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THE INFLUENCE OF THE MULTIPASS DRAWING PROCESS IN CLASICAL AND HYDRODYNAMIC DIES ON RESIDUAL STRESSES OF HIGH CARBON STEEL WIRES

WPŁYW WIELOSTOPNIOWEGO PROCESU CIĄGNIENIA W CIĄGADŁACH KLASYCZNYCH I HYDRODYNAMICZNYCH NA NAPRĘŻENIA WŁASNE W DRUTACH ZE STALI WYSOKOWĘGLOWEJ

In the paper the influence of the multipass drawing process on residual stresses of high carbon steel wires has been assessed. The drawing process of ϕ5.5 mm wires to the final wire of ϕ1.6 mm was conducted in 11 passes, in industrial conditions, by means of a modern Koch multi-die drawing machine. The drawing speed in the last passes was 10 m/s. The experimental measure of residual stresses in wires drawn in classical and hydrodynamic dies by Sachs-Linicus method has been done. On the basis of numerical analyses of the wire drawing process, the distributions of longitudinal residual stresses on the cross section of wires, temperatures and redundant strain have been determined.

The investigations have shown the essential influence of the multipass drawing process in hydrodynamic dies on residual stresses of high carbon steel wires. In the case of the wires drawn with hydrodynamic dies, in comparison to the wires drawn in classical dies, the 30% decrease of longitudinal residual stresses have been noted.

It has been shown that the decrease of residual stresses in wires drawn in hydrodynamic dies is connected with a lower redundant strain by 14.7%. In addition, the application of hydrodynamic dies in the multipass drawing process leads to significant decreasing of temperature of the wire surface (in the last pass above 500 ^{o}C). Undoubtedly, the large increase of temperature in the sub-layer of wires drawn in classical die caused the rise of internal stresses related to the thermal expansion of steel. In consequence, it caused the increase of residual stresses.

Keywords: residual stresses, high carbon steel, multipass wire drawing, classical and hydrodynamic dies, temperature, redundant strain

W pracy określono wpływ wielostopniowego procesu ciągnienia na naprężenia własne w drutach ze stali wysokowęglowej. Proces ciągnienia drutów o średnicy 5,5 mm na średnicę końcową 1,60 mm zrealizowano w 11 ciągach, w warunkach przemysłowych, na nowoczesnej ciągarce wielostopniowej Kocha. Prędkość ciągnienia na ostatnim ciągu wynosiła 10 m/s. Naprężenia własne w drutach po procesie ciągnienia w ciągadłach klasycznych i hydrodynamicznych wyznaczono w oparciu o badania doświadczalne wykorzystując metodę Sachsa-Linicusa. Natomiast w oparciu o analizę teoretyczną procesu ciągnienia określono rozkłady wzdłużnych naprężeń własnych na przekroju drutów, temperaturę, odkształcenia postaciowe i intensywność odkształcenia.

Wykazano, że stosowanie w procesie wielostopniowego ciągnienia drutów wysokowęglowych ciągadeł hydrodynamicznych przyczynia się do znaczącego spadku wzdłużnych naprężeń własnych. Dla drutów ciągnionych w ciągadłach hydrodynamicznych, w stosunku do drutów ciągnionych w ciągadłach klasycznych, odnotowano spadek o około 30% wzdłużnych naprężeń własnych I rodzaju.

Spadek naprężeń własnych w drutach ciągnionych w ciągadłach hydrodynamicznych należy wiązać z występowaniem dla tego wariantu mniejszych o 14,7% odkształceń postaciowych. Ponadto zastosowanie ciągadeł hydrodynamicznych w procesie wielostopniowego ciągnienia prowadzi do zasadniczego spadku temperatury drutu na jego powierzchni (w ostatnim ciągu o ponad 500 ^{o}C). Znaczący wzrost temperatury w warstwie przypowierzchniowej drutów ciągnionych klasycznie przyczynił się do powstania naprężeń wewnętrznych związanych z rozszerzalnością cieplną stali, co w konsekwencji spowodowało wzrost naprężeń własnych.

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1. Introduction

The residual stresses which appear after the drawing process cause a negative influence on the quality and properties of high carbon steel wires and can disqualify them as the material on ropes, tyre or springs.

