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Plasma Hardening Parameters Effect on the Surface Layer Quality of Heavily Loaded Products

¹KANAYEV Amangel'di, *Dr. of Tech. Sci., Acting Professor, aman-kanaev2012@yandex.ru,*
²*TOLEUOVA Ainagul, *PhD, Associate Professor, rymkul.ainagul@gmail.com,*
³TOPOLYANSKIY Pavel, *Cand. of Tech. Sci., Associate Professor, topoljansky@mail.ru,*
¹SARSEMBAYEVA Tolkyn, *PhD, Senior Lecturer, tolkyn_adil@mail.ru,*
¹MOLDAKHMETOVA Aliya, *Doctoral Student, aliya-981@mail.ru,*
¹NCJSC «S. Seifullin Kazakh Agro Technical Research University», Zhenis Avenue, 62, Astana, Kazakhstan,
²NPJSC «Abylkas Saginov Karaganda Technical University», N. Nazarbayev Avenue, 56, Karaganda, Kazakhstan,
³Peter the Great Saint Petersburg Polytechnic University, Polytechnicheskaya Street, 29, Saint Petersburg, Russia,
**corresponding author.*

Abstract. *There has been studied the effect of the hardening current, the distance between the nozzle and the hardened surface of the product, the flow rate of the plasma-forming gas, the dependence of the cooling rate during plasma hardening on the speed of the plasma torch movement (treatment speed), and the diameter of the nozzle. Based on the theory of thermal processes, the cooling rates have been calculated for various values of the current strength. It has been shown that the ratings characterizing the significance of the main technological parameters of the plasma hardening mode for the depth and width of the hardened zone are practically the same. While the effect of the current strength on the dimensions (depth and width) of the plasma hardening zone significantly exceeds the effect of the other parameters of the hardening mode. This indicates that the arc current is the main controlled parameter of the plasma hardening process. There has been shown the possibility of regulating the mechanical properties of the hardened surface of the solid-rolled railway wheel rim depending on the required level of mechanical characteristics by means of controlling the speed of the wheelset.*

Keywords: *surface hardening, technological parameters, heat input, wheelset, rotation mechanism, structure, microhardness, hardening depth.*

Introduction

It is known that surface plasma hardening of steels is a promising but insufficiently studied heat treatment process [1]. Of particular interest are the studies of temperature fields in the heating zone, the heating and cooling rates of metal with a moving local heat source [1, 2].

The plasma method of surface hardening of machine parts is currently one of the most relevant directions in modern materials science. It is characterized by low cost, availability of necessary equipment, environmental friendliness and economic efficiency of use, large dimensions (depth and width) of the reinforced zone. The implementation of this method can be implemented in a typical production facility [3, 4].

The cooling of the part during hardening takes place at ultra-high speeds. This is ensured due to the small volume of the heated metal and the locality, unlike traditional heating methods [1]. The locality of heat treatment is characteristic only for the most loaded working surface of products of responsible purpose. This is due to the technical characteristics of hardening and wear resistance.

After plasma hardening, the parts have an increased hardened surface layer with a depth of 1.0-1.5 mm. Such hardening, without changing the chemical composition and physico-mechanical properties of the part, is one of the final processes of heat treatment, is quite effective and allows you to effectively increase the operational durability and service life of heavily loaded products [5, 6].

Materials and research methods

The object of the study is a solid-rolled railway wheel made of carbon structural steel

65Mn of the following chemical composition, %: 0.44-0.52 C; 0.80-1.20 Mn; 0.40-0.60 Si; 0.08-0.15 V; no more than 0.035P (GOST 10791-2011). The increased carbon content in this steel grade provides the necessary level of wear resistance, crack resistance and heat resistance.

The studies were performed on a mobile certified plasma hardening unit UDGZ-200, which provides non-contact arc ignition, smooth adjustment of the hardening current and gas purging before and after hardening [7, 8].

To harden the surface layer of the wheel, an electrode with a rounded end and a ceramic nozzle with an inner diameter of 12mm (GOST 859-98) were used. The installation is equipped with a plasma-forming gas flow regulator with an AR-40 flow indicator designed to lower the pressure of the gas coming from the cylinder.

