Improving the mechanical and operational characteristics of aluminum alloys by multi-contact deformation treatment

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Abstract. Experimental studies of the possibility of improving the mechanical and operational characteristics of aluminium alloys by surface plastic deformation (SPD) have been carried out. As a processing method, wave strain hardening (WSH) was chosen. The adaptation of the existing equipment for hardening aluminium alloys was carried out and the limiting technological modes of processing were established. As a result of experimental studies of hardened samples, it was found possible to provide a hardened layer depth of 10 mm with a maximum degree of hardening 2.12 times higher than the original, as well as the possibility of increasing the operational characteristic - resistance fatigue - up to 3 times is established.

1. Introduction

Parts made of aluminum alloys are widely used in aerospace and transport industries. With a lower specific gravity, aluminum alloys are significantly inferior to steel in fatigue resistance. To ensure the durability of parts operating under alternating loads, hardening by surface plastic deformation (SPD) methods has been successfully applied [1-3]. At the same time, dynamic SPD methods are the most effective [1, 4-7]. In order to improve the operational properties of machine parts made of aluminum alloys, the application of the wave strain hardening technology is the most promising one (WSH) [1-3]. However, there are limitations associated with the WSH processing of aluminum alloys:

- it is necessary to avoid overhardening of the material, the formation of micro-cracks in the surface layer, due to the application of excess impact energy during processing;
- it is necessary to adapt the available equipment, aimed at reducing the pressure of the tool on the processed material in the deformation zone.

The solution is possible due to the use of multi-tool processing, which makes it possible to vary the tool pressure on the material and effectively redistribute the impact energy. Previously, multi-tool processing in relation to the method of wave strain hardening has not been studied there is a need to identify the dominant structural and technological parameters, their influence on the mechanical properties as well as operational characteristics of the processed material [8-10].

2. Design and technological parameters of multi-contact wave strain hardening

Depending on the choice of technological processing parameters, a hardened surface layer with a different depth and degree of hardening is formed. To determine the rational processing conditions for aluminum alloys, a series of experimental studies has been carried out. The following structural and
technological parameters that have a dominant influence on the processing process are taken into account as initial data (Figure 1):

\[ L_1, L_2, d_1, d_2, D_T, P_{ST}, A, f, s, \]

where \( L_1, d_1 \) and \( L_2, d_2 \) – the length and diameter of the striker and waveguide, respectively, mm; \( D_T \) – tool diameter, mm; \( P_{ST} \) – static tool preload, N; \( A \) – impact energy, J; \( f \) – shock frequency, Hz; \( s \) – feed rate of the workpiece relative to the tool, m/s.

The choice of these parameters and the range of their variation is based on previously conducted studies and the capabilities of existing technological equipment [1]. So, the WSH equipment has the following design parameters: \( L_1 = 480 \text{ mm}, L_2 = 160 \text{ mm}, d_1 = d_2 = 48.5 \text{ mm}. \) This ratio of structural parameters provides high efficiency of the processing in addition changing these parameters is difficult and economically irrational. The effective value of the \( P_{ST} \) parameter is 10% of the dynamic component of the load. The influence of the parameters \( f \) and \( s \) is considered through a complex parameter - the overlap coefficient of individual plastic prints \( K \), which is determined by the formula [1, 4]:

\[
K = 1 - \frac{s}{\delta f 60^\circ},
\]

where \( \delta \) – characteristic size of the plastic print, mm.

Aluminum-magnesium alloy AlMg2, which is widely used for the manufacture of frame parts in aviation and transport equipment, was chosen as a test material. Steel balls and cylindrical rods with a spherical end face of various diameters were selected as a processing tool. Based on the mechanical characteristics of the material, the areas of variation of the values of the WSH main technological factors during the processing of AlMg alloys are determined:

\[ A_{\text{min}} \ldots A_{\text{max}} = 5 \ldots 80 \text{ J}; D_{T_{\text{min}}} \ldots D_{T_{\text{max}}} = 8 \ldots 250 \text{ mm}; K_{\text{min}} \ldots K_{\text{max}} = 0.2 \ldots 0.8. \]

![Figure 1. Scheme of wave strain hardening (WSH): 1 - striker, 2 - waveguide, 3 - tool, 4 - hardened sample, \( A \) - impact energy, \( f \) - frequency of impacts, \( P_{ST} \) - static load, \( P_c \) - contact force in the deformation zone, \( s \) - feed, \( b \) - tool width, \( L_1, L_2 \) - length of the striker and the waveguide, \( d_1, d_2 \) - diameter of the striker and waveguide cross sections, \( \delta \) - plastic print size.](image)

In addition, new technological parameters typical for multi-contact WSH were identified: \( S_{\text{REL}} \) - the ratio of the sum of the cross-sectional areas of the tools and the cross-sectional area of the waveguide; \( N_T \) - the number of tools in the loading system, pcs; \( p \) - the total deformation zone pressure, MPa; \( \delta' \) is the distance between adjacent plastic prints, mm.
The ratio of the sum of the cross-sectional areas of the tools and the waveguide cross-sectional area $S_{REL}$ is defined as (Figure 2):

$$S_{REL} = \frac{S_{N1} + S_{N2} + \ldots + S_{NT}}{S_{WAVES}},$$

where $S_{N1}, S_{N2}, \ldots S_{NT}$ – the sum of the cross-sectional areas of the tools is from 1 to $N_T$, mm$^2$, and $S_{WAVES}$ is the cross-sectional area of the waveguide, mm$^2$.

