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Increasing the Quality of Forming of Spinning Details of Aluminum Alloys by Controlling the Residual Stresses in Their Surface Layer

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***Abstract*. In the article are analyzed the effect of technological modes and processing parameters on the stress of spinning (cold flow turning) details of aluminum alloys. As the object of the study was used a detail of aluminum alloy AMg5, obtained after 3-stage spinning with intermediate heat treatments between the stages. As a control criterion was used non-destructive resistive electro contact method, based on the correlation between the integral electric and mechanical characteristics of metals and alloys – specific conductivity or electrical resistivity within the h-layer of the metal and the amount of deformation in the crystal lattice of the material due to the residual stresses.**

Keywords: non-destructive method, residual stresses, resistive method, spinning (cold flow turning).

I. Introduction

When products are manufactured from metals and alloys, in many cases they are subjected to mechanical or thermal effects, which lead to plastic deformations of the crystal lattices of the materials of the products. This, in turn, results in occurrence of mechanical stresses in the deformed layer of the material, which can be the reason for destruction of the details at loads, even lower than calculated.

In a process of spinning the cause of internal stresses is the focus of the plastic deformation. The occurrence of such stresses can lead to local deformations and defects of the workpiece. An increase in the compressive stresses can cause formation of corrugations on the surface of the workpieces, while the tensile stresses can give rise to surrounding cracks. Both consequences are indicators for rejection of the products.

This determines the need for exercising reliable control of residual stresses during the technological process of producing details and during their operation [1] – [5]. Many methods are known for carrying out such a control - destructive methods (Davidenkov method, hole drilling method, the washer method, etc.) and non-destructive ones (radio-wave, ultrasonic, magnetic, X-ray diffraction method, etc.), and each of them has its own advantages and disadvantages. The research, presented here, uses a newly developed measuring complex, based on a resistive electro-contact method, which combines in one the advantages of the destructive methods (high reliability, guaranteed error for determining the residual stresses, possibility to determine the distribution of the residual stresses along the depth from the surface) and the non-destructive principle of action.

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II. Materials and methods

A study of the stress states of a part, made of aluminum alloy AMg5 GOST 21631-76 by spinning, performed on a two-roll Leifeld ST-400 rotary machine, in three transitions with intermediate heat treatments between them, was conducted. The research object was a thin-walled conical body, made of aluminum alloy AMg5, whose initial wall thickness of 6 mm was reduced to 2 mm in the first spinning transition (with a cone angle of 64°), to 1, 2 mm in the second pass (with a cone angle of 43°), and up to 0.8 mm in the third one (with a cone angle of 25°) (Fig. 1).

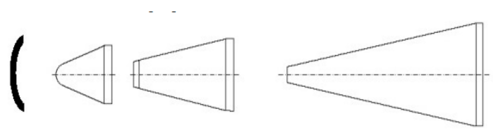

Fig. 1 Detail of AMg5, obtained after spinning in 3 transitions (the transitions are indicated by dashed lines) - a) original workpiece; b) first spinning; c) second spinning; d) third spinning.

For analysis and evaluation of the residual stresses in the process of technological processing of this part, a resistive electro-contact method for non-destructive control was applied. The method is based on the correlation between the integral electrical and mechanical characteristics of metals and alloys - specific electrical conductivity γ or specific electrical resistance ρ in the h-layer of the metal, and the magnitude of the deformation of its crystal lattice in result of the stresses in its surface layer q.

There is a relationship between the specific electrical conductivity γ (1) and the mechanical stresses [6]:

$$\gamma = \frac{e^2 E n_0}{mkTV_T N_0 \pi} \cdot d \qquad (1),$$

where e is the electron charge, C; m – the rest mass of the electron, kg; n_0 – the number of conductive electrons per unit volume; E – field strength, V/m; k – Boltzmann's constant, J/K; T – absolute temperature, K; V_T – speed of thermal movement of the electrons, m/s; N_0 – number of atoms per unit of volume; d – period of the crystal lattice, m. The relationship between the specific electrical conductivity γ and the specific electrical resistance $\rho = 1/\gamma$ is also known.