The plasmatron is designed for the current of 220-250 A, which is quite enough to carry out the surface treatment process. Cooltec20 was used as a plasma torch coolant, which increases its service life due to the neutrality of the effect on the treated material and significant reducing the amount of scale deposits on the inner surface of the cooling system.

The results obtained and their discussion

The main parameters of plasma treatment are: gas consumption, the magnitude of the current, the distance between the nozzle and the surface of the product, the speed of movement of the plasma torch at different diameters of the ceramic nozzle, the distance from the nozzle cutoff to the quenched surface [9]. Argon of normal purification degree of purification was used as a plasma gas.

As a result of the experiments carried out, it was revealed that in order to prevent melting of the quenched surface, when choosing the quenching mode, it is necessary to limit the maximum heating temperature of the metal (for wheeled steel no more than 1100-1200°C) [10].

Table 1 shows the dependence of the treatment speed, heat input dependence on the current strength. This dependence is also presented in the form of a graph in Figure 1.

For practice, the treatment speed (displacement of the plasma torch), which de-

Table 1 – The treatment speed and the heat input dependence on the current strength

№	I at d_c = 3.0 mm, s = 20 mm										
1	I, A	40	60	70	80	100	120	140	160	180	200
2	V, m/h	-	100	120	70	42	34	21	17	13	11
3	q, J/mm	15	30	31	170	200	305	420	550	690	840

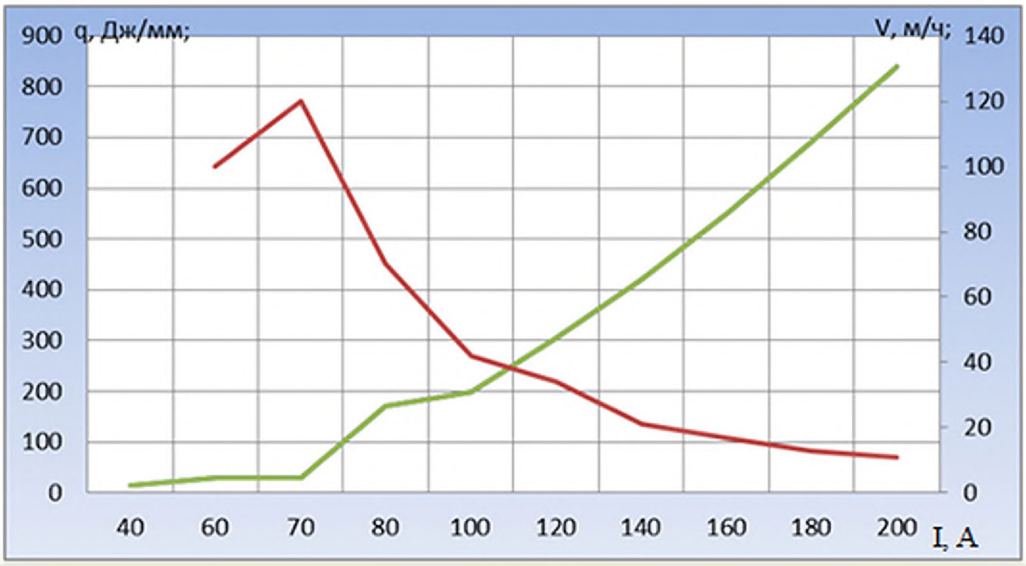

Figure 1 – The plasma arc current effect on the treatment speed and heat input at d_c = 3.0 mm, s = 20 mm

termines the hardening process productivity and the heat input, which affects the degree of thermal deformation of the product, is of great importance. The experiments show that in order to prevent melting of the surface layer of the product, the speed of the plasma torch must be reduced. So, at the current strength of 140A and lower (the treatment speed of 21 m/h or 0.006 m/s), no melting of the surface layer was observed. The heat input over 420 J/mm, corresponding to the current strength of 140-200 A, leads to melting of the surface layer of the hardened part with its rough damage accompanied by the formation of small drops of molten metal. This leads to the need for cleaning to improve the hardened surface appearance [11].

Thus, the obtained results show that the modes of plasma hardening without micromelting of the surface layer in terms of the treatment speed and heat input are in the interval of V = 21-100 m/h and q = 30-420 J/mm, respectively.

