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RELAXATION OF THE RESIDUAL STRESSES PRODUCED BY PLASTIC DEFORMATION

RELAKSACIJA ZAOSTALIH NAPETOSTI ZARADI PLASTIČNE DEFORMACIJE

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The relaxation of residual stresses in cold-rolled strips of the alloy AA5083 and drawn bars of the steels 1.1141 and 1.7015 depending on the important parameters of the thermal and mechanical relaxation process were investigated. The measurement of residual stresses and the control of their complete or partial removal were performed using the deflection method and *x-ray* diffraction. The residual stresses are very unstable and intensely affect the changes of shape and dimensions when their balance is disturbed. This instability serves to their relaxation. The performed analyses and dependences enable the efficient planning and control of the relaxation processes.

Key words: cold rolling, drawing, residual stresses, thermal relaxation, mechanical relaxation

Raziskana je bila relaksacija notranjih napetosti v hladno valjanem traku iz zlitine AA5083 in v vlečenih palicah iz jekla 1.1141, ki je odvisna od pomembnih termičnih in mehanskih značilnosti. Notranje napetosti in kontrola njihove delne ali popolne odprave so bile izmerjene z metodama defleksije in uklona rentgenskih žarkov. Notranje napetosti so zelo nestabilne in močno vplivajo na spremembo oblike in dimenzij, ko je spremenjeno njihovo ravnotežje, kar je podlaga za relaksacijo Izvršeni preizkusi in njihova analiza omogoča učinkovito načrtovanje in kontrolo procesa relaksacije.

Ključne besede: hladno valjanje, vlečenje, notranje napetosti, termična relaksacija, mehanična relaksacija

1 INTRODUCTION

The technological processes of plastic deformation are characterized by the presence of different non-homogeneities that cause non-homogeneous deformation. The consequence of non-homogeneous deformation is the inevitable occurrence of residual stresses, which are permanently retained in metal products [1–3]. The residual stresses are spatially balanced, but they are also latently unstable. In case of an uncontrolled disturbance of their balance in further treatments and exploitation, permanent changes of the shape and dimensions of metal elements are possible. The typical examples are the bending and distortion of cold-rolled strips and pressed profiles, bending, distortion and changes in diameter of drawn bars and wires, etc. [2,4–7]. Furthermore, the total stress of the elements exposed to an external load, due to the superposition of the residual stresses, can reach the limit value and cause damage or reduce the reliability of the structural elements [8]. Therefore, the residual stresses need to be relaxed, i.e., completely removed or transformed to a more appropriate form that cannot cause permanent consequences. For the performance and control of the relaxation process it is necessary to know the values of the stress, their distribution within the element and the changes in the relaxation processes.

The values of the residual stresses were obtained by a measurement that had to be adapted to the shape of the element, the stress condition and the material condition. The typical methods for the determination of residual stresses are destructive (mechanical) and non-destructive. The mechanical methods are based on the destruction of the stress balance and the measurement of the elastic effects. In rolled plates and strips the procedure consists of the removal of metal layers from one side, while in bars it consists of longitudinal cutting. Both procedures are based on the deflection method, i.e., on the determination of the residual stresses on the basis of measurements of an elastic bend.

The model of stress distribution in the cross-section can also be performed on the basis of a deflection using the equivalent moment load for balanced residual stresses [7,10–15]. Typical non-destructive methods are based on the measurements of physical constants of the material in the presence of residual stresses, such as measurement of the changes of diffraction properties of the waves in the presence of residual stresses (e.g., x-ray) [7,9].

The most important processes that cause complete or partial relaxation of the residual stresses can be thermal or mechanical. The thermal processes consist of heating at the temperatures necessary for active thermal processes for the relaxation of residual stresses (e.g., low-temperature tempering), the kinetics of which is described by the known *Zener-Wert-Avrami*'s function [10,17,18]. The mechanical processes imply a limited plastic deformation for the relaxation of residual stresses, mostly by axial stress acting or bending (cyclic bending) [8,16].

In this paper the investigation results of the relaxation of residual stressess in cold-rolled and drawn products by thermal and mechanical processes is presented. The stress relaxation curves were determined depending on the parameters of the thermal and mechanical process, and the models of comparative analogy which can contribute to the prediction of the process of total or partial relaxation were derived.

2 EXPERIMENTAL

2.1 Materials and preparation

For the investigation of cold-rolled strips the commercial aluminum alloy AA5083 was chosen, while for the investigation of drawn bars the construction steels 1.1141 and 1.7015 were chosen. Their chemical composition and mechanical properties in the initial state are shown in **Table 1**.

The thickness of the initial strips was 1.28 mm in the soft-annealed condition. For cold drawing the initial hot-rolled bars with a diameter of 16 mm were pickled in a hot dilute solution of H_2SO_4 according to the usual technological process for surface cleaning. The bars were then machined by milling to half of the diameter, and then the two parts were connected by a rivet joint. This kind of bar is an initial sample for the drawing process.

