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INFLUENCE OF THE IMPACT ANGLE OF A SOLID PARTICLE JET ON THE EROSION WEAR OF 38GSA AND HARDOX 500 STEEL

WPŁYW KĄTA PADANIA STRUMIENIA CZĄSTEK STAŁYCH NA ZUŻYCIE EROZYJNE STALI 38GSA I HARDOX 500

Key words: solid particle erosion, deformation, 38GSA steel, Hardox 500 steel.

Abstract The paper investigated the influence of the impact angle of a solid particle jet on the erosion wear of 38GSA and Hardox 500 steel. The basis of the analysis was the assumption of the existence of a correlation between mechanical properties of the material, represented by the work of deformation (P) determined from the stress-strain diagram (U). The impact angle of quartz sand particles (30, 60, and 90 °) was considered through the separation of kinetic energy of particles impacting the eroded surface perpendicularly and tangentially.

Słowa kluczowe: erozja cząstkami stałymi, praca odkształcenia, stal 38GSA, stal Hardox 500.

Streszczenie W pracy dokonano analizy wpływu kąta padania strumienia cząstek stałych na zużycie erozyjne stali 38GSA i Hardox 500. Podstawą analizy było założenie istnienia korelacji między szybkością erozji i właściwościami mechanicznymi materiału reprezentowanymi przez pracę odkształcenia (W_0) wyznaczoną z wykresu rozciągania do zerwania i udarność (*U*). Kąt padania cząstek piasku kwarcowego (30, 60 i 90°) uwzględniano poprzez rozdzielenie energii kinetycznej atakujących cząstek na kierunek prostopadły i styczny do powierzchni erodowanej.

INTRODUCTION

Erosion is a process which occurs as a result of material loss caused by moving particles coming in contact with the surface of a material. For example, through the influence of grains of sand carried by its current the banks and bed of the river are eroded. The wearing out of curvatures of water mains as well as the blades of impellers used to move water occurs in the same way. Erosion is the basis for such technologies as abrasive jet cutting, the removal of corrosion and coatings from construction elements or large structures, as well as the elimination of permanent stains from teeth in dentistry. It has been ascertained that, in individual cases, approximately 8% of the wear on construction elements are caused by erosion **[L. 1]**. Design and process engineers would like to know which properties of the material influence its resistance to erosion as well as the attributes of the particles of the particle stream. A material is most often characterized through its basic mechanical properties. Particles making up the particle stream are usually described through their shape, speed, and impact angle **[L. 2]**. This data allows the determination of the mechanisms of erosion as well as its rate and, hence, the duration of a given process or the utilization period of a structure.

Erosion is a tribological process connected to the loss of material on its surface. The question whether the rate of erosion can be determined on the basis of properties applying to the entire volume of the material and which could be different in respect to its surface is significant. Additionally, is it possible to assess the influence of the angle at which the particle stream strikes the surface through its kinetic energy when it is perpendicular or tangential on the rate of erosion?

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PROBLEM ANALYSIS

Theoretical analysis of the process of erosion had been carried out by Finnie **[L. 3, 4]** and Bitter **[L. 5]**. Applying the principle of energy conservation, Finnie examined two possibilities. In the first case, the kinetic energy of the particle is sufficient to remove part of the material, while in the second, it only deforms it. In both cases, the impact angle of the particle is taken into consideration. Bitter **[L. 5]** as well as Nelson and Gilchrist **[L. 6]** believe that material removal W_t is the sum of energy caused by the perpendicular – W_d and tangential – W_e velocities in respect to the material's surface. Erosion produced by a particle stream having a velocity V has been presented using the following formula:

$$W_t = W_d + W_e = \frac{\frac{1}{2}M(V sin\alpha - K)^2}{\varepsilon} + \frac{\frac{1}{2}M(V^2 cos^2\alpha - v_p^2)}{\phi} \quad (1)$$

where K – is the velocity component designating particles striking the material's surface perpendicularly and v_p – the component of velocity striking it tangentially. The material is characterized using two parameters defining the energy through which a unit of material's mass is removed from its surface: ε – when struck perpendicularly and ϕ – when hitting on a tangent.

