case of 65G steel.

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## Information about the Authors

***Indira M. Kossanova***, *Master Student, Doctoral*, S. Seifullin Kazakh AgroTechnical University
***ORCID:*** 0000-0002-9092-8982
***E-mail:*** ind_jm@mail.ru

## Сведения об авторах

***Индира Муратовна Косанова***, *магистр, докторант*, Казахский агротехнический университет имени Сакена Сейфуллина
***ORCID:*** 0000-0002-9092-8982
***E-mail:*** ind_jm@mail.ru

***Amangel'dy T. Kanayev**, Dr. Sci. (Eng.), Prof. of the Chair of Standardization, Metrology and Certification*, S. Seifullin Kazakh AgroTechnical University
***ORCID:*** 0000-0002-2530-038X
***E-mail:*** aman-kanaev2012@yandex.ru

***Temirkhan A. Tolkynbayev**, Dr. Sci. (Eng.), Prof.,* L.N. Gumilyov Eurasian National University
***ORCID:*** 0000-0002-8549-3064
***E-mail:*** temtol1961@mail.ru

***Makpal A. Jaxymbetova**, Senior Lecturer*, L.N. Gumilyov Eurasian National University
***ORCID:*** 0000-0002-3345-4071
***E-mail:*** dzhaksymbetov@list.ru

***Tolkyn E. Sarsembaeva**, PhD, Senior Lecturer*, S. Seifullin Kazakh Agrotechnical University
***ORCID:*** 0000-0002-7674-313X
***E-mail:*** tolkyn-adil@mail.ru

***Амангельды Токешович Канаев**, д.т.н., профессор кафедры стандартизации, метрологии и сертификации*, Казахский агротехнический университет имени Сакена Сейфуллина
***ORCID:*** 0000-0002-2530-038X
***E-mail:*** aman-kanaev2012@yandex.ru

***Темирхан Анапияевич Толкынбаев**, д.т.н., профессор*, Евразийский национальный университет им. Л.Н. Гумилева
***ORCID:*** 0000-0002-8549-3064
***E-mail:*** temtol1961@mail.ru

***Макпал Адликановна Джаксымбетова**, старший преподаватель*, Евразийский национальный университет им. Л.Н. Гумилева
***ORCID:*** 0000-0002-3345-4071
***E-mail:*** dzhaksymbetov@list.ru

***Толкын Ержановна Сарсембаева**, к.т.н., старший преподаватель*, Казахский агротехнический университет имени Сакена Сейфуллина
***ORCID:*** 0000-0002-7674-313X
***E-mail:*** tolkyn-adil@mail.ru

## Contribution of the Authors

***I. M. Kossanova*** – assessment of crack resistance of plasma-hardened steel, statistical processing of the obtained data.
***A. T. Kanayev*** – statement the problem, analysis of the research results, formulation of the conclusions.
***T. A. Tolkynbayev*** – complex metallographic and electron microscopic testing.
***M. A. Jaxymbetova*** – measurement of steel hardness, tabular and graphical representation of the results.
***T. E. Sarsembaeva*** – description of the results, formulation of the conclusions, critical literary analysis.

## Вклад авторов

***И. М. Косанова*** – оценка трещиностойкости плазменно-упрочненной стали, статистическая обработка полученных данных.
***А. Т. Канаев*** – постановка задачи, анализ результатов исследований, формулировка выводов.
***Т. А. Толкынбаев*** – комплексное металлографическое и электронно-микроскопическое исследование.
***М. А. Джаксымбетова*** – измерение твердости стали, табличное и графическое представление результатов.
***Т. Е. Сарсембаева*** – описание результатов, формулировка выводов, критический анализ литературы.

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