2.2 Deformation processes

The cold rolling was performed on a laboratory duo-rolling stand, using rolls with a diameter of 125 mm and a speed of 0.17 m/s. The dimensions of the strips (width and thickness) and the reduction ratio were chosen in order to provide conditions of plane strain [2]. The cold drawing was performed on an industrial drawing machine with the reductions of diameter normally used in production for calibration drawing. The lubrication was made using oil, the drawing speed was 0.35 m/s, and the matrix angle was 0.314 rad. The dimensions of the samples and the reduction ratio (ε) are shown in **Table 2**.

2.3 Measurement of the residual stresses

The residual stresses arising from the rolling of thin strips and the bar drawing are in accordance with the stress state of the processes [2,3], and the two-dimensional residual stresses state is formed in rolled strips, while the axisymmetric residual stresses state is formed in drawn bars. All the components of the stress include the whole cross-section, they are balanced and they have maximum values on the surface and/or in the centre [3,5,7]. The longitudinal residual stresses have a dominant influence on the properties and shape of the elements, so the experimental process was adapted to their measurement.

The measurement of the longitudinal residual stresses was performed using the deflection method, based on the stress balance disruption and the measurement of the formed elastic lines (bends). The stress balance disruption in flat-rolled strips was performed by the removal of metal layers on one side by etching in a 20 % NaOH solution at room temperature, while the remaining part of the sample was protected. Due to the stress balance disruption the strip is elastically bent, symmetrically with respect to the transverse axis. The strip after rolling and after layer removal is in **Figure 1**.

In drawn bars the stress balance change was performed by the rivet joint removal at one end of the connected halves. After the removal of the joint, the halves were bent in the form presented in **Figure 2a**. In

Table 1: Chemical composition and mechanical properties of the investigated alloys in the initial state
Tabela 1: Kemična analiza in mehanske lastnosti raziskanih zlitin v začetnem stanju

Alloy	Chemical composition, *w*/%						Mechanical properties			
	Mn	Mg	Cu	Si	Fe	Zn	$R_{p0.2}$/MPa	R_m/MPa	*A*/%	*E*/MPa
AA5083	0.42	4.23	0.015	0.13	0.26	0.02	134.7	289.7	22.86	70000
	C	Si	Mn	P	S	Cr				
1.1141*	0.15	0.40	0.3-0.6	0.035	0.035	–	275	434.2	–	191400
1.7015*	0.18	0.40	0.60	0.035	0.035	0.80	328	479.6	–	203400

* En 10027-2

Table 2: Dimensions of the samples and the parameters of the processes
Tabela 2: Dimenzije vzorcev in parametri procesa

Process	Alloy	*B*/mm	H_0/mm	H_1/mm	/%	Measuring length, *l*/mm
Rolling	AA5083	20	1.28	1.088–0.512	15–60	80
Drawing		(D_0/mm)/(D_1/mm)				
	1.1141	16/15; 16/14.5; 16/14			12.11–23.44	225
	1.7015					

B – width of strip; H_0, H_1 – thickness of initial and rolled strip; D_0, D_1 – diameter of initial and drawn bar

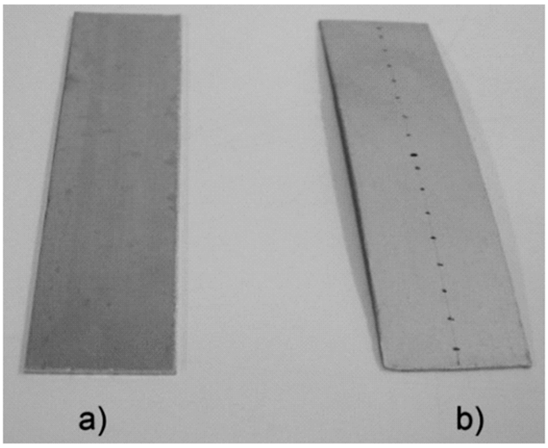


Figure 1: Rolled strip: initial state (a) and after the removal of metal layer (b)
Slika 1: Valjan trak: začetno stanje (a) in po odstranitvi plasti kovine (b)

both cases the measured elastic line follows the form of the bent sample after balance disruption. The elastic line model is the initial data for the calculation of residual stresses and it is derived by the measurement of the bending along the length of the rolled strip, i.e., along the length of bent halves of the bar. In order to derive the final relation for the calculation of residual stresses, the model of their distribution along the cross-section, i.e., the equivalent exterior load corresponding to the presented elastic line model as well as to the balance of residual stresses, must be known. The detailed investigation showed that the measured elastic lines can be described with high precision by the elastic line of the cantilever bend. It also defined the model of the equivalent exterior load. The complete procedure for these measurements and the calculation of residual stresses in cold-rolled strips and drawn bars were presented in [12,14]. The derived final relations for the elastic line, the distribution model and the value of longitudinal residual stresses are shown in **Table 3**.

If the metal layers from the strip surface are removed successively (Δ is changed from 0 up to half the thickness), the elastic lines retain exactly the same properties. This means that the residual stresses can be precisely described by the model equation presented in **Table 3**.