The residual stresses, so called the internal stresses are the ones which occur in materials unbiased any external forces [1-2]. In terms of the area of the appearance, they can be divided into the first, the second and the third kind. Another criterion of the division is the direction of action of residual stresses, i.e. longitudinal, district and radial stresses. In this work the longitudinal residual stresses of the first kind, which balance in macro-volume, has been examined.

At present the most common methods of investigation of residual stresses are: mechanical, chemical itching, X-ray and magnetic method. These methods are very often labour-consuming and time-consuming. A new method of measurement of residual stresses is the numerical analysis of wire the drawing process.

The residual stresses in wires are result from a non-uniform of strain, a non-uniform distribution of temperature in a plastic strain range and a phase transformation.

In the work [3] it was shown that multi-pass wire drawing with high speed causes the intensity of heating of wire surface what in consequence can lead to deterioration of lubrication condition and it causes the increase of the friction coefficient as well. In consequence it causes the appearing of redundant strains which increase the non-uniform of strain [4]. It can lead to the increase of residual stresses in steel wires.

One of the method of reduction of the friction coefficient is drawing process in hydrodynamic dies, where during drawing almost the complete separating of the wire surface and a die occur [5].

In the literature the information concerning to the influence of the wire drawing technology on residual stresses can be found [6-7]. Unfortunately, those investigations are made for the wires drawn on a bull block with a small drawing speed, which usually did not reach 2 m/s.

Therefore, the present work makes an attempt to assess the influence of the multipass drawing process in classical and hydrodynamic dies on residual stresses of high carbon steel wires.

2. Material and applied drawing technologies

The material applied for the investigation was of C72 high carbon steel wire rod. Before drawing, the wire rod was patented, itched and boraxed. The drawing process of ϕ5.5mm wires in the final wire of ϕ1.6mm was conducted in 11 passes, in industrial conditions, by means of a modern Koch multi-die drawing machine. The drawing speeds in the last pass was 10 m/s.

Individual drafts, D_i, total drafts, D_t, and drawing speeds, V, for wires from variants A÷B are summarized in Table 1. In drafts 1÷4 calcareous lubricant CONDAT Vicafil SUMAC 2T was applied while in drafts 5÷11 soda lubricant TRAXIT SL 202 BS was used. The wires from variant A were drawn in classical dies while the wires from variant B in hydrodynamic dies.

TABLE 1

Distribution of individual drafts, total drafts and drawing speed for wires from variant A÷B

Draft number	0	1	2	3	4	5	6	7	8	9	10	11
ϕ, mm	5.50	4.92	4.38	3.90	3.50	3.12	2.80	2.50	2.22	2.00	1.78	1.60
D_i, %	-	19.98	20.75	20.72	19.46	20.54	19.46	20.28	21.15	18.84	20.79	19.20
D_t, %	-	19.98	36.58	49.72	59.50	67.82	74.08	79.34	83.71	86.78	89.53	91.54
V, m/s	-	1.06	1.34	1.69	2.09	2.63	3.27	4.10	5.20	6.40	8.08	10

3. Experimental measuring of residual stresses

The experimental measuring of residual stresses on the basis of longitudinal grinding wires, so called Sachs-Linicus, method was done. According to this method, wires are ground up to half diameter what causes the violation of stress equilibriums (Fig. 1).

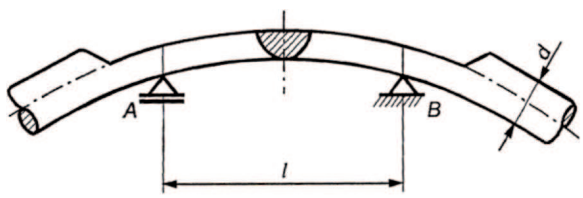

Fig. 1. The deformation of wires after longitudinal grinding to the half diameter [8]

The residual stresses σ_{rsurf} on the wire surface can be measured by formula (1), presented in [8]

$$\sigma_{r\,surf} = \frac{48EIf}{l^2 r^3},\ MPa \tag{1}$$

where:

σ_{rsurf} – longitudinal residual stress on wire surface,
E – Young modulus,
l – length of wire between supports,
r – wire radius (r=0.5d),
f – band arrow of wire between supports,
I – moment of inertia semi-circle in relation to neutral axis (I=0.1098r^4).