In order to compare the rate of erosion of various materials, Huchings **[L. 7]** defined a dimensionless factor D as follows:

$$D = \frac{\rho V^2}{R_e} \quad (2)$$

where ρ, R_e are respectively the density and the yield strength of the material being eroded with V – being the particle velocity. Values of factor D of various materials allow the comparison of their resistance to erosion.

To assess the erosion of materials the authors **[L. 8]** defined an erosion parameter E_p as follows:

$$E_e = \frac{\left\{1 - \frac{3,06 H^{\frac{5}{4}}}{\rho_p^{\frac{1}{4}} \cdot V_i^{\frac{1}{2}}} \cdot \left[\frac{1-\mu_t^2}{E_t} + \frac{1-\mu_p^2}{E_p}\right]\right\}}{T \cdot L} \quad (3)$$

where H – is the material hardness, V_i – particle velocity, E_t, E_p – modules of material and particle elasticity, ρ – particle density, μ_t, μ_p – Poisson's ratios of the material and the particles of the particle stream, T – tensile strength, V – volume of the plasticized zone. Values of erosion losses of materials being considered were proportional to the value of this parameter.

In our work **[L. 9, 10]**, the authors assume that, during the process of erosion, a surface layer having a thickness h_u is created **(Fig. 1)**. The moment at which this layer forms determines the critical state. Subsequent contact of particles of the particle stream causes material loss from the material's surface layer as well as its simultaneous recreation. The experiment confirms a constant rate of erosion at predetermined process conditions **[L. 11]**. The detachment of a particle of material is caused by a particular deformation characteristic to that material.

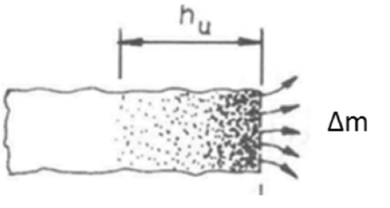

Fig. 1. A schematic of the surface layer
Rys. 1. Schemat warstwy wierzchniej

The article **[L. 10]** contains an attempt to assess whether strain energy P needed to remove a portion of the sample and resilience U expressed as $1/(U \cdot P)$ can be used to measure the resistance of materials to dynamic processes of erosion. It was expected that greater total strain energy needed to remove a portion of the sample as well as greater impact resistance should have meant slower rates of erosion. Study results showed that the greatest correlation of these values occurred when the particle impact angle measured 30°. However, a significant decrease of the $1/(U \cdot P)$ value was not accompanied by a simultaneous reduction in the rate of erosion. Whenever the impact resistance values of two materials were similar, then the material characterized by the greater value of strain energy displayed a lower erosion rate. The correlation, therefore, between the two factors U/P or tensile strength and strain energy may be important. It may become useful in the assessment of a given material's susceptibility to erosion but does not allow the determination of the influence of the impact angle of the particle stream. Erosion is the effect of the kinetic energy E transferred by particles impacting the surface. It is the sum of energies E_p and E_t or of particles impacting the surface being eroded perpendicularly and tangentially. Under stable process conditions, the kinetic energy of the particle stream may be expressed in the following way:

$$E = \frac{1}{2}mV^2 = E_p + E_t = \frac{1}{2}m(V^2 sin^2\alpha + V^2 sin^2\alpha) \quad (4)$$

Assuming that the rate of erosion I is proportional to the kinetic energy of particles striking the surface perpendicularly and on a tangent then

$$I = I_p + I_t = a \cdot sin^2\alpha + b cos^2\alpha \quad (5)$$

where I_p, I_t are the perpendicular and tangential rate of wear, a and b are the factors characteristic to a given material that are also dependent on the mass and velocity of particles. When $\alpha = 90°$, then the rate of erosion caused by particles traveling tangentially to the surface should be $I_t = 0$ while $I_p = a$. This can be verified analysing the rate of erosion when the particle stream is established at, for example, $\alpha = 30°$, 60°, and 90°.

The aim of this work is the analysis of the rate of erosion of material when its strain energy *P* and resilience *U* is known as well as the determination whether the angle at which the particle stream impacts the surface of that material influences erosion through the separation of the kinetic energy of particles striking the surface being eroded perpendicularly and on a tangent.