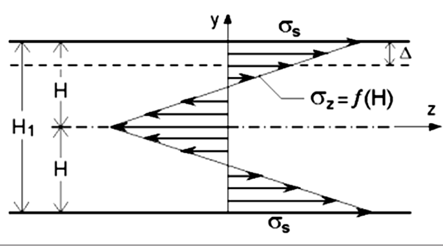
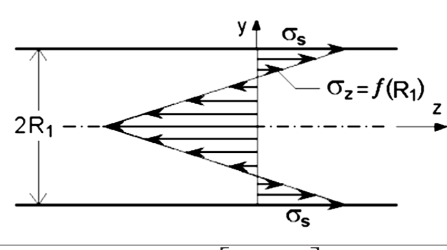
In the measurement of residual stresses in drawn bars after cyclic bending it is not possible to use the previously described measurement procedure because the cyclic bending demands a compact bar (made of one piece). Therefore, the measurement of residual stresses was performed by the x-ray ($\sin^2 \psi$) method using apparatus of the DRON-2 type.

2.4 Processes of relaxation of residual stresses

The thermal stress relaxation in AA5083 strips was performed by annealing at a temperature of 140 °C for 1 min to 10 min. The process was conducted in original samples after the cold rolling and removal of the layer from one side. These elastically bent strips were placed on a 3-mm-thick metal plate, afterwards attached and aligned, and thermally treated. In drawn bars the annealing regime of 370 °C/h was used. The experiment consisted of the connection of the bar halves at the separated end and annealing. In both cases after annealing the connection of the samples was removed again and the elastic line was measured. If annealing continues the procedure is repeated in the same way.

The mechanical relaxation of the residual stresses with axial tension was performed with a permanent

Table 3: Schemes and equations for elastic line and residual stresses
Tabela 3: Shema in enačbe za elastično linijo in notranje napetosti

	Cold rolled strips	Drawn bars
Scheme of stress distribution through the thickness / cross-section		
Equation for stress distribution	$\sigma_z = \sigma_s \left[2\dfrac{h}{H} - 1 \right]$	$\sigma_z = \sigma_s \left[3\dfrac{r}{R_1} - 2 \right]$
Equation for elastic line	$y = a \cdot (z/L)^2$	$y = a \cdot (z/L)^2$
Equation for surface stress	$\sigma_s = \dfrac{8E(H - \Delta/2)^3}{\left[6\Delta H - 6\Delta^2 + \Delta^3/H\right]} \dfrac{f}{L^2}$	$\sigma_s = 12\left(\dfrac{\pi}{8} - \dfrac{8}{9\pi}\right)\dfrac{f}{L^2}$

where:
y – strip bend, in bars the half of distance between the separated halves; a – coefficient; z – coordinate in the length direction; L – half of measuring length of the strip, measuring length of the bar; σ_z, σ_s – longitudinal stress along the cross-section and surface respectively; H – half the thickness of rolled strip ($H_1/2$); Δ – thickness of the removed layer; R_1 – radius of the drawn bar; E – modulus of elasticity; f – maximum bend

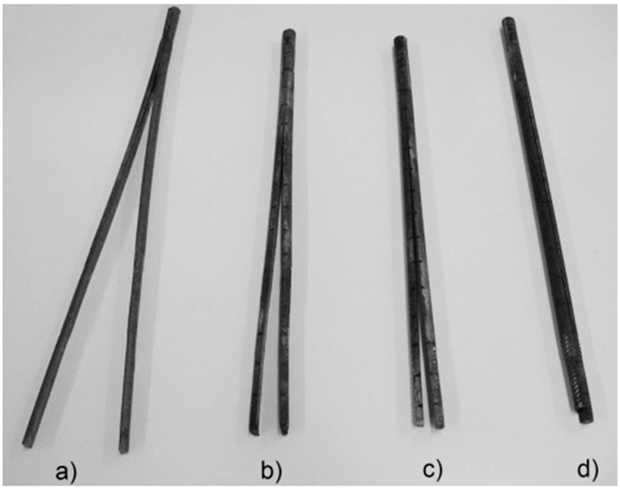


Figure 2: Appearance of drawn bar after the removal of joint rivet (a) and after mechanical relaxation by the tension with a deformation degree of 0.5 % (b), 0.7 % (c) and 1.65 % (d)

Slika 2: Videz vlečenih palic po odstranitvi vezne zakovice (a) in po mehanski relaksaciji z nategom s stopnjo deformacije 0.5 % (b), 0.7 % (c) in 1,65 % (d)

deformation degree of 0.5–1.65 %. The cold-rolled strips after tension were chemically etched in order to remove the metal layer from one side and measure the elastic line. The drawn bars were connected at the separate end and deformed by tension, afterwards the connection was removed again and the elastic line was measured (**Figures 2b, c, d**).