The investigations of residual stresses for wires ϕ1.6mm drawn according to variant A and B were done (10 specimens on each variant). The data investigation are presented in Table 2.

TABLE 2
The results of residual stresses tests carried out by the Sachs-Linicus method

Variant	Longitudinal residual stress σ_{rsurf}, MPa
A	595.1
B	415.6

The test that was carried out have shown that applying hydrodynamic dies in the multipass wire drawing process of high carbon wires causes the decrease of residual stresses. For wires drawn in hydrodynamic dies (variant B), in comparison to wires drawn in classical dies (variant A), the decrease of longitudinal residual stresses by 30.2% has been noted.

As the method of Sachs-Linicus enables to estimate residual stresses only on the wire surface, numerical analysis of multipass wire drawing of high carbon steel wires has been conducted in the work. On the basis of simulations the residual stresses on the cross section of wires were determined.

4. The theoretical analysis of wiredrawing process

The experimental determination of the distribution of residual stresses on the cross-section of wire being drawn is difficult to accomplish, therefore the present work proposes a theoretical analysis of this problem based on the software Drawing 2D [9].

The simulation of the multi-stage drawing process was performed for a wire with plastic properties corresponding to those of the pearlitic-ferritic steel C72 (~0.72%C). It was assumed that the drawing process took place with the identical distribution of individual and total drafts to that of the experimental tests (table 1), with the friction coefficient of μ=0.008 for variant A and μ=0.075 for variant B.

The analysis of the distribution of stress σ_y (longitudinal stresses compatible with the drawing direction) on the cross section of wire makes it possible to estimate the residual stresses. From the distributions of longitudinal stresses of ϕ1.6 mm wires (Fig. 2) the numerical values of the stress on cross section of wire were read out.

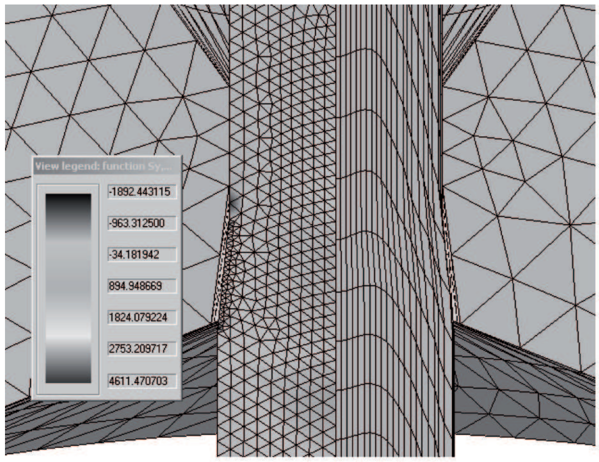

Fig. 2. The example of the distribution of longitudinal stresses σ_y in the final wire ϕ1.6 mm drawn according to variant A (classical dies)

In the drawn wire after exit from a die the longitudinal stress σ_y is the sum of drawing stress σ_d and a distribution of residual stresses σ_r. In order to determine the drawing stress and the distribution of residual stresses, longitudinal stresses σ_y, described in wire radius r function, were approximated with the function of second-degree, which reflects the distribution of residual stresses [10]. The functions approximating the distribution of longitudinal stresses σ_y in wire radius r function, the value of drawing stresses σ_d and maximum values of residual stresses (on wire surface) in Table 3 was shown, while in Fig. 3÷4 the functions illustrative the distribution of longitudinal and residual stresses in wires ϕ1.6 mm were presented.