In the absence of mechanical stresses, the metal has a nominal value of the lattice period d_0 and a corresponding nominal value of the specific electrical conductivity γ_0. Under the influence of the changes in the mechanical stresses Δσ, a change in the period of the metal lattice Δd is observed. In the zone of elastic deformations, this change can be assumed to be proportional to the mechanical stress. In accordance with (1), the change in the electrical conductivity Δγ is also proportional to the average mechanical stresses Δσ according to the formula (2):

$$\Delta\gamma = K_\sigma \cdot \Delta\sigma \qquad (2),$$

where K_σ is an experimentally determined coefficient, characterizing the properties of the material.

Thus, the mechanical stresses in conductive materials can be determined by measuring their electrical properties. In doing so, it is necessary to measure the distributions of the electrical parameters and mechanical stresses along the depth of the products.

To measure the distribution of the specific resistance in depth, the skin effect phenomenon is used, in which the high-frequency currents are concentrated in that area from the surface of the conductor, which is located closest to the sources of the field, causing the currents. Based on the solution of the system of Maxwell's equations for the conductive semi-area, the penetration depth of the current h in such a conductor is determined as it follows (3):

$$h = \frac{1}{\sqrt{\pi f \mu \gamma}} \qquad (3),$$

where f is the current frequency, Hz; μ – the magnetic permeability of the material, Gn/m; γ – the specific electrical conductivity of the material, Ohm^{-1}.

The magnitude of the current density decreases exponentially with increasing the depth, and *h* represents a value of the depth (3), at which the current density drops by "e" times compared to the initial value of the surface current. By definition *h* is the depth of current penetration into the conductor, i.e., the thickness of the surface layer, in which the main part of the current propagates.

The use of the skin-effect phenomenon allows to examine the surface layer of the product in depth - level by level - supplying it with currents of different frequencies and measuring the response signal, whose parameters are related to the change in the stress state of the product material. By reducing the frequency of the alternating current, applied to the product in accordance with formula (3), the depth of the investigated layer is increased. The choice of the operating frequencies ensures the required range of the measured depths of the product [7].

Based on the given method, with the aim of studying the influence of the spinning modes on the residual stresses in the surface layer of the samples, made of AMg5 material, a stress optimization process was carried out, according to the following plan:

- measurement and analysis of the stressed state of the samples by means of a resistive electro-contact method of control after each spinning transition;
- study of the influence of both the machining and heat treatment modes on the level of residual stresses in the material of the workpieces by applying the theory of experimental design;
- obtaining technological modes of processing, ensuring the lowest possible magnitude of residual stresses in the surface layer of the workpieces.

III. Results and discussion

The SITON-TEST measuring complex (System for measuring technological residual stresses), developed by the Department of Instrumentation Technologies at the Saint Petersburg National Research University of Information Technologies, Mechanics and Optics (ITMO University), was used to determine the voltages. Based on the physical nature of the resistive electro-contact method, described above, it was implemented in this case in the following sequence:

– current with a different frequency was directed into the tested product through the supply electrodes, and measurements were performed in three points, located at an angle of 120o with respect to each other;
– the strength of the supplied current was measured for each of the set frequencies;
– the voltage of the response signal from the device was measured for each of the set frequencies;
– the distribution of the specific electrical resistance along the depth of the product material was calculated;
– a calibration dependence was derived between the specific electrical resistance and the mechanical stresses in the material of the studied product at depths, corresponding to the penetration depths of the current for the set frequencies;
– on the basis of the obtained dependence, the calculated distribution of the specific electrical resistance was converted into a distribution of the mechanical stresses along the depth of the studied product material [8].

The results of the measurements, performed according to the described algorithm, are shown in Fig. 2.

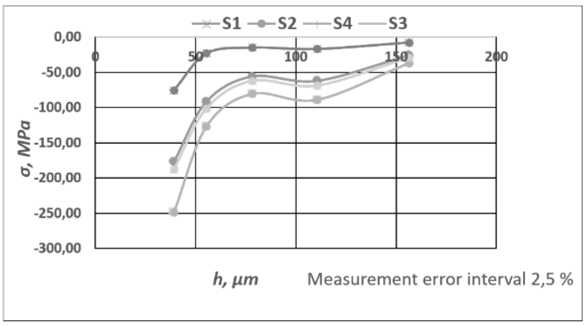

Fig. 2 Distribution diagram of the residual stresses, where S1 illustrates the stresses, measured in the original sample after heat treatment; S2 – in a heat-treated sample after the first spinning; S3 – in a heat-treated sample after the second spinning; S4 – in a heat-treated sample after the third spinning; h - depth of the studied material.