In the other series of experiments, the effect of the plasma arc current and the diameter of the plasma nozzle (d_n = 3.0 mm) at the distance from the nozzle to the hardened surface (s = 20 mm) on the depth of the hardening zone was studied. Their results are presented in Table 2.

Analyzing the data presented in Table 2 shows that in the region of hardening modes corresponding to the current of 50 A from 0.06 mm to 1.0 mm at 80 A, the depth of the hardened layer increases and gradually decreases to 0.43 mm at the current of hardening 200 A. The diameter of the plasma nozzle and the distance from the nozzle exit to the hardened surface were kept constant.

It can be seen that for structural steel 65Mn with the constant diameter of the plasma nozzle of 3 mm, the dependence of the hardening zone depth on the arc current is extreme. Two regions of possible modes of plasma hardening can be distinguished. In the region of modes characteristic of relatively low arc currents (50-79 A) and low treatment speeds, the size of the hardening zone limits the metal cooling rate. For structural steel 65Mn at the heating (hardening) temperature of 850°C, the critical cooling rate is 100 K/s (373°C/s).

The surface temperature of the hardened metal should not exceed the allowable temperature (1100-1200°C). This temperature is lower than the melting temperature of the metal to exclude subsequent grinding operations on hardened surfaces.

In the area of high plasma arc currents (over 80 A) and high treatment speeds (plasma torch movement), the hardening zone dimensions are limited by the surface temperature of the hardened metal that should not exceed the specified allowable temperature.

It should be noted that the maximum value of the hardening zone depth corresponds (Table 2) to the modes characteristic at the border of relatively low currents (50-79 A) of the arc and increased currents of the plasma arc (over 80 A) and high treatment speeds.

The effect of the plasma hardening current on the width of the hardened zone at d_n = 3.0 mm, s = 20 mm are presented in Table 3. A comparative analysis of the data obtained shows that the nature of changing the width of the hardening zone depending on the arc current and the diameter of the plasma nozzle (d_n = 3.0 mm) at the distance from the nozzle to the hardened surface (s = 20 mm) is close to the depth of the hardening zone presented in Table 2 that has practical significance for assessing the surface hardened layer quality.

According to the results of the experiments, Table 4 shows the dependence of the the surface zone cooling rate (v, K/s) on the plasma arc current.

From the data in Table 4 it follows that with

Table 2 – The hardening zone depth dependence on the arc current

№	I, (A) at d_c = 3 mm; s = 20 mm										
1	I, A	50	60	67	80	95	115	140	160	180	200
2	h, mm	0.06	0.37	0.92	1.00	0.9	0.77	0.66	0.60	0.52	0.43

Table 3 – The hardening zone width dependence on the constricted arc current

№	I at d_c = 3 mm; s = 20 mm										
1	I, A	50	60	72	80	90	110	120	140	160	180	200
2	h, mm	-	0.38	0.60	6.2	6.0	5.6	5.5	5.4	5.3	5.2	5.1

increasing the current strength in the range from 60 A to 200 A, the cooling rate continuously increases from 200 K/s (373/s) to 4800 K/s (4973/s). The heating (~1500-3000°C/s) and the cooling (~700-800°C/s) rate during plasma hardening provide for this case a hardening (martensite-bainite) structure at the current strength of 100-200 A.

The variation of the plasma nozzle diameter that leads to changing the effective radius of the plasma arc heating spot, leads to extreme changing the cooling rate (Table 5).

It can be seen that transition from a nozzle with the diameter of 2.0 mm to a nozzle with the diameter of 4.0 mm at constant current (80 A) and the distance from the cut to the treated surface (10 mm) leads to decreasing the cooling rate from 2900 K/s to 110 K/s, which affects changing the depth and width of the hardening zone. This is probably due to changes in the degree of localization of plasma treatment with decreasing the nozzle diameter. It follows from these data that selecting a nozzle diameter of 2.8-3.0 mm provides the critical hardening rate and is quite justified.

Increasing the size of the hardening zone is more rational when using a nozzle of a larger diameter; for example, for a nozzle with the diameter of 4 mm at the current of 110 A, the depth of 1.24 mm and the width of the hardening zone of 7.94 mm are achieved, i.e. respectively 22% and 28% more than the values obtained for a nozzle with the diameter of 3.0 mm at the current of 80 A.

