Structuring carbon alloys due to carbon mass transfer

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Abstract. The wear of parts of the threshing apparatus of a combine harvester inevitably leads to the deterioration of the threshing of the grain mass, which in turn leads to the loss of grain. One of these parts involved in the direct threshing process is the whipping threshing drum made of high carbon steel. Used steels of increased strength for the manufacture of parts, components and structures of agricultural machines requiring restoration using surfacing with wear-resistant coatings are hampered due to the tendency of such steels to form hot and cold cracks in the near-weld zone. The main reason for the formation of cold cracks during the welding of steel parts is considered to be the unfavorable development of physicochemical processes in the heat-affected zone of welding. The highest probability of the formation of deformations and residual stresses in austenitized regions of the heat-affected zone is characteristic of steels with a high carbon equivalent. As a result of the research conducted, the possibility of reducing the carbon content in the welded edges and weld surfaces of carbon steel products by creating a temperature gradient in them directed from the surface to the core was substantiated and experimentally confirmed. The local decarburization that occurs during this process is reversible, and after performing the surfacing, it is easily eliminated by normalization.

1. Introduction

One of the most important factors affecting the high performance of combine harvesters is the good technical condition of the threshing machine. And the process of threshing grain mass is the main in the working process of the combine.

The threshing process takes place with the help of drum and deck whips. During the operation of the combine, the wear of the scourges of the drum, namely, the fine side of the scourge occurs [1]. This leads to an increase in the gap between the drum and the deck, and as a result, the threshing of the grain worsens. This is due to the fact that the grain mass under the action of friction forces and high speed of rotation of the threshing drum tends to the center, and this is where the main wear occurs. When the combine is repaired, worn pests are removed and sent to scrap, replacing them with new ones, which is not economically feasible. We propose a method for restoring worn out scourges by surfacing with wear-resistant coatings.

As shown by spectral analysis, whips are made of high carbon steel (0.43% C), the corresponding steel 45 g. This steel belongs to steels with low weldability, due to the danger of hot and cold cracks in the weld area and heat-affected zone.
The mechanism of the formation of hot cracks in the metal, which was subjected to partial melting during the surfacing, consists in the violation of its continuity over the unconsolidated liquid interlayers under the action of shrinkage stresses due to difficult shrinkage. The heat-affected zone is rigidly connected with the hardening seam and therefore the temperature decreases sharply. The ductility of the metal, as well as the ability to compensate for the shrinkage of the solidifying metal, is also reduced. Under these conditions, the lower the temperature to which the liquid phase presents, the more likely the formation of hot cracks.

Wilkinson [2] to evaluate the sensitivity of steel to the formation of hot cracks during welding proposed a figure that is calculated by the expression:

$$K = \frac{C(S + P + \frac{Si}{25} + \frac{Ni}{100})}{3Mn + Cr + Mo + V}$$

(1)

From the above expression it can be seen that the tendency to the formation of hot cracks to the greatest extent increase sulfur, phosphorus and carbon.

The liquid phase due to the development of micro-dilution processes at the end of solidification can be enriched with phosphorus, sulfur, carbon and other elements to form a multiphase low-melting eutectic with a solidification temperature of ≈940°C. An element such as manganese contributes to counteracting cracking, linking sulfur to refractory MnS sulfides. A positive effect on the grinding of steel grains, due to which the total surface area of the grains increases, and the film of low-melting liquates becomes thinner and becomes broken, the presence of molybdenum, chromium and vanadium obviously has [3-18].

During the period of completion of cooling or after complete cooling of the metal in the heat-affected zone near the weld, where under the action of thermal processes it becomes possible to form hardened structures and a sharp decrease in local ductility of steel cold cracks occur. The development of high internal stresses of thermal and phase nature leads to the formation of cold cracks in the embrittled hardening region [19-24]. The resistance to plastic deformation of hardened steel, that is, hardness, is determined by the carbon content, which dissolves in the ferrite by the type of penetration and causes the maximum distortion of the crystal lattice. Substitution solid solutions with iron form almost all alloying elements and have little effect on hardness, but they can expand the zone of formation of quenching structures, increasing the hardenability of steel.

By carbon equivalent [1], it is customary to evaluate the effect of the chemical composition of carbon steel on crack sensitivity, calculated using the formula:

$$C_e = C + \frac{1}{6}Mn + \frac{1}{24} Si + \frac{1}{40} Ni + \frac{1}{5} Cr + \frac{1}{4} Mo$$

(2)

Steel with a carbon equivalent of $C_e \geq 0.65\%$ has a low weldability, and at values of $C_e \geq 0.4\%$, they are characterized and are considered to be difficult to weld.

From the expression (2) it follows that the carbon content has a decisive effect on the weldability of steel, the influence of other components is many times weaker.

Since 45G steel, which is a steel with reduced weldability, is used for making drum scourges, it is necessary to remove carbon from the heat-affected zone to the depth of the part when surfacing.

2. Materials and research methods

Studies were carried out on worn out above the allowable values of the whips (Figure 1) of the «Don» combine harvesters - 1500B and ACROS 530.