The mechanical relaxation of the residual stresses by the removal of surface layers was performed by the treatment of the bars drawn on a lathe. The connected halves of the bars were machined through the projected number of feeds with the constant thickness of the removed layer. After each operation the connection was removed and the elastic line was measured.

The mechanical relaxation of the residual stresses with cyclic bending was investigated on compact bars which were drawn under the same conditions as the connected ones. The experiment was performed in industrial strike with hyperbolic rollers with parallel bending and bar rotation. The measurement of the residual stresses in this case was done using the x-ray method.

3 RESULTS AND ANALYSIS

3.1 Thermal relaxation of residual stresses

The thermal relaxation of the residual stresses is based on the initiation of thermally active processes for relaxation of the accumulated elastic energy. The parameters of the processes (temperature, time) are coordinated with the material state, the stress state and the dominant mechanism of the process. The mechanism of the processes that led to the relaxation of the residual stresses can be performed on the basis of *Zener-Wert-Avrami*'s function (equation 1), where numerous values of coefficients, together with the temperature (T) and time (t), can indicate known structural changes. The reactions that take place during the relaxation of elastic energy are: vacancy creep, dislocation creep and dislocation climb, and they are based on the diffusion in metal lattice. At a low tempering temperature the limiting process is thermal dislocation climb with the activation energy equal to the energy of self-diffusion. However, the determination of activation energy of thermally active processes does not always enable a precise separation of the dominant mechanism [17,18]. Therefore, in this section the investigation was focused on the choice of temperature and time with the decrease of the projected values of residual stresses, according to the equation:

$$\sigma_{t,T} / \sigma_0 = \exp\left[-(A \cdot t)^m\right] \tag{1}$$

where:

σ_0, $\sigma_{t,T}$ – the value of the residual stresses for the initial state and the after-annealing state in t-T conditions;

m – the numerical value that indicates the dominant mechanism;

A – the parameter that depends on the temperature, the activation energy and *Boltzmann*'s constant.

In cold rolled strips of the alloy AA5083 the temperature of 140 °C was chosen, within the area of the lower limit of the temperature interval of recovery. The annealing time varied within the interval 1 min to 10 min. The investigations were performed with the samples shown in **Table 4**, and they included the variation of strip thickness, i.e., the reduction ratio, the thickness of the removed layer and the annealing time.

Table 4: Parameters of the processes and effects of the relaxation of residual stresses for the cold rolled strips

Tabela 4: Parametri procesa in vpliv relaksacije notranjih napetosti v valjanem traku

Sample	H_1/mm	ε/%	Δ/mm	f_0/mm	σ_0/MPa	t/min	$f_{t,T}$/mm	$\sigma_{t,T}$/MPa	$\sigma_{t,T}/\sigma_0$
1	0.512	60.0	0.240	4.664	53.30	1	4.580	52.34	0.982
2	0.886	30.8	0.323	2.475	62.61	2	2.405	60.84	0.972
3	0.826	35.5	0.383	2.555	47.41	3	2.175	40.36	0.851
4	1.081	15.5	0.327	1.64	63.60	3	1.325	51.39	0.808
5	0.512	60.0	0.189	4.426	63.76	5	1.142	16.45	0.258
6	1.005	21.5	0.331	1.813	58.84	5	0.810	26.29	0.447
7	0.576	55.0	0.270	5.167	66.43	5	1.224	15.74	0.238
8	0.63	50.8	0.310	4.865	67.18	8	0.973	13.44	0.200
9	0.704	45.0	0.340	3.986	61.78	10	0.696	10.79	0.175

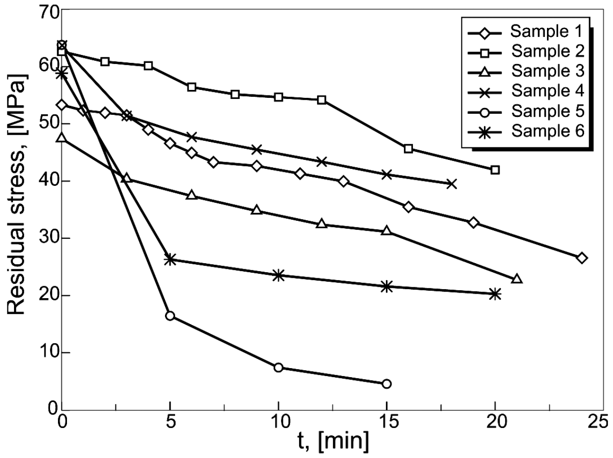


Figure 3: Change of residual stresses depending on the annealing time in multilevel relaxation
Slika 3: Sprememba notranjih napetosti pri večstopenjski relaksaciji v odvisnosti od časa žarjenja

For samples 1 to 5 the multilevel annealing was performed, and the time interval was constant with the value presented in **Table 4**.

After each annealing, the elastic line was measured. The values of the residual stresses are presented in **Figure 3**.