From Fig. 2 it can be seen, that after each spinning of the sample, despite the performed heat treatment, the internal stresses increase. Thus, after the last machining transition, the stresses are at the border to the yield point of the material. This justifies the need to study the influence of the technological modes of processing a workpiece with the aim of minimizing the internal stresses in its surface layer.

The theory of experimental design was used to analyze both the obtained results and the next stage in the process of optimizing the internal stresses. The aim was to determine the lowest levels of residual stresses when varying with the factors, affecting the changes in the crystal lattice of the material in the process of its technological processing - in other words, to determine the parameter and the factors of optimization.

The magnitude of the residual stresses σ was determined to be the optimization parameter (the maximum values of the residual stresses measured in the surface layer of each sample were taken for the calculations).

When selecting the optimization factors, analysis of the physics of the spinning process was carried out. It is known that the successful spinning process depends on many factors [9] – [12]: degree of deformation, space between the deforming element (roller) and the mandrel, feed rate, spindle revolutions, shape and geometry of the working parts of the rolls, roll diameter, coolants, modes of intermediate heat treatment (in multi-pass spinning), etc.

The degree of deformation of the material, directly related both to its stability at a certain power of the rotary machine and to the cone angle of the workpiece, determines the necessary number of transitions for producing the finished part. To avoid making additional mandrels and fixtures for the spinning process, in this study the degree of deformation and the angle of the cone were taken with their drawing values (given above in the text, before Fig. 1).

The space between the deforming roll and the mandrel is directly dependent on the initial thickness of the original workpiece S_0 and the thickness of the finished detail S and follows the well-known law of sine $S_1 = S_0 \sin\alpha$. Any deviation from the indicated dependence leads to deterioration in stability of machining, and therefore the specified factor was not varied in the given study, while the details specified in the technological documentation were observed.

Productivity and quality of workpiece processing during spinning depend to a significant extent on the feed rate S and the radius of rounding of the working part of the roll ρ. In case of incorrect selection of these parameters, formation of cracks on the surface of the part is possible. When spinning with a feed f, greater than the allowable tool feed rate for the given material, and in case of an incorrectly selected roll shape, high tensile stresses may arise, which can lead to a complete rupture of the workpiece. Breakage may also occur in case of significant deviation of the wall thickness from the calculated value and a change in the clearance between the roller and the mandrel. Taking all this into account, the first factor of optimization was assumed to be the operational feed rate f. In the process of machining during this study, deforming elements were used with an angle of the working part φ=20^0.

The rotational speed of the workpiece during machining should be as high as possible. The higher speed results in greater flange stability. For this reason, the level of the rotary machine spindle revolutions was determined as the second factor in the optimization process.

The modes of the performed intermediate heat treatment have the most significant influence on the relaxing properties of the material to return to its initial unstressed state after the impact of the plastic deformation. Therefore, the heat treatment temperature was chosen to be the third optimization factor in the presented study.

Thus, based on the analysis, as factors of the process of optimization were adopted the technological modes of spinning and the modes of the intermediate heat treatment performed between the spinning transitions (feed rate *f*, spindle revolutions *n*, heat treatment temperature *T*).

Their basic levels are: f= 0.41 mm/tr, n= 800 min^{-1}, T= 350°*C*. The ranges of variation of the factors were chosen based on the results of the conducted preliminary experiments (whose results are presented in Fig. 2): f=±0.39 mm/tr, n =±20 min^{-1}, T=±20 °*C*.