The total pressure in the deformation zone $p$ affects the change in the hardening degree along the surface layer depth and is defined as:

$$p = \frac{P_D}{S_D},$$

where $P_D$ – impact force, N; $S_D$ – the area of the plastic print in the deformation zone, mm$^2$.

$$P_D = \frac{C_1 C_2}{C_1 + C_2} \sqrt{\frac{2A}{m_1}},$$

where $C_1, C_2$ – acoustic stiffness of the striker and waveguide, respectively, kg / s; $A$ - impact energy, J; $m_1$ - the striker mass, kg.

The scheme for determining the $\delta'$ parameter is presented in Figure 2.

![Figure 2](image)

Figure 2. Scheme for determining: a) $S_{REL}$, b) $\delta'$ and $\alpha$ (view in the tool cross-section).

The possibility to adjust the parameter $\delta'$ is provided by turning the multi-tooling at a given angle $\alpha$ within $0^\circ$...$90^\circ$ with an accuracy of $\pm 1^\circ$. The change of $\delta'$ allows us to control the surface layer micro-hardness chart as well as determines the processing performance.

$$\alpha = \arccos\left(\frac{\delta \pm \delta'}{D_T}\right),$$

The “±” sign before $\delta'$ indicates the relative position of adjacent prints: if one print is superimposed on another, then “−” is used before $\delta'$.

3. Mechanical and operational characteristics of AlMg2 alloy after wave strain hardening

As a result of experimental studies with given initial structural and technological processing parameters, it was established that the hardening depth reaches 6 ... 10 mm, and the degree of hardening is 80 ... 110% at $A = 30 ... 50$ J per tool and $D_T = 12 ... 27$ mm (for reference plane the surface of the sample after the defective layer removal is taken). Dependences of the degree of the surface layer hardening ($\Delta H_{\mu}$) on technological parameters are presented in Figure 3.

As a result of bending resistance impact studies, it was found that during a single treatment with multi-contact WSH, the decrease in impact strength ($KCU$) in comparison with the initial one practically does not occur (Figure 4). After multi-contact WSH for all tools and $K = 0.2 ... 0.6$, the
impact strength is in the range of 87 ... 96 J / cm². The second pass reduces the toughness by 8-10%, which negatively affects the operational properties.

Figure 3. Dependence of the surface layer hardening degree $\Delta H_{\mu}$ on: a) the diameter of the ball and the depth of the layer; b) the diameter of the spherical end face of the cylindrical indenter and impact energy.

Figure 4. Impact bending resistance tests.

Rational values of the total pressures $p$ in the deformation zone, the ratio of the sum of the cross-sectional areas of the tools and the $S_{REL}$ waveguide at a constant impact energy $A = 50$ J are established. At these values close gradients of the hardening degree of the surface layer depth are provided:
- for tool-balls with $0.2 < K < 0.4$ and $D_T = 27$ mm: $130 < p < 590$ MPa (reduced by 1.45 ... 4.5 times compared to the single-contact loading scheme);
- for tool-rods at $0.2 < K < 0.6$ and the diameter of the spherical end of $27 \text{ mm} - 130 < p < 950 \text{ MPa}$ (reduced by $1.3 \ldots 7.3$ times).

It was found that with $S_{REL} = 0.2 \ldots 0.8$ and $N_T = 2 \ldots 3$ the following parameters are provided: depth $h = 8 \ldots 10 \text{ mm}$ and the degree of hardening $\Delta H_{\mu}> 80\%$.

Figure 5. Torsional fatigue resistance test results.

Thus, the field of rational design and technological parameters of multi-contact WSH has been experimentally established, providing a multiple increase in the mechanical and operational characteristics of aluminum alloys on the example of AlMg2 alloy.

4. Conclusion
The possibility of increasing the mechanical characteristics of parts made of aluminum alloys as a result of multi-contact WSH with the formation of a hardened surface layer with a hardening depth of up to $10 \text{ mm}$ and a maximum degree of hardening of up to $112\%$ (or $2.12$ times higher than the original), as well as the possibility of increasing the operational characteristic - resistance fatigue - up to $3$ times is established.

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