EXPERIMENTAL TESTING

38GSA and Hardox 500 steels, materials having a high resistance to frictional wear, were chosen for erosion testing. The conditions for the experiment were described in article **[L. 10]**. The distance of the sample from the opening through which a stream of sand particles would be hurled at the material measured along the axis of the stream was 1 = 10 mm. Tests were conducted using three particle impact angles: 30°, 60°, and 90°. Erosion tests were carried out on both surfaces of the sample. The measure of erosion wear was the loss of mass. Samples were weighed with the precision up to 0.0001 g every 30 seconds. Because of the constant rate of wear, the test duration was limited to 2.5 minute.

Resilience *U* of three samples was determined using the Charpy impact test with a mass of 30 kg. The samples had a sharp notch in the shape of a V. Tensile strength tests were conducted using an extensometer at a measuring distance of 25 mm. Nominal sample diameter was 5 mm. The test was carried out on three samples of each type of steel. Strain energy *P* consisted of an area located under the tensile strength graph curves in an σ-ε coordinate system (tension – deformation). Every type of test was done on three samples. The analysis considered average test values.

TEST RESULTS AND ANALYSIS

Basic mechanical properties of 38GSA and Hardox 500 steels determined through tensile strength tests as well as resilience tests are presented in **Table 1**. As shown by data, the considered steels are characterized by a similar value when it comes to tensile strength, but Hardox 500 steel displays more than double resistance to stretching R_m. A list of correlations between hardness, the energy of tension *1/UP* and *U/P,* is shown in **Figures 2** and **3**. The chemical composition of both types of steel were obtained from articles **[L. 12 and 13]** and presented in **Table 2**.

Table 1. Summary of mechanical properties of 38GSA and Hardox 500 steel
Tabela 1. Zestawienie właściwości mechanicznych stali 38GSA i Hardox 500

Type of steel	R_e [MPa]	R_m [MPa]	P energy of tension [MPa]	Resilience [J/cm^2]	Hardness [HV20]
38GSA	**426**	**723**	**158**	**28**	**221**
Hardox500	**1337**	**1623**	**152**	**41**	**511**

Table 2. Chemical composition of 38GSA steel [L. 12] and Hardox 500 steel [L. 13]
Tabela 2. Skład chemiczny stali 38GSA **[L. 12]** i Hardox 500 **[L. 13]**

Element	C	Si	Mn	P	S	Ti	B	Cr	Ni	Al	Mo
38GSA	**0.3–0.38**	**0.8–1.1**	**0.7–1.1**	**0.035**	**0.04**	**0.06–012**	–	–	–	**0.02–0.06**	–
Hardox500	**0.27–0.3**	**0.07**	**1.6**	**0.025**	**0.01**	–	**0.004**	**1–1.5**	**0.25–1.5**	–	**0.25–0.6**

Results of erosion tests for 38GSA and Hardox 500 steels performed with the particle stream hitting the surface at three impact angles of 30°, 60°, and 90° are presented in **Figures 2** and **3**.

Results of erosion tests of considered steel types are presented in **Figures 4** and **5**.

Data presented in **Figures 4** and **5** shows that the erosion caused mass loss has a linear correlation to time. A summary of the rate of the erosion of individual steel types are shown in **Figure 6**. Analysis of data from **Figure 2** suggested that Hardox 500 steel, because of a lower 1/*HP* quotient, should be more resistant to