The conducted statistical calculation [13] allows to obtain:

- an adequate mathematical model of the process (according to Fisher's criterion), describing the relationship between the parameter and the factors of optimization (4):

$$\sigma = 207{,}3 + 13{,}7f - 3{,}2n - 5{,}8T + 2{,}1fn + 3{,}275nT + 2{,}75fnT \quad (4);$$

- the technological modes of processing the part (optimal for the specific production conditions), providing minimum values of residual stresses in the surface layer of the AMg5 sample in the spinning process: f=0.21 mm/tr, $n=815$ min^{-1}, $T=360$ °C.
- the optimal distribution of the residual stresses along the depth of the surface layer of the workpieces, processed under the given modes (Fig. 3).

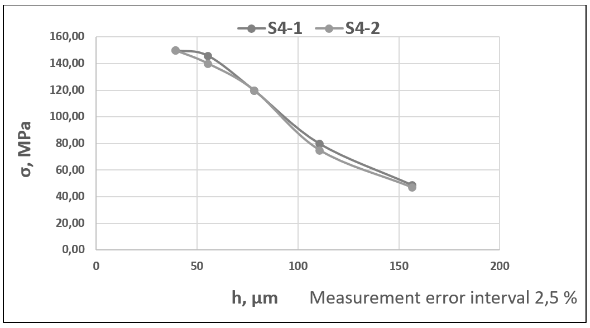

Fig. 3. Optimal distribution of the residual stresses along the depth of the surface layer of the workpieces, where S4-1 and S4-2 illustrates the optimal distribution of the residual stresses along the depth of the surface layer of two workpieces, processed under the given modes; h - depth of the studied material.

The obtained results illustrate the manageability of the residual technological stresses and prove the efficiency of using the resistive electro-contact method in search of optimization of the given parameter [14], [15]. The task, no doubt, as well as similar tasks, can be also solved by applying other methods of stress control – non-destructive (ultrasound, radio-wave, X-ray diffraction etc.) or destructive (the Davidenkov and Berger method, the method of probing holes, the ring method etc.) [16] – [23]. However, given the need for a fast, reliable, non-destructive control and a diagram of the stress distribution in the depth of the surface layer, the presented approach is accepted in this study as optimal.

To verify the mechanical properties of the material in conclusion of the study of workpieces, having a distribution of residual stresses as it is shown in Fig. 3, samples were cut in accordance with GOST 1497-84. The tests show that from the moment of yield onset of the material (at a load of 140 MPa) to the moment of rupture of the sample (at a load of 290 MPa), the relative elongation is 15%. The obtained results from the rupture test (at tension) satisfy the requirements for yield point $\sigma_т$, tensile strength $\sigma_в$ and relative maximum elongation δ of the AMg5 material.

IV. Conclusion

The proposed methodology for optimization of the residual stresses in the surface layer of details allows to study and evaluate their influence in the spinning process of thin-walled details from aluminum alloys. The means of mathematical support of the process by statistical analysis, provide possibilities to derive the optimal technological modes for quality products formation. The applied resistive electro-contact non-destructive method allows to trace the nature of the stresses in the surface layer of the details. The availability of a distribution diagram of these stresses along the depth of the surface layer illustrates their technological controllability, which can contribute to increasing the quality of the manufactured products in mechanical and instrumental engineering.

References

[1] A.Y. Ivanov, D.B. Leonov. Analysis of the methods for control and measurement of residual stress // Journal of the Technical University - Sofia, Plovdiv branch, Bulgaria «Fundamental Sciences and Applications», 2012, Volume 17. pp. 13–19.

[2] A.Y. Ivanov, D.B. Leonov. Technological methods of providing product quality, Scientific and technical journal of SPbGU ITMO, 2011, No. 5(75), pp. 111 – 113 (in Russian).

[3] S.P. Burkin. Residual stresses in metal products: textbook. Yekaterinburg: Publishing House of the Ural University, 2015. p. 12 (in Russian).

[4] V.F. Bezyazychny, R.N. Fomenko. Technological support of the operational properties of gas turbine engine parts // Journal of Metalworking, Politechnika Publishing House. 2017. No. 1. pp. 16–22 (in Russian).

[5] V.S. Mukhin. Surface. Technological aspects of the strength of GTE parts. M., 2005. p.295.

[6] V.A. Valetov, S.D. Vasilkov, O.S. Yulmetova. Methods of researching the characteristics of the surface layer of device parts, Teaching manual, St. Petersburg, 2010 (in Russian).

