SCIENCE FOR PRODUCTION

SURFACE ALLOYING OF STEELS IN THE PROCESS OF MECHANICAL PULSE TREATMENT

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It is shown that intense saturation of the surface layers of a hardened metal with nickel, copper, and chromium from electroplates occurs in the course of mechanical pulse treatment in the zone of frictional contact. In this case, the mass transfer coefficients range from $0.95 \cdot 10^{-7}$ to $1.1 \cdot 10^{-7}$ $\text{m}^2/\text{sec}$. It is established that the number of alloying elements is defined by the number of generated dislocations.

Mechanical pulse treatment is one of the most promising methods of improvement of surface layers of alloys [1]. It is characterized by rapid thermoplastic deformation with simultaneous fast heating and cooling, during which a redistribution of alloying elements occurs in the surface regions of the hardened metal. In this case, the diffusion coefficient is as high as $10^{-9}$ $\text{m}^2/\text{sec}$ [2]. This high mobility of alloying elements under conditions of thermoplastic deformation with a rate of $10^{-1}$ $\text{sec}^{-1}$ and higher is better known as mass transfer [3]. The redistribution of many chemical elements (carbon, chromium, nickel, silicon, copper, iron, manganese) in a so-called white layer of alloyed steels was detected [1], and the accelerating effect of dislocations on mass transfer of substitutional elements within the framework of the Hart–Mortlock model was demonstrated [2]. However, it should be born in mind that it is just the mechanical pulse treatment that creates a high dislocation density in a hardened layer ($\rho = 10^{11} - 10^{12}$ $\text{cm}^{-2}$) [1, 2]. The value of the mass transfer coefficient depends on the rate of plastic deformation [4].

To determine the possibility in principle of alloying the near-surface layers of fabricated metal products, we investigated saturation with alloying elements from previously deposited electroplates during mechanical pulse treatment. Cylindrical specimens 20 mm in diameter made of armco-iron and 45 steel were studied in various structural states.

The mechanical pulse treatment was performed on a special unit [5] under the following conditions: the linear rate of rotation of the hardening tool was 70 $\text{m/sec}$, the angular frequency of the specimens was 0.21 $\text{sec}^{-1}$, and the longitudinal feed of the tool was 2 mm/rev. Chromium, nickel, and copper, used as alloying elements, were deposited by the galvanic method. In the zone of contact of the workpiece and the tool, the surface regions of the specimens were heated to temperatures above the point $A_{C3}$, which was accompanied by a simultaneous plastic shear deformation with a rate of $(10^{3} - 10^{4})$ $\text{sec}^{-1}$. The contact pressure attained 0.56 GPa; the rate of cooling was 1500 $\text{K/sec}$ due to a heat removal into the working medium (1-5 A industrial oil), the hardening tool, and the hardened workpiece [2].

The investigations showed that the surface regions of armco-iron were saturated with chromium, nickel, and copper under the given temperature-force conditions of hardening (Fig. 1). The distribution of the elements in depth $\delta$ was determined by layer-by-layer chemical analysis. Analysis of the concentration curves performed by the Fischer procedure indicates the predominant distribution of the alloying elements at grain boundaries [6].

To study the effect of defects present in the initial structure of the metal on the process of mass transfer, we investigated specimens made of 45 steel in ferritic-pearlitic, sorbitic-troostitic, and martensitic states (after normalizing, tempering, and quenching with subsequent low tempering), for which the dislocation density is, respectively,
The stabilized structures were found to cause a higher mobility of chromium atoms (Fig. 2). This correlates with the known fact that mass transfer is slowed down as the density of defects (vacancies, dislocations) in the initial structure increases [3]. Spinning with rollers was also used to increase the number of defects in the surface regions of annealed specimens. This decreased the concentration of the alloying elements (nickel and chromium) in the course of hardening (Fig. 3) due to an increase of the dislocation density up to $10^{11}$ cm$^{-2}$ in the initial structure [8].

![Graph](image)

**Fig. 1.** Distribution of nickel (1), copper (2), and chromium (3) in armco-iron specimens (treated in air).

On the basis of the experimental data (see Fig. 1), we calculated the mass transfer coefficients for nickel, chromium, and copper. It is customary to describe distributions of atoms in depth by the exponential dependence [3]:

$$C_\delta = \frac{C_0}{\sqrt{\pi D\tau}} \exp\left(\frac{-\delta^2}{4D\tau}\right),$$

where $\tau$ is the time of deformation, $D$ is the mass transfer coefficient, which is a characteristic of the mobility of atoms, and $C_0$ is the content of the penetrating element at the moment preceding the onset of deformation.

The time of deformation was determined from the rate of rotation of the specimen (0.21 sec$^{-1}$) and the width of the contact region (0.22 mm) [1]. Then, taking into account the number of cycles [9], we find $\tau = 51$ msec. Taking the nickel concentration at depth $\delta = 25$ $\mu$m to be 3.26 wt.%, we establish that $C_\delta = 2.75 \cdot 10^{-6}$ g/cm$^3$. The nickel content on the surface for a coating thickness of 80 $\mu$m is $C_\delta = 0.68 \cdot 10^{-6}$ g/cm$^2$. Then $D = 1.00 \cdot 10^{-7}$ m$^2$/sec. The mass transfer coefficients for chromium and copper are, respectively, 1.03 and 0.76 $\cdot 10^{-7}$ m$^2$/sec. The obtained magnitude of $D$ for the chromium-armco-iron system far exceeds the diffusion coefficient of chromium in 45 steel ($D = 4.2 \cdot 10^{-15}$ m$^2$/sec) from the electroplate on fast electroheating ($V_h = 3 \cdot 10^3$ K/sec) and a temperature of 1273 K [6]. It is also higher than the self-diffusion coefficient in the bulk of the liquid metal ($= 10^{-9}$ m$^2$/sec) by a factor of about 100 [3]. Thus, under mechanical pulse treatment in the zone of frictional contact, favorable conditions for implantation of alloying elements arise. In this case, the initial structures whose lattices are highly saturated with defects slow down the mass transfer of these elements.