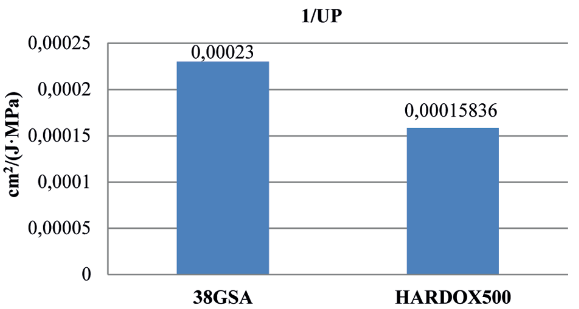

Fig. 2. Summary of dependence between 1/UP values of 38GSA and Hardox500 steel

Rys. 2. Zestawienie wartości zależności1/UP stali 38GSA oraz Hardox500

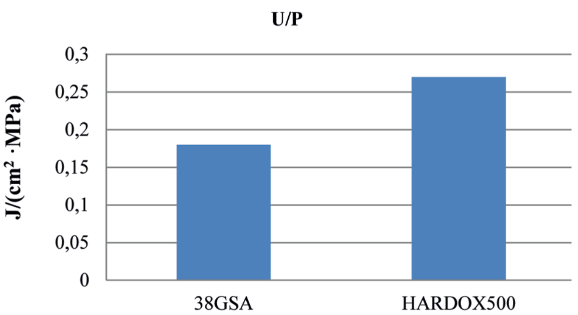

Fig. 3. Summary of dependence between U/P values of 38GSA and Hardox 500 steel

Fig. 3. Summary of dependence values U/P of 38GSA and Hardox 500 steel

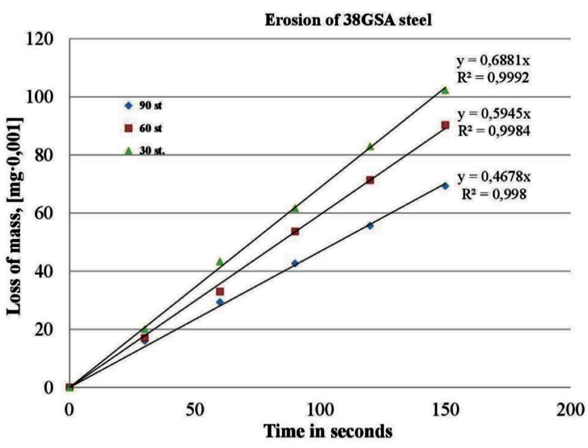

Fig. 4. Relationship between mass loss and duration of 38GSA steel sample erosion test (impact angle of abrasive particles: 30°, 60°, 90°)

Rys. 4. Zależność miedzy ubytkiem masy i czasem trwania testu erozji próbek stali 38GSA (kąt padania cząstek erozyjnych: 30°, 60°, 90°)

erosion in respect to 38GSA steel. Data from **Figure 6** shows that it is completely opposite. It turns out that the correlation between the hardness and strain energy expressed as a *U/P* quotient is significant. When the values of strain energy are similar, then the material with the greater resilience is characterized by a lower rate of erosion. This correspondence applies to all tested particle impact angles. **Figure 7** presents the influence of the particle impact angle on the rate of erosion.

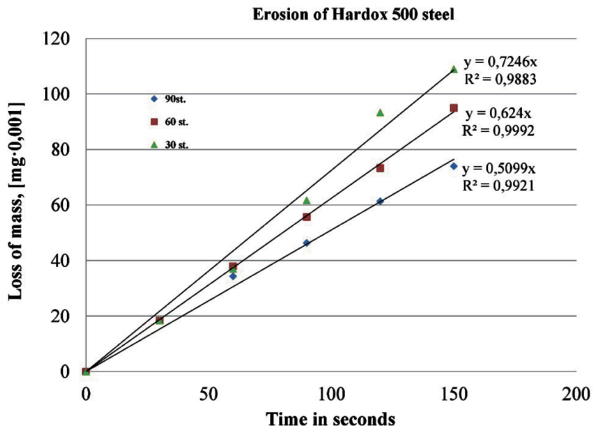

Fig. 5. Relationship between mass loss and duration of Hardox 500 steel sample erosion test (impact angle of abrasive particles: 30°, 60°, 90°)

Rys. 5. Zależność miedzy ubytkiem masy i okresem trwania testu erozji próbek stali Hardox 500 (kąt padania ścierniwa: 30°, 60°, 90°)

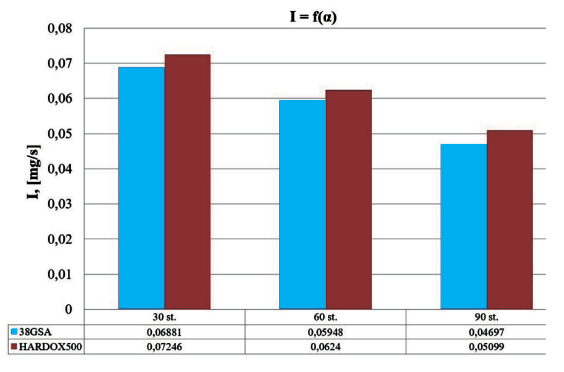

Fig. 6. Summary of 38GSA and Hardox 500 steel rate of erosion at three impact angles of particles' jet α = 30°, 60°, 90°