TABLE 3
The approximation functions of the distributions of longitudinal stresses σ_y, the values of drawing stress σ_d and maximum values of residual stresses $\sigma_r$for the final wires ϕ1.6 mm drawn according to variants A and B

Variant	σ_y=f(R)	σ_d MPa	σ_rMPa
A	σ_y=1271.1 r^2+557.92	830.6	545.3
B	σ_y=967,59 r^2+503.09	709.5	412.8

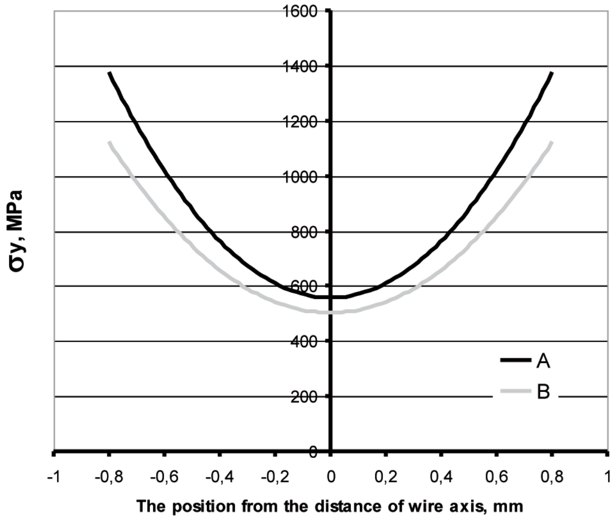

Fig. 3. The distribution of the longitudinal stresses σ_y for ϕ1.6 mm wires drawn according to variant A (classical dies) and B (hydrodynamic dies)

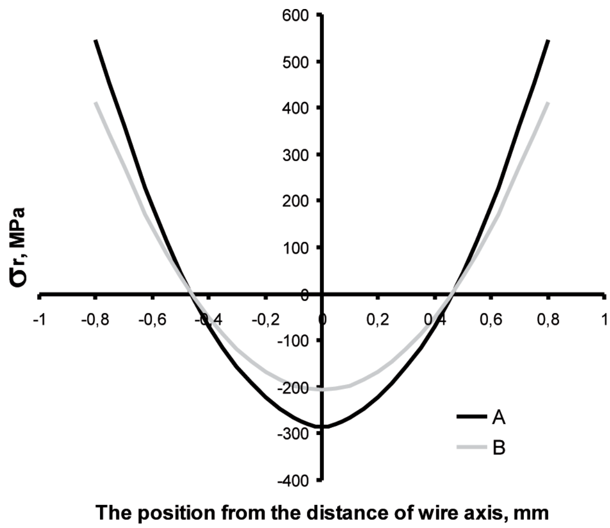

Fig. 4. The distribution of the first type longitudinal residual stresses $\sigma_r$for ϕ1.6 mm wires drawn according to variant A (classical dies) and B (hydrodynamic dies)

In Fig. 5, the data investigations from measuring of residual stresses by Sachs-Linicus method to those which were obtained from numerical analysis were compared.

On the basis of Table 3 and Fig. 4 it can be observed that in the drawing process the application of hydrodynamic dies fundamentally influences the value and the distributions of residual stresses of high carbon steel wires. It was found that in the surface layers of drawn wires there are tensile residual stresses, while in internal layers there are compressive ones.

The wires from variant A (classical dies), as compared to the wires from variants B (hydrodynamic dies), exhibit higher residual stresses, on the surface by 24.3% and in the axis by 27.7%, respectively. The data investigation from numerical analysis are conformable with those obtained by Sachs-Linicus method, Fig. 5.

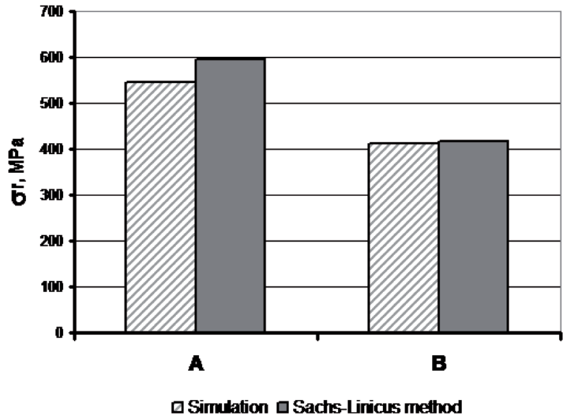

Fig. 5. The values of the first type longitudinal residual stresses σ_r on the surface for ϕ1.6 mm wires drawn according to variants A (classical dies) and B (hydrodynamic dies)

One of the factors which has a significant influence on residual stresses is temperature and inhomogeneity of strain. Therefore, the effect of the wire drawing in classical and hydrodynamic dies on the temperature and redundant strain has been established within the present work.