The results presented in **Table 4** and **Figure 3** show that the relaxation of residual stresses begins even at the shortest annealing time and it continues without interruption with its prolongation. This shows the high stress instability under the conditions of thermal treatment. However, within the area of small annealing times (1 min to 3 min), the stress relaxation is partial, with not very excessive changes, typical for the initial nucleation period. The results of multiple heating indicate that each new phase starts with the initial nucleation period, therefore the changes are small, and the shape of the curves is approximately linear. The intensive stress changes start at an annealing time of 5 min, when the stresses decrease even to 75 %, and in further annealing cycles this change has a lower intensity, similar to the shorter heating times. The different intensity of relaxation at the same annealing times is the consequence of the different thickness of samples, and therefore the consequence of through heating conditions. Obviously, the relaxation of the stress is sensitive to the important factors presented by the *Zener-Wert-Avrami*'s function, on the one hand, and the stress values (factors presented by the equation for the calculation of residual stresses: H_1, Δ and f) on the other hand.

The basic shape of the curve of the stress change with the annealing time is shown in **Figure 4** and it corresponds to the literature data in [10,17,18].

In the area of small annealing times the initial nucleation period is present, which continues with the intensive relaxation (middle part of the curve), and ends with a repeated slowed relaxation until the end of the annealing time. Therefore, the relaxation of residual stresses demands a relatively short time, which needs to be adapted to the properties of heating devices and the dimensions of the piece, i.e., to the conditions of reliable recovery temperature and reliable time of through heating of the piece.

In drawn steel bars the possibility of a precise prediction of the conditions of thermal treatment was checked, where the residual stresses can relax at half of the initial value. Therefore, a temperature of 370 °C and an annealing time of 1 hour were chosen. The procedure was conducted on two bars made of chosen steels, and drawn with a D_0/D_1 = 16/15 ratio. The results of the change of the residual stresses along the elastic line for the drawn and thermally relaxed state are presented in **Figure 5**.

In the obtained diagrams the influence of thermal treatment on the continuous relaxation of the residual stresses within the interval 36 % to 46 % can be identified. The present differences were influenced by

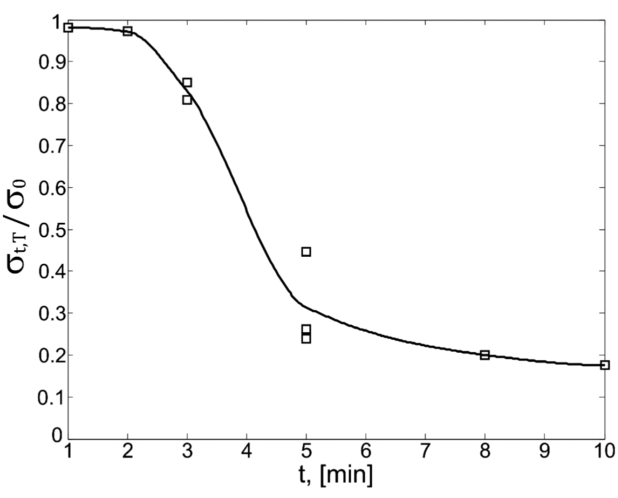


Figure 4: Change of $\sigma_{t,T}/\sigma_0$ ratio depending on the annealing time
Slika 4: Sprememba razmerja $\sigma_{t,T}/\sigma_0$ v odvisnosti od časa žarjenja

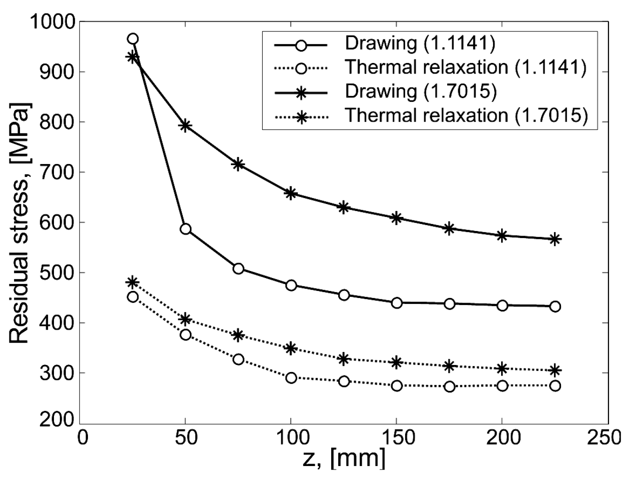


Figure 5: Distribution of residual stresses along the elastic line for the drawn and thermally relaxed state for the steel bars 1.1141 and 1.7015
Slika 5: Porazdelitev notranjih napetosti vzdolž elastične linije za vlečene in termično relaksirane palice jekel 1.1141 in 1.7015

the different modules of elasticity, stress level as well as the different activation energies for relaxation in accordance with the *Zener-Wert-Avrami*'s function. The obtained results are acceptable enough and they are in accordance with the results obtained for strips. They also show that for accurate planning of complete relaxation, the properties of the furnace for thermal treatment and the conditions of reliable recovery temperature as well as reliable time of the heating of the piece must be known.