Rys. 6. Zestawienie szybkości stali 38GSA oraz Hardox 500 przy trzech kątach padania strumienia cząstek, α = 30°, 60°, 90°

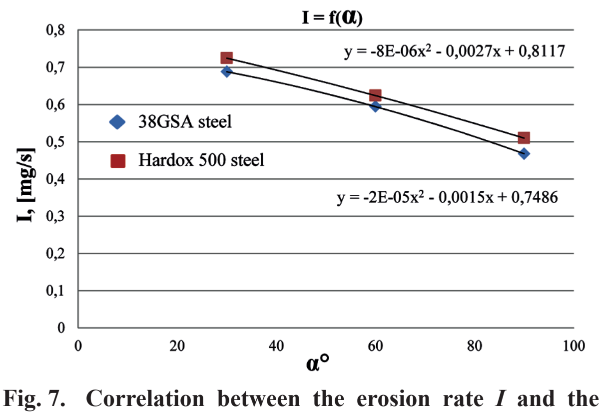

Fig. 7. Correlation between the erosion rate *I* and the impact angle of particles

Rys. 7. Zależność prędkości erozji *I* od kąta padania strumienia cząstek

Data presented in **Figure 7** shows a non-linear correlation between the rate of erosion and the particle impact angle. If the impact angle changes, then the relation of the kinetic energy of particles striking the eroding surface perpendicularly as well as on a tangent also changes. The analysis of the rate of erosion with changes to angle α° have been conducted using formula (5) and data from **Figure 6**. Assuming constant values for coefficients *a* and *b,* the formula for impact angles of α = 30° and 60° for 38GSA steel is as follows:

$$I_{30} = a_1 \sin^2 30° + b_1 \cos^2 30° = 0.06881 \text{ mg/s},$$
$$I_{60} = a_1 \sin^2 60° + b_1 \cos^2 60° = 0.05948 \text{ mg/s}. \quad 6)$$

And for Hardox500 steel:

$$I_{30} = a_2 \cdot \sin^2 30° + b_2 \cos^2 30° = 0.07246 \text{ mg/s},$$
$$I_{60} = a_2 \cdot \sin^2 60° + b_2 \cos^2 60° = 0.0624 \text{ mg/s}. \quad (7)$$

Formulas (6) and (7) present a system with two unknowns *a* and *b* and have been solved separately for 38GSA and Hardox 500 steels. The results of those calculations are the following:

$$a_1 = 0.054815 \text{ mg/s}, b_1 = 0.0734815 \text{ mg/s} \text{ (38GSA).} \quad (8)$$

$$a_2 = 0.05737 \text{ mg/s}, b_2 = 0.07749 \text{ mg/s} \text{ (Hardox 500).} \quad (9)$$

An analysis of formula (5) shows that for angle α = 90°

$$I_{90} = a_3 \cdot \sin^2 90° + b_3 \cos^2 90° = a_3 \cdot \sin^2 90° = a_3 = 0.04697 \text{ mg/s} \quad \text{(38GSA steel)}, \quad (10)$$

$$I_{90} = a_4 \cdot \sin^2 90° + b_4 \cos^2 90° = a_4 \cdot \sin^2 90° = a_4 = 0.05099 \text{ mg/s} \quad \text{(Hardox 500 steel)}. \quad (11)$$

A comparison of coefficients a_1 and a_3 (38GSA) and a_2 and a_4 (Hardox 500) demonstrates that $a_{1/}a_3 \approx 1.17$ and $a_{2/}a_4 \approx 1.13$. This means that erosion (a_3) at a 90° impact angle is greater than estimated erosion a_1. The reason for this difference may include disturbances in the jet of particles caused by particles that bounced off the material's surface. This concerns angles smaller than 90°.

Figure 8 shows the material's surface at angles 30° and 90°, first for 38GSA steel and then for Hardox 500 steel.