In plasma hardening modes close to the mode with the maximum dimensions of the hardening zone at constant values of the plasma nozzle diameter, the arc current, the surface temperature of the hardened product of various thicknesses, the hardening zone of almost the same width is formed, and the hardening depth ceases to decrease, starting from the thickness of 4 mm (Figure 2, Table 6).

It can be seen that changing the depth and width of the hardened layer depending on the diameter of the plasma nozzle at I = 80 A, s = 10 mm has the same character, increasing to the diameter of 3.2 mm and gradually decreasing to h = 0.05 mm and b = 0.95 mm with the nozzle diameter of 3.8 mm. The depth of the hardened layer is a more sensitive characteristic of the hardening mode compared to the width of this zone.

The effect of the plasma nozzle diameter dn on the treatment speed (the speed of the plasma torch movement) and the heat input of the plasma arc at I = 80 A, s = 10 mm is given in Table 7. It can be seen that the diameter of the plasma nozzle has the opposite effect on the treatment speed and heat input of the plasma arc. So, with increasing the diameter of the plasma nozzle from 2 mm to 4 mm, the treatment speed (without micromelting of the surface layer) decreases from 60 m/h to 3.6

Table 4 – The cooling rate dependence on the constricted arc current

№	I at d_c = 3 mm; s = 20 mm										
1	I, A	60	70	80	90	100	120	140	160	180	200
2	v, K/s	200	220	400	600	900	1500	2100	2900	3700	4800

Table 5 – The cooling rate (v) dependence on the nozzle diameter (d_n)

№	Cooling rate	d_c at I = 80 A, s = 10 mm									
		2.0	2.2	2.4	2.5	2.6	2.8	3.0	3.4	3.6	4.0
1	v, K/s	2900	2100	1300	1090	750	600	400	210	160	110

Table 6 – The depth (h) and width (b) of the hardening zone dependence on the diameter (d_c) of the plasma nozzle at I = 80 A, s = 10 mm

№	Hardening zone dimensions	d_c, mm at I = 80 A, s = 10 mm										
		2.0	2.5	3.0	3.2	3.4	3.5	3.6	3.7	3.8	3.9	4.0
1	h, mm	0.5	0.75	1.03	1.10	1.17	0.95	0.46	0.30	0.05	-	-
2	b, mm	0.75	1.0	6.25	6.36	6.30	6.5	5.75	3.19	0.95	-	-

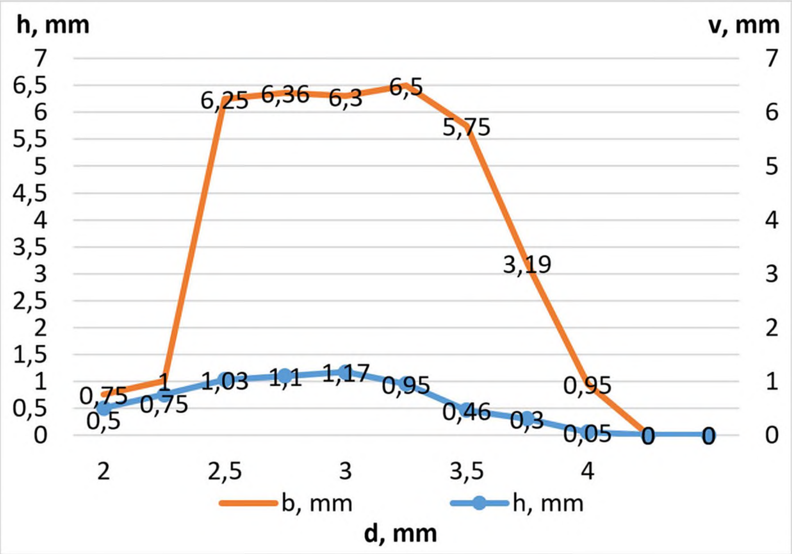

Figure 2 – The depth (h) and width (b) of the hardening zone dependence on the diameter (d_c) of the plasma nozzle at I = 80 A, s = 10 mm

Table 7 – The movement speed (V) and heat input (q) dependence on the diameter of the plasma nozzle (d_c) at I = 80 A, s = 10 mm

