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Influence of Brazing Process Parameters on the Strength of Liquid Rocket Engine Brazed Structures

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Abstract: The article addresses the issues of brazing parameters optimization: mediums; pressure; rate of temperature change; transition from one rate of temperature change to another one; the excess pressure in the cavity of the installation with respect to the medium pressure in the brazing cavity. Impact of the parameters is demonstrated by the examples of the engine gimbal flange, booster pump unit rotor and guide vanes of the turbo-pump unit pump. Improvement in the quality of the soldered joints of the flange can be achieved by introducing homogenizing annealing after brazing. A theoretical calculation of the nonstationary temperature distribution in the structural elements during soldering was preliminarily carried out to solve the problem of soldering the guide apparatus. The calculation resulted in that a reduction in the rate of heating and cooling, and temperature exclusions were excluded. The problem of an impregnated rotor of the booster aggregate was solved by analyzing the thermal interaction of the brazed components, which determined the need for a slow rate of the initial stage of heating the rotor and introducing a soak in temperature.

1. Introduction

Nowadays, brazing, or hard soldering, is successfully used in many engineering branches. The significant progress in its development has been achieved in rocket engineering, particularly, in the production of liquid rocket engines. The prime advantage of brazing in comparison with an alternative method of producing a fixed joint of materials, i.e. welding, is that the process is performed at a temperature below their fusing point. This enables selecting the process temperature depending on the requirement to maintain the brazed materials properties. Brazing, however, also has disadvantages that include the change of structural and phase state of some alloys at high brazing temperatures with the probability of crack formation, defects in the joint area such as pores, microporosity, dry joints, formation of brittle layers, etc. The process of producing the brazed joint is performed in special brazing machines and represents heating to the brazing temperature, soaking at the brazing temperature and cooling. At the same time, the experience of NPO Energomash, JSC in brazing liquid rocket engine structures has proven that the following brazing process parameters are of great importance: atmosphere in the brazed structure (vacuum or shielding gas); gaseous atmosphere pressure in the brazing machine working cavity; rate of temperature variation during heating and cooling; transition from one temperature variation rate to another, overpressure in the machine cavity with respect to the pressure of the atmosphere in the brazing cavity. The optimum combination of these process parameters enables producing a high-quality, defect-free, sound brazed joint and the strength of the brazed structure in general.

2. Pros and cons of brazing in vacuum

Brazing may be performed both in neutral atmosphere (argon, helium) and in vacuum, i.e. in the rarefied gas state created by pumping gas out from the brazing cavity. Brazing in vacuum prevents the brazed part from oxidation providing for a high-quality brazed joint, with no use of flux as required by the gaseous atmosphere. It also prevents embrittlement of stainless steels and heat-resistant alloys. [1]

Moreover, brazing in vacuum allows to provide the contact force between the brazed parts required to produce the brazed joint. A higher contact force is provided by creating the shielding gas increased pressure in the brazing machine working cavity.

Despite all the positive features, vacuum has a certain disadvantage, namely that an intensive evaporation of the brazed materials is possible at high temperatures, particularly, of brazes containing high vapor pressure components. As a result, the braze becomes enriched with infusible components that results in increase of the braze fusing temperature and reduction of its fluidity that may lead to defects and the brazed joint strength reduction.

Mn-base braze is the braze containing a high vapor pressure component that is, in the meantime, widely used in NPO Energomash when brazing structures [2].

3. Influence of the degree of vacuum and homogenizing annealing during the engine gimbal flange brazing

The engine gimbal flange is one of the liquid rocket engine assemblies where Mn-base braze is used (Figure 1).

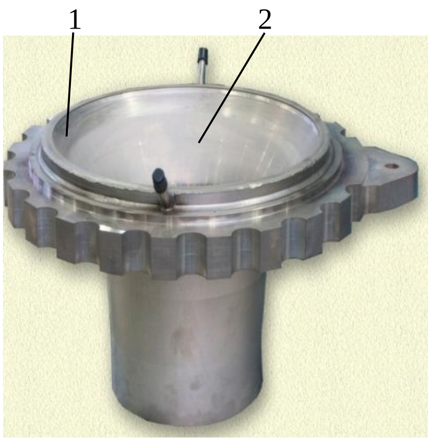

Figure 1. Engine gimbal flange
1 - outer wall; 2 - inner wall

NPO Energomash brazing experience has shown that the brazed joints of the flange