[7] A.D. Ilyina. Resistive electrocontact method for determining residual stresses in parts after machining. Young Scientists Forum.- 2022, No. 5(69), 2019, pp. 145-148 (in Russian).

[8] D.B. Leonov, A.Y. Ivanov. Control of residual stresses during spinning of aluminum alloy parts // Proceedings from the "Jubilee Scientific Conference on the occasion of 10 years since the establishment of the NVU". - Volume 7., V. Tarnovo, 2012,pp. 120–126 (in Bulgarian).

[9] D.V. Dudka, V.I. Tregubov. Influence of technological parameters on flow formation during rotational spinning of axially symmetric parts, News of Tula State University, TulSU Publishing House, 2011, pp. 3 – 13 (in Russian).

[10] P.M. Vinnik, T.V. Vinnik, A.I. Olehver, A.Y. Remshev. Calculation of the influence of material hardening on stresses and formed mechanical properties during successive drawings with wall thinning. Metalworking, No. 1, 2019, p. 30-34.

[11] V.M. Kishurov, N.K. Krioni, V.V. Postnov, P.P. Chernikov, M.V. Kishurov. Processes of forming parts in mechanical engineering: textbook. M.: Journal of Mechanical Engineering, 2015. p. 496.

[12] A. S. Chumadin1 , D.A. Baturin1. Modeling and control of the Springback Effect in the Bottom Sheet Metal Part One stage Drawing Process. Science and Education of the Bauman MSTU, 2014, no. 9, pp. 106–118.

[13] RDMU 109-77. Method of selection and optimization of controlled parameters of technological processes. Introduction 07/01/1978. M, Standards Publishing House, 1978, p. 48 (in Russian).

[14] D.V. Vasilkov, S.D. Vasilkov, A.V. Nikitin. Measurement of residual stresses by the resistive electrocontact method // Journal of Metalworking. 2017. No. 6. pp. 30–34.

[15] D.V. Vasilkov, D. A. Mezentsev, A. V. Nikitin [et al.] Technological residual stresses and their deforming ability during cutting //Journal of Metalworking. 2018. No. 4. pp. 2–6.

[16] G.V. Muratkin. Processes of formation and reduction of technological residual deformations of non-rigid parts // Journal of Metalworking. 2019. No. 6. pp. 17–26.

[17] Saha S. Non-Destructive Evaluation of Residual Stresses in Welding. 2022. DOI: http://dx.doi.org/10.5772/intechopen.101638.

[18] Suvi-Santa-aho, Laitinen A, Sorsa A, Vippola M. Barkhausen noise probes & modelling: A review. Journal of Nondestructive Evaluation. 2019;38(4): 2-4.

[19] A.H. Mahmoudi, A. Ghasemi, G.H. Farrahi, K.A. Sherafatnia. Comprehensive experimental and numerical study on redistribution of residual stresses by shot peening // Materials & Design. 2016. N 90. P. 478–487.

[20] N.N. Stolyarov, A.D. Sukhikh, M.V. Tabanyukhova, Residual Stresses in 3D-Printed Models. Proceedings of the Novosibirsk State University of Architecture and Civil Engineering (Sibstrin), 24-1/2(79/80) 48-54 (2021).

[21] M. Tabanyakhova, , N. Slolyarov, A. Nagel, The issue of residual stresses in Additive Technologies. MATEC Web of conferences, Volume 376, AMEFP 2022, DOI: https://doi.org/10.1051/matecconf/202337601008.

[22] G.V. Samandasyuk, I.A. Slesarev, M.S. Kozhen, Additive Technologies in Construction. Globe: Engineering Sciences 2(33) 18-1 (2020).

[23] A.D. Sukhikh, N.N. Stolyarov, M.V. Tabanyukhova, The Issue of Residual Stresses in 3D-Printed Models. In the coll.: The Intellectual Potential of Siberia. Collection of Scientific Papers of the 29thRegional Scientific Student Conference dedicated to the Year of Science and Technology in Russia. In 5 Parts. Ed. D.O. Sokolova, Novosibirsk, 88-92 (2021).