№	Plasma hardening parameters	d_c, mm at I = 80 A, s = 10 mm								
		2.0	2.5	3.0	3.3	3.5	3.75	3.85	3.92	4.0
1	V, m/h	60	25	12	8	7.5	5.0	4.8	4.7	3.6
2	q, J/mm	50	140	300	490	615	790	800	870	1050

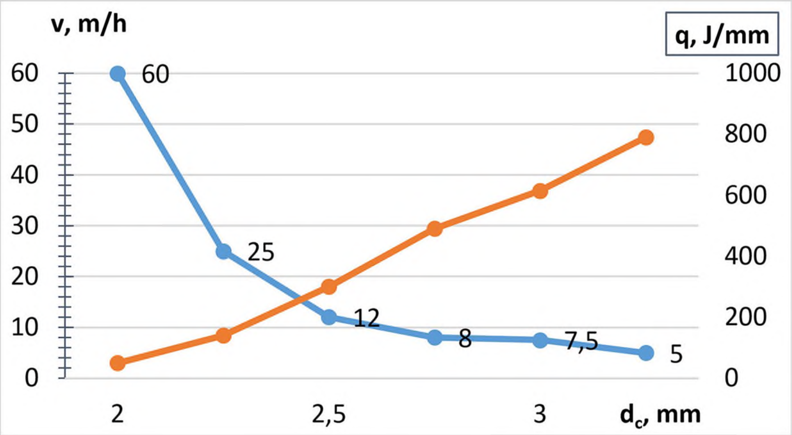

Figure 3 – The movement speed and heat input dependence on the diameter of the plasma nozzle (I = 80 A, s = 10 mm)

m/h [12-14]. Input energy of the plasma arc with increasing the diameter of the plasma nozzle in specified range continuously increases and reaches 1050 J/mm at the diameter of 4.0 mm.

The results of experimental work show the importance of the plasma nozzle diameter effect on the treatment speed and heat input and the need to take these factors into account when developing the technology of surface plasma treatment of parts.

Conclusion

1. It has been shown that the effective thermal power of the plasma arc can be controlled over a wide range not only by changing the plasma arc current but also by the flow rate of the plasma gas, the diameter and length of the gas channel, and the distance between the nozzle and the surface of the workpiece.

2. It has been established that the indicators characterizing the significance of the main parameters of the plasma hardening mode for the depth and width of the hardened zone practically coincide. The effect of the current strength on the dimensions of the plasma hardening zone significantly exceeds the effect of the other parameters of the hardening mode, indicating that the arc current serves the main controlled parameter of the plasma hardening process.

3. The calculation method of estimating the values of the cooling rate depending on the speed of the plasma arc (hardening rate) shows that with high-speed heating of the railway wheel rim, the critical cooling rate required for plasma hardening is provided in almost the entire selected treatment range.

4. There has been shown the possibility of regulating the mechanical properties of the plasma-treated surface of the rim of a railway wheel depending on the required level of mechanical characteristics of the product, by adjusting the speed of the wheelset.

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Плазмалық қатайту параметрлерінің ауыр жүктелген бұйымдардың беткі қабатының сапасына әсері

[1]**ҚАНАЕВ Амангельды Токешович,** *т.ғ.д., профессор м.а., aman-kanaev2012@yandex.ru,*
[2]***ТОЛЕУОВА Айнагүл Рымқұлқызы,** *PhD, қауымдастырылған профессор, rymkul.ainagul@gmail.com,*
[3]**ТОПОЛЯНСКИЙ Павел Абрамович,** *т.ғ.к., доцент, topoljansky@mail.ru,*
[1]**САРСЕМБАЕВА Толкын Ержановна,** *PhD, аға оқытушы, tolkyn_adil@mail.ru,*
[1]**МОЛДАХМЕТОВА Алия Ерлановна,** *докторант, aliya-981@mail.ru,*
[1]«С. Сейфуллин атындағы Қазақ агротехникалық зерттеу университеті» КеАҚ, Жеңіс даңғылы, 62, Астана, Қазақстан,
[2]«Әбілқас Сағынов атындағы Қарағанды техникалық университеті» КеАҚ, Н. Назарбаев даңғылы, 56, Қарағанды, Қазақстан,
[3]Ұлы Петр Санкт-Петербург политехникалық университеті, Политехническая көшесі, 29, Санкт-Петербург, Ресей,