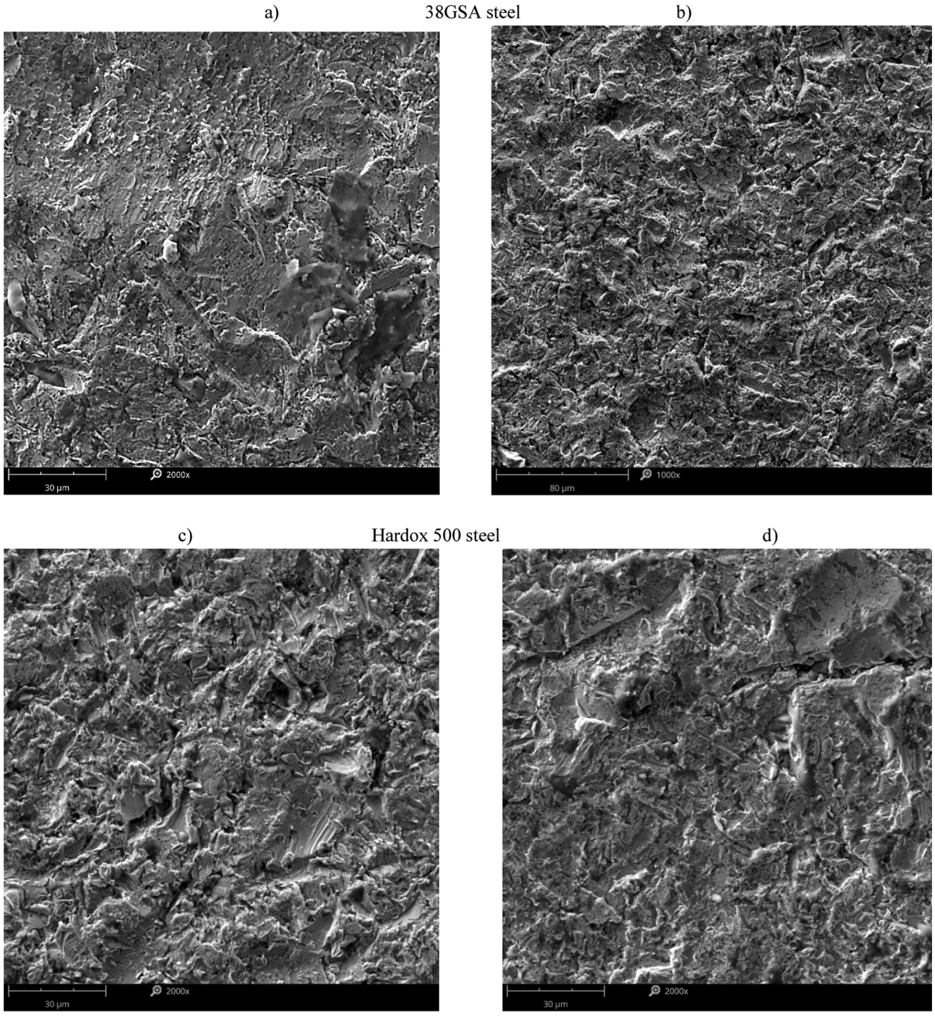

Fig. 8. Photographs of the surface of samples (magnification 2000×): 38GSA – a) 30°, b) 90°; Hardox 500 – c) 30°, d) 90°

Rys. 8. Widok powierzchni stali (powiększenie 2000×): 38GSA – a) 30°, b) 90°, Hardox 500 – c) 30°, d) 90°

The state of the surface of samples after erosion tests depended on the type of steel. A comparison of surfaces of steel samples tested using a particle impact angle of 30° shows that a sample made of 38GSA steel has smaller indentations and exhibits evidence of particles sliding off as well as small grooves. At an impact angle of 90°, the surface of a sample of Hardox 500 steel shows deep, irregular deformations. This type of structure favours the removal of larger fragments of material which also have greater mass. The surface of samples made of 38GSA steel show smaller and more regularly spaced deformations. 38GSA steel samples demonstrated greater resistance to erosion in comparison to samples made of Hardox 500 steel.

CONCLUSIONS

The results of the rate of erosion tests conducted on samples made of 38GSA and Hardox 500 steel at various particle impact angles (30°, 60° and 90°) allow us to make the following conclusions:

- The quotient of resilience and strain energy expressed as *U/P* can be used to determine a material's resistance to erosion.
- Smaller *U/P* values correspond to slower rates of erosion.
- The influence of the perpendicular component of the energy of the eroding particle stream is greatest at an impact angle of $\alpha = 90°$.
- The surface of samples made of Hardox 500 steel showed greater deformation in comparison to samples made of 38GSA steel which has smaller yield point *Re* and resilience *U* values but is characterized by a higher strain energy *P*.

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