In Fig. 6 the changing temperature of wire surface T_{surf} and average temperature T_{av} in total draft function for variant A and B has been shown. In Fig. 7 temperature distributions on the cross-section of ϕ1.6 mm wires drawn according to Variants A and B after exit from the bearing zone of die has been shown.

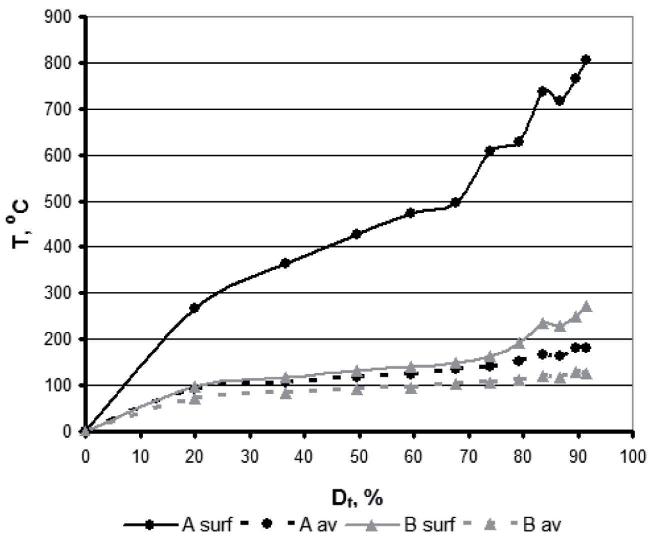

Fig. 6. The change of temperature on the surface and the axis after exit from the bearing zone of die for wires drawn according to variant A and B in total draft function

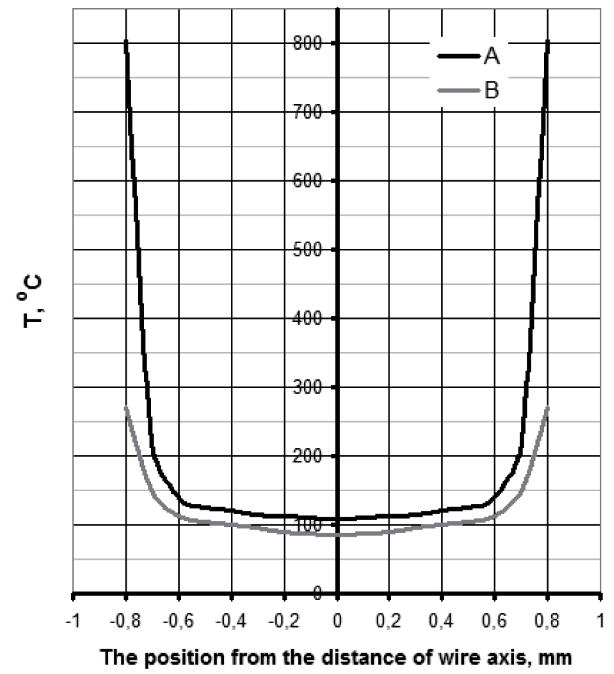

Fig. 7. The distribution of temperature on the cross-section of ϕ1.6 mm wires drawn according to Variants A and B after exit from the bearing zone of die

In Fig. 8 the change of redundant strain ε_{xy} of wire surface in total draft function for variant A and B has been shown. In Fig. 9 redundant strain distributions on the cross-section of ϕ1.6 mm wires drawn according to Variants A and B has been shown.

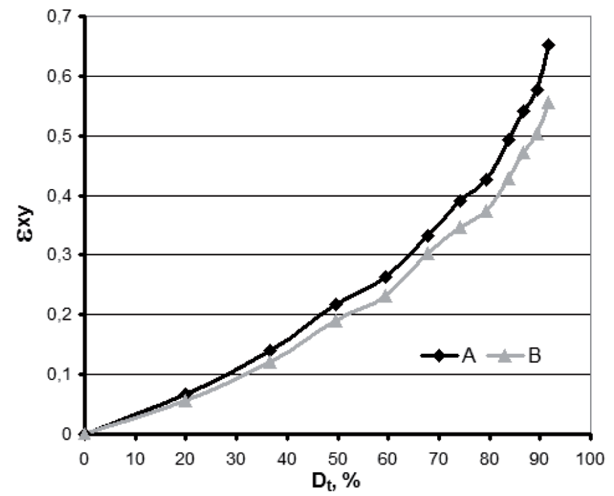

Fig. 8. The change of redundant strain ε_{xy} of wire surface in total draft function for variant A and B