The formation of a stressed structure due to thermal effects during surfacing, can cause the appearance of such defects as hot and cold cracks. In order to avoid hot and cold cracks, before restoring the worn-out part of drum scourges by surfacing under a flux layer, it is necessary to lower the carbon content in the thin face of the scourge. To this end, carbon mass transfer studies were carried out in a gradient temperature field, in which a stationary temperature difference was created along the length of a massive sample of a threshing drum cut from a pest of a threshing drum.
A sample of 45G steel (0.43% C) 20 mm wide and \( L = 45 \) mm long was heated from one end by direct contact with a plate heated to 1000 °C, and the opposite end was cooled with a water-cooled copper refrigerator. To isolate the sample from the radiation of a hot plate and create a sharp temperature difference in the local area of the sample, an asbestos screen was used, mounted on the sample at a distance of 23 mm from the heating element (Figure 2a). The temperature gradient was maintained for 20 minutes, then the sample was quenched in water.

The structure of the part of the sample located between the cooler and the screen corresponded to the initial one and did not change during the experiment; in the area of the screen, it was biphasic (austenitic-ferritic), below the screen, fully austenitic (Figure 2b).

This method has shown that it is possible to create a gradient of carbon activity, and to carry it out into the depths of an experimental sample, i.e. the possibility of obtaining diffusion fluxes of carbon in a chemically homogeneous austenite by imposing on the part thermal gradients causing activity gradients, which are the driving force of the ascending diffusion of carbon.

Figure 1. Scourge combine scourge: \( L \) - wear zone; 1 and 2 - faces; 3 - reefs.
3. Results and discussion

In accordance with the equation given in [3, 4, 7], with an increase in temperature, the thermodynamic activity of carbon decreases:

\[
\log a_c = \log \left( \frac{N_c}{1 - 5N_c} \right) + \frac{2105}{T} - 0.6735 + \frac{317}{T} \frac{N_c}{1 - N_c};
\]

(3)

\(a_c\) – thermodynamic activity of carbon; \(N_c\) is the atomic fraction of carbon; \(T\) – temperature, K.

The possibility of a sharp cooling of the surface to create a gradient of carbon activity sufficient for its flow directed toward a hotter core is an important consequence of the expression (3). Such mass transfer inevitably leads to the decarburization of the surface and an increase in the concentration of carbon in the hot deep layers.

Using the Benzo-Elliott isoactivity diagram, it was found that the thermodynamic activity of carbon \(a_c\) in the binary alloy Fe-0.43\% C at 1000 °C is equal to \(\approx 0.3\), and at 800 °C it is \(\approx 0.52\) (Figure 3).

Calculating the mass balance under the conditions of creating a stationary gradient by calculation, it was determined that the homogenization of steel by chemical potential and thermodynamic activity of carbon will occur due to the transfer of 0.05-0.06\% C, i.e. in the heated part of the sample the carbon content should increase to 0.44-0.45\%, and in the screen area (\(t \approx 800\) °C) decrease to 0.33-0.34\%.

The steady-state distribution of carbon in the sample under test under the action of a temperature gradient and fixed by quenching was studied by the method of local spectral analysis. The considered spectrum was carried out at points located on the longitudinal axis of the sample at a distance of 1.5-2.0 mm from each other (Figure 4).
Figure 3. Determination of values of $a_c$ in a prototype according to the Benz-Elliott diagram.

From figure 4 it can be seen that the carbon content in the hot end region reached 0.50%, at a distance of 23 mm from it (screen area), the concentration decreased to 0.40%, while in the cold part of the sample it remained almost unchanged without undergoing phase transformations.

Figure 4. Distribution of carbon under the action of temperature gradient, established in the sample of steel 45g.

After partial decarburization of the fine side of the sample (worn-out part), automatic surfacing was performed under a flux layer. The surfacing was performed on the U-653 universal surfacing machine with the A-1406 surfacing head and the VDU-504 welding current source. During the surfacing, manganese fused silicon-fused flux was used in combination with a low carbon electrode wire with a diameter of 19 mm. Current 210 A, voltage 30 V, deposition rate 25 m/h, electrode feed rate 125 m/h.

The criterion characterizing the strength and wear resistance of the metal is hardness. The average hardness of the metal plating was determined on the device ITR-60150-M and was equal to HRC32, which is two times higher than the hardness before surfacing.

4. Conclusion
Thus, the action of the temperature gradient for 20 minutes turned out to be sufficient for the diffusion redistribution of carbon in accordance with the created gradient of its thermodynamic activity and made it possible to weld without threat of the formation of cold and hot cracks.
The results of the studies confirm the ability to control the local concentration of carbon by creating a temperature gradient.

For such a movable diffusion element as carbon, the development of new technologies becomes real, for example, associated with the temporary removal of carbon from some zones of a steel part to perform any technological operations with this decarbonized volume and subsequent homogenization of the product on the carbon content. This can be useful in restoring the welding and welding of worn parts of high-carbon steel agricultural machines. In the heat-affected zone of such steel, it is possible to reduce the carbon content for the time of surfacing or welding, pushing it into nearby metal layers using gradient heating and fixing the achieved distribution by quenching. After the welding or cladding operation is completed, the carbon content is easily leveled by short-term austenization or isothermal annealing.

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