**автор-корреспондент.*

Аңдатпа. *Шынықтыру тогының күші, саптама мен бұйымның қатайтылатын беті арасындағы қашықтық, плазма түзетін газ шығыны, плазмалық сөндіру кезіндегі салқындату жылдамдығының плазмотронның қозғалу жылдамдығына (өңдеу жылдамдығына), саптаманың диаметріне тәуелділігі зерттелді. Жылу процестерінің теориясына сүйене отырып, ток күшінің әртүрлі мәндеріндегі салқындату жылдамдығының есептеулері жасалады. Шынықтыру аймағының тереңдігі мен ені үшін плазмалық шыңдау режимінің негізгі технологиялық параметрлерінің маңыздылығын сипаттайтын көрсеткіштер іс жүзінде сәйкес келетіні көрсетілген. Токтың плазмалық шынықтыру аймағының өлшемдеріне (тереңдігі мен ені) әсері шыңдау режимінің басқа параметрлерінің әсерінен айтарлықтай асып түседі. Бұл доғалық токтың плазмалық шынықтыру процесінің негізгі реттелетін параметрі ретінде қызмет ететінін көрсетеді. Доңғалақ жұбының айналу жылдамдығын реттеу арқылы механикалық сипаттамалардың қажетті деңгейіне байланысты тұтас прокаттағы темір жол доңғалақтарының жиектерінің беріктендірілген бетінің механикалық қасиеттерін реттеу мүмкіндігі көрсетілген.*

Кілт сөздер: *беттік шынықтыру, технологиялық параметрлер, жылу беруі, доңғалақ жинағы, айналу механизмі, құрылымы, микроқаттылығы, шынықтыру тереңдігі.*

Влияние параметров плазменного упрочнения на качество поверхностного слоя тяжелонагруженных изделий

[1]**КАНАЕВ Амангельды Токешович,** *д.т.н., профессор, aman-kanaev2012@yandex.ru,*
[2]***ТОЛЕУОВА Айнагуль Рымкуловна,** *PhD, ассоциированный профессор, rymkul.ainagul@gmail.com,*
[3]**ТОПОЛЯНСКИЙ Павел Абрамович,** *к.т.н., доцент, topoljansky@mail.ru,*
[1]**САРСЕМБАЕВА Толкын Ержановна,** *PhD, старший преподаватель, tolkyn_adil@mail.ru,*
[1]**МОЛДАХМЕТОВА Алия Ерлановна,** *докторант, aliya-981@mail.ru,*
[1]НАО «Казахский агротехнический исследовательский университет имени С. Сейфуллина», пр. Женис, 62, Астана, Казахстан,
[2]НАО «Карагандинский технический университет имени Абылкаса Сагинова», пр. Н. Назарбаева, 56, Караганда, Казахстан,
[3]Санкт-Петербургский политехнический университет Петра Великого, ул. Политехническая, 29, Санкт-Петербург, Россия,

**автор-корреспондент.*

Аннотация. *Исследованы влияние силы тока закалки, расстояния между соплом и упрочняемой поверхностью изделия, расхода плазмообразующего газа, зависимость скорости охлаждения при плазменной закалке от скорости перемещения плазмотрона (скорости обработки), диаметра сопла. На основе теории тепловых процессов выполнены расчеты скоростей охлаждения при различных значениях силы тока. Показано, что показатели, характеризующие значимость основных технологических параметров режима плазменной закалки на глубину и ширину упрочненной зоны, практически совпадают. Влияние силы* *тока на размеры (глубину и ширину) зоны плазменной закалки существенно превышает влияние других параметров режима закалки. Это свидетельствует о том, что ток дуги служит основным регулируемым параметром процесса плазменной закалки. Показана возможность регулирования механических свойств упрочняемой поверхности обода цельнокатаного железнодорожного колеса в зависимости от требуемого уровня механических характеристик путем регулирования частоты вращения колесной пары.*

Ключевые слова: *поверхностная закалка, технологические параметры, погонная энергия, колесная пара, механизм вращения, структура, микротвердость, глубина закалки.*

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