3.2 Mechanical relaxation of residual stresses by axial tension

The relaxation of residual stresses by axial tension is possible only with the elements of simple shape, such as strips and bars. In order to examine the conditions for the relaxation of stress the model of their distribution presented in **Table 3** and stress-strain diagram for the chosen materials (**Figure 6**) are analyzed.

The analysis of the influence of external axial tension on the removal of residual stresses starts from the balance of the forces:

$$F_e + F_s + F_c = F_r \tag{2}$$

where: F_e – external tension force; F_s – the force of the residual stresses in surface layer; F_c – the force of the residual stresses in the core; and F_r – resultant force.

The transfer from the balance of the force to the stress equation is possible if the surfaces of the cross-sections with the stresses of the same sign are known. Starting from the equation:

$$A_s + A_c = A_t \quad \text{i.e.} \quad \frac{A_s}{A_t} + \frac{A_c}{A_t} = 1 \tag{3}$$

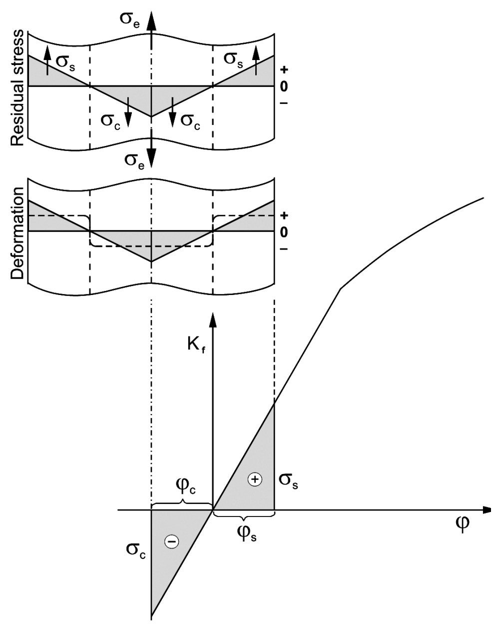


Figure 6: Scheme of the conditions for the relaxation of residual stresses by uniaxial tension

Slika 6: Shema pogojev relaksacije notranjih napetosti pri enoosnem nategu

and combining equations (2) and (3) the stress equation is obtained:

$$\sigma_e = \sigma_r - \left[\sigma_c\left(1 - \frac{A_s}{A_t}\right) + \sigma_s\frac{A_s}{A_t}\right] \tag{4}$$

where: σ_e – external stress on the total surface A_t; σ_s – resultant residual stress in the surface layer of the surface A_s; σ_c – resultant residual stress in the core of the surface A_c; and σ_r – resultant stress on the total surface A_t.

The resultant stress σ_r causes plastic deformation along the whole cross-section and it changes according to the curve stress-strain presented in Figure 6. If we replace σ_r in equation (4) with the equation of the curve of the strain hardening of the material, the final form of the equation for external stress which causes permanent plastic deformation for the relaxation of residual stresses is obtained:

$$\sigma_e = (K_0 + K\varphi^n) - \left[\sigma_c\left(1 - \frac{A_s}{A_t}\right) + \sigma_s\frac{A_s}{A_t}\right] \tag{5}$$

where: K_0 – yield stress, K – strength coefficient, n – strain hardening index, and φ – deformation degree.

When the residual stresses in the surface layer and in the core are symmetrically balanced ($-\sigma_c = \sigma_s = \sigma$ i $A_s = A_c$), as in the case of rolled strips, their effects are canceled, on the right-hand side of the equation (5) the member in the brackets is equal to zero. In that case the external stress is equal to the deformation resistance of the metal. This means that in these cases the beginning of the relaxations of residual stresses immediately after the beginning of plastic flow, as well as intense flow and ending with the limited degree of deformation, can be expected.

In the case of the asymmetrical balance of residual stresses, as in the case of rolled bars ($-\sigma_c = 2\sigma_s = \sigma$ and $4A_s = 5A_c$), the resultant residual stress is different from zero, and equation (5) is transformed into the form:

$$\sigma_e = (K_0 + K\varphi^n) + \frac{\sigma}{6} \tag{6}$$

The presence of resultant residual stress in equation (6) indicates that their intensity and direction affect the value of the external residual stress, which causes the relaxation of the residual stresses. Accordingly, in drawn bars, slightly higher permanent deformations, which cause complete relaxation of residual stresses in relation to the rolled strips, should be expected.