On the basis of Fig. 6 it can be observed that in the multipass drawing process the application of hydrodynamic dies essential influences on the decrease of temperature on the wire surface (in last draft above 500°C). Furthermore, wires drawn according to variant A (classical die), in comparison to wires from variant B (hydrodynamic dies) have a larger non-uniform distribution of temperature on the cross-section. The difference of temperature between axis and the surface of wire for variant A was above 600°C, Fig. 6.

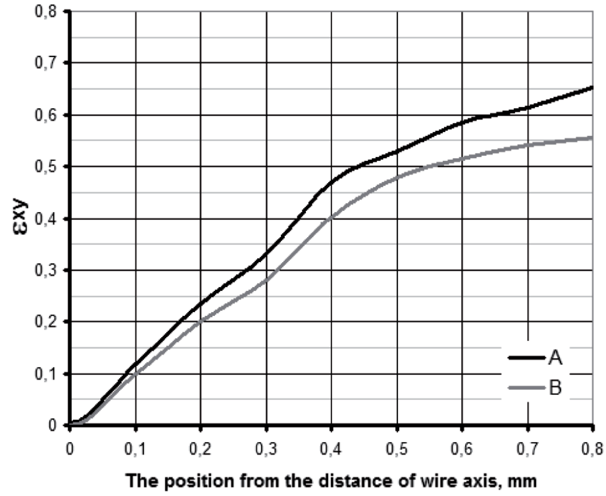

Fig. 9. The distributions of the redundant strain ε_{xy} on the cross-section of ϕ1.6 mm wires drawn according to Variants A and B

Undoubtedly, the large increase of temperature in the sub-layer of wires drawn in classical die caused the rise of internal stresses related to thermal expansion of steel. In consequence, it caused the increase of residual stresses.

The second factor which causes appearing of residual stresses are the redundant of strain. The external layers, in comparison to central layers, have bigger redundant of strain (Fig. 9) what causes non-uniform distribution of stresses in the drawn wire. In consequence after the drawing process are forming the residual stresses.

On the basis of Fig. 8÷9 it can be observed that the application of hydrodynamic dies reduce the redundant of strain. The wires from variant B (hydrodynamic dies), as compared to the wires from variants A (classical dies), exhibit lower redundant of strain by 14.7%. Surely it had an impact on decreasing of residual stresses.

5. Conclusions

From the theoretical studies and experimental tests that have been carried out, the following findings and conclusions have been drawn:

1. The application in the multipass drawing process of high carbon steel wires of the hydrodynamic dies causes the essential decrease of longitudinal residual stresses. The wires from variant A (classical dies), as compared to the wires from variants B (hydrodynamic dies), exhibit higher residual stresses, on the surface by 24.3% and in the axis by 27.7%, respectively.

2. The decrease of residual stresses in wires drawn in hydrodynamic dies is related to a non-uniform distribution of the temperature and redundant of strain for this variant.
3. The adaptation of hydrodynamic dies in multipass drawing process essentially influences the decrease of the temperature on the wire surface (in the last draft above 500 ^{o}C).
4. The large increase of the temperature in the sub-layer of wires drawn in classical dies caused the rise of internal stresses related to thermal expansion of steel. In consequence, it caused the increase of residual stresses.
5. The drawing process in conditions of terms of semi-fluid/fluid friction (hydrodynamic drawing) makes it possible to reduce the non-uniform of strain by 14.7%, thereby it declines the residual stresses in the drawn wire.
6. The reduction of residual stresses of wires drawn in hydrodynamic dies should have a positive influence on fatigue strength and technological properties of high carbon steel wires.
7. The obtained data of investigations can be applied in the wire industry while implementing the new technologies of high speed drawing process of high carbon steel wires.

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