EFFECT OF THE STRESS STATE OF THE COATING
ON THE QUALITY AND EFFICIENCY OF ENAMELED
CHEMICAL APPARATUS

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The stress state in the metallic base-enamel coating system, which is a composite of two materials
that are diverse in nature and physical properties, exerts a considerable effect on the physiomechanical
properties of the composition as a whole, and also on the quality and reliability of operation of enameled
chemical equipment. Such coating defects as chips, delamination, hairlines and cracks, breaks, and the like
are caused by the generation of stresses in one stage or another in formation (baking) of the coating which
exceed the failure stress of the enamel in magnitude. Stretching stresses present the greatest danger for
brittle coatings.

If we assume that the stresses caused by the use of welding in making apparatus are completely re-
moved in preliminary baking, then it may be considered that the main reasons for the generation of stresses
in the coating during the process of its formation are the following:

- the difference in physiomechanical properties of the elements of the composite (metal and enamel),
  mainly in the coefficients of thermal expansion (CTE) and, in smaller degree, in the modulus of elastic-
  ity, E, which leads to the generation of a stretching stress, $\sigma_0$, in the enamel;

- the temperature gradient between the metallic backing and the coating, caused by the large difference
  in their thermal conductivities (50 and 1.5 kcal/m·h·deg., respectively), due to which technological
  stretching stresses $\sigma_{\Delta t}$ may arise in the coating on heating;

- a temperature gradient over the surface of the article due to a nonuniform temperature field in the
  furnace and the shielding action of some constructional elements (flanges, collar, and compensator)
  and technological equipment (mounting) used in baking the enamel, as a result of which, in individual
  sites in the apparatus where the temperature differs from that in the main mass of the article, local
  bending deformations may arise, which cause large stretching stresses $\sigma_{\Delta t}$.

It should be noted that the stress caused by the reasons enumerated above is not constant. It varies
with time and with change in the temperature of the apparatus. However, at any moment and at any point of
the enameled apparatus surface, the total stress is given by

$$\sigma = \sigma_0 + \sigma_{\Delta t} + \sigma_{\Delta t}.$$  

To obtain a high-quality coating, it is necessary that during the heating and cooling of the article during
the formation process the total stress should not exceed the stress which is allowable for the coating material
over the whole temperature range. Otherwise, if this does occur during heating, fusion cracks, hairlines,
and breaks are formed on the enamel; if it occurs on cooling, hairline cracks are formed.

The compatibility of the enamels with the metal to be protected, in magnitude of the CTE has much im-
portance in the creation of compression stresses in the coating at the operating temperatures of the item [1].
In the practice of enameling steel chemical equipment, often up to the transformation temperature of the ena-
mel $T_g$, the CTE of the metal slightly exceeds that of the enamel, but above this temperature the CTE of the
enamel appreciably exceeds that of the metal. In this case a region of stretching stresses and a second (lower)
zero point (Fig. 1) is observed on the curve of the temperature dependence of the stress $\sigma_0$ in the enamel on
heating and cooling.

According to the data of [1], the maximum value of the stretching stresses and the width of the temper-
ature region of their existence are determined by the ratio of the CTE of the enamel to that of the metal above
and below the transformation temperature. For most of the enamels used in chemical engineering, their

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transformation temperatures on heating and cooling are at 400–550 and 350–450°C, respectively. The investigations of [2] show that defects of the type mentioned above arise, as a rule, at a temperature close to \( T_g \), where the stretching stresses have their maximum value and the enamel is in an elastic-solid state.

Analysis of the temperature dependence of the \( \sigma_0 \) stresses and of the CTE of the enamel and metal (Fig. 1) makes it possible to note a route for reducing the maximum stretching stresses in the \( T_g \) region and for preventing the formation of the defects caused by them. Using known formulas for calculating stresses in a metal-enamel system in the absence of thermal gradients [3, 4], the magnitude of the maximum stretching stresses \( \sigma_{0s} \) at the temperature \( T_g \) can, with a certain approximation, be represented as a function of the difference in CTE of the enamel and the metal at temperatures above \( T_g \), and of the difference between the softening point of the enamel \( T_s \) and the temperature of the start of its transformation \( T_g \):

\[
\sigma_{0s} = k \left( \alpha_e'' - \alpha_m'' \right) (T_s - T_g),
\]

where \( \alpha_e'' \) is the CTE of the enamel above the temperature for start of the transformation (in the range \( T_g - T_s \)), \( \alpha_m'' \) is the CTE of the metal in the same range, and \( k \) is a coefficient which takes into account the elastic properties of the materials.

Analysis of Eq. (1) shows that by reducing (by changing the chemical composition of the enamel) the CTE at temperatures above \( T_g - T_s \), it is possible to decrease considerably the magnitude of the stretching stresses in the critical temperature region and reduce the probability of forming hairlines and cracks.

Reducing the technological stretching stresses \( \sigma_{At_1} \) caused by the temperature gradient between the metal and the enamel is associated mainly with reducing the heating rate of the enameled article. However, a decrease in heating rate reduces the output of the baking furnaces on one hand, and increases the consumption of energy, and on the other hand, helps increase the stretching stresses in the critical temperature range due to shrinkage of the enamel [5], which, in a number of cases, as our experiments on enameling some low-alloy steels have shown (in particular with type 10G2S1 steel) leads to the formation of a network of hairlines and cracks.

As concerns thermal stresses of the third type \( \sigma_{At_2} \) studies performed in the Scientific-Research Institute of Enameled Chemical Machinery (NIIemal’khimmash) have shown that on heating in an electrical elevator furnace and cooling the apparatus (capacity 1.25 and 2 m³) in air, the temperature distribution on their surfaces is extremely nonuniform (Fig. 2): The temperatures at some points in the apparatus differ by 250–300°C. As is evident from Fig. 2, one of the main reasons for nonuniformity of the temperature field over the surface of the apparatus is welded parts of the type of collars and compensators (see I and II in Fig. 2).