The experimental control of this approach in cold-rolled strips was conducted on a series of samples rolled with reduction ratios of 15 % to 50 %, and the values of residual stresses within the interval of 40 MPa to 70 MPa. These samples were then deformed by axial tension with the plastic deformation degrees of (0.5, 0.7 and 1)%. With the further application of the deflection method, the residual stresses were not identified in any of the three deformation degrees. This confirmed the

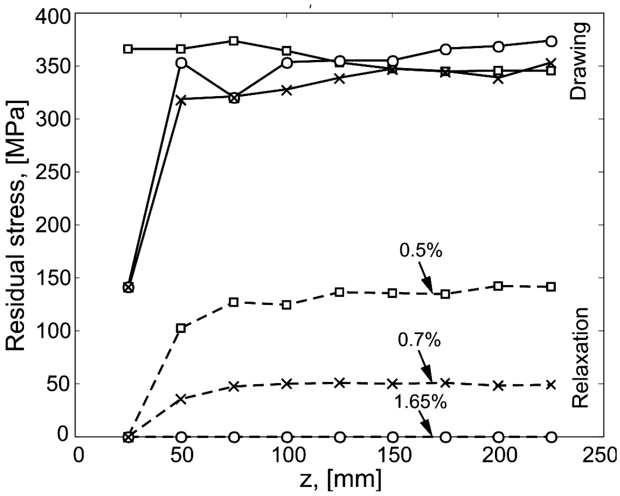


Figure 7: Distribution of the residual stresses along the elastic line for drawn and mechanically relaxed states

Slika 7: Porazdelitev notranjih napetosti vzdolž elastične linije za vlečeno in mehansko relaksirano stanje

expected complete relaxation of the residual stresses immediately at the beginning of the interval of plastic flow. The obtained results are in accordance with the results presented in [16].

In the bars the experiment was conducted with the original samples of steel 1.1141 drawn with a D_0/D_1 = 16/14 ratio and residual stresses within the interval 345 MPa to 375 MPa. The axial tension of these samples was conducted with the degrees of plastic deformation of (0.5, 0.7 and 1.65)% (**Figure 2b, c, d**). The change of the values of the residual stresses along the elastic line before and after the relaxation is presented in **Figure 7**.

The relaxation effects are very pronounced and at the first two degrees of deformation they are 60 % and 88 %, respectively. At the deformation degree of 1.65 % the connected halves of the bar were not bent after the removal of the connection, which indicated the total

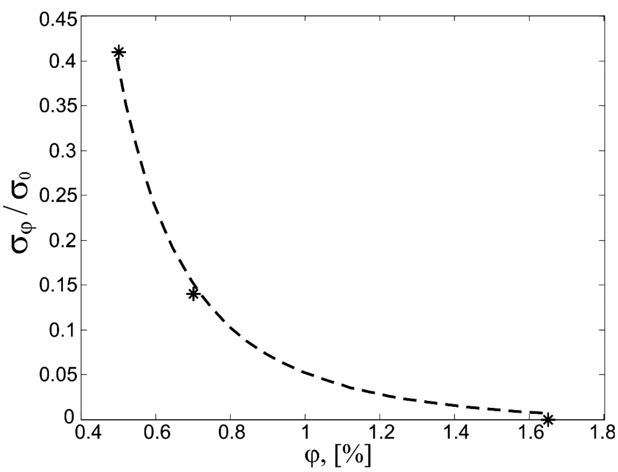


Figure 8: The stress ratio after (σ_φ) and before (σ_0) the relaxation in dependence on the deformation degree by axial tension

Slika 8: Razmerje napetosti po (σ_φ)-relaksaciji in pred (σ_0)-relaksacijo v odvisnosti od stopnje deformacije pri aksialnem nategu

relaxation of the stress (**Figure 7**). The obtained values of the plastic deformation for the relaxation of residual stresses in drawn bars with respect to the drawn strips are in accordance with equation (6). In both cases, the experimental values of the deformation are within the interval of recommended deformations up to 2 to 3 %[8,16].

The curve of the stress change with the degree of permanent deformation shown in **Figure 8** can be described by the equation:

$$\frac{\sigma_\varphi}{\sigma_0} = A \cdot \varphi^{-b} \tag{7}$$

where: *A, b* – coefficients. The shape of the curve is close to the shape at the thermal relaxation, and the most important differences start from general regulations of the thermal processes described by exponential functions, and the deformation processes, which are predominantly described by the degree functions.

3.3 Machining and relaxation of residual stresses

The physical disturbance of the continuum in the presence of residual stresses causes their change. Therefore, it is very important to predict the state and possible consequences within these actions. Precisely, with the even removal of the metal layers the accumulated elastic energy in the complete element is removed also, which brings also the relaxation and inevitable redistribution of residual stresses. This is particularly important for the final operations performed by machining.

The investigations of the relaxation in machining by scraping were conducted on drawn bars made of two halves. In order to use this procedure, the residual state should not be disturbed by the cyclic separation and connection of the halves of the bars between two operations on the lathe. The basic presumption was that the stress change was performed according to the initial model of the distribution and thickness of the removed layer. In this manner the change of the elastic line as a function of the sample diameter after machining was obtained.

The bars of steel 1.1141 drawn with the D_0/D_1 = 16/15 ratio were investigated. During seven operations on the lathe the bar diameter was reduced from 15 mm to 11.7 mm, with the same thickness of the removed layer of 0.2 mm in one operation. The change of the axial residual stress as a function of the reduced diameter shown in **Figure 9** indicates the clear effects of relaxation – the values of stress are reduced from 446.7 MPa to 159.6 MPa.

The relaxation process was followed by the redistribution of the residual stresses. In order to predict the behavior it was necessary to provide a physically acceptable model for the reduction of the diameter and the redistribution of stress. It is real to assume that in machining together with the layer the elastic energy which belonged to that layer is also removed in one

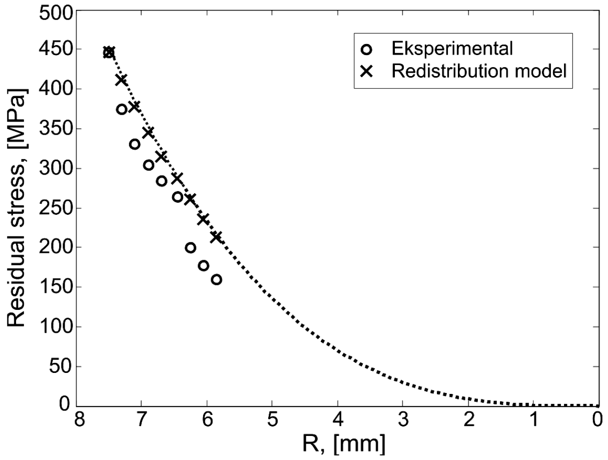


Figure 9: Residual stresses obtained experimentally and according to the model of redistribution as a function of reduced radius

Slika 9: Notranje napetosti, izmerjene eksperimentalno in po modelu porazdelitve v odvisnosti od zmanjšanega polmera

operation. In this way the stress at the new surface retains the value that corresponds to the presented position in the initial drawn state. The formation of the new surface with the given stress has as a consequence the establishment of the new balance of the stress which retains the initial distribution model along the cross-section. After each machining operation the same conditions are used. The presented model for the stress change depending on the removed layer has the form presented by the following equation [13]:

$$\frac{\sigma_{\mathrm{s,n}}}{\sigma_{\mathrm{s}}}=\prod_{i=1}^{n}\left[\frac{R_1-(i+2)\Delta}{R_1-(i-1)\Delta}\right] \tag{8}$$

The equation (8) contains all the relevant parameters of the redistribution model: the initial value of the stress on the surface (σ_{s}), the stress values on the surface after n-th operation ($\sigma_{\mathrm{s},n}$), the initial radius (R_1), the thickness of the removed layer (Δ) and the number of operations (n). The confirmation of the equation is evident for the condition $\sigma_{\mathrm{s},n} = 0$, i.e., it is completely compatible with the thickness of the removed layer, the initial radius and the number of operations.

The redistribution curve obtained with equation (8) as a function of the reduced radius is shown in parallel with the experimental values in **Figure 9**. The values of the stress obtained by the model of redistribution are extrapolated to the values of the reduced radius when the total relaxation of the residual stresses is expected. The obtained curve form is also similar to the form in the described thermal and mechanical relaxation of the residual stresses.

In **Figure 9** the good correlation of the results obtained experimentally and using equation (8) is evident, as well as physically realistic behavior in the case of extrapolation, i.e., the stress values that corresponds to the less-reduced radius: $\sigma_{\mathrm{s},n} = 0$ for $R = 0$.

3.4 Mechanical relaxation of residual stresses by cyclic bending

The experiment was conducted on three bars of steel 1.1141 drawn with different ratios D_0/D_1. The measurement results of the residual stresses after drawing and cyclic bending on the strike with hyperbolic rollers are presented in **Table 5**.

Table 5: Parameters of the drawing process and measurement results of the residual stresses using the diffraction method

Tabela 5: Parametri procesa vlečenja in notranje napetosti, izmerjene po metodi difrakcije

D_0/D_1	State	σ/MPa
16/15	Drawing	520
	Straightening	> −150
16/14.5	Drawing	360
	Straightening	−280
16/14	Drawing	640
	Straightening	−420

Straightening enables little plastic deformation by cyclic bending with a very small percentage, which is enough to relax the residual stresses. Since the straightening process brings too limited compression of the bar surface, the residual stresses on the surface are transformed from tensile stresses to compression stresses, which was also confirmed in ref. [19]. This process is adequate for the increase of the properties within the elements which demand higher mechanical properties on the surface.

4 CONCLUSIONS

The investigations of the relaxation of the residual stresses by thermal and mechanical processes in cold-rolled strips and drawn bars showed:

– the high instability of the residual stresses in thermal and mechanical processes with similar effects and shape of the change curve;
– the projected level of relaxation of residual stresses can be achieved with sufficient precision in thermal process by optimum temperature choice and annealing time in accordance with the function which describes the kinetics of thermal processes;
– in mechanical process by axial tension, the complete relaxation of the stress appears at low values of the plastic deformation, and the differences that occur in cold-rolled strips and drawn bars appear as a consequence of the model of the balance of residual stresses;
– the machine scraping of drawn bars was followed by the relaxation and redistribution of residual stresses. The suggested model of redistribution gives a real picture of made changes;
– the mechanical process by cyclic bending of the drawn bars was followed by the reduction of tensile

residual stresses and their transformation into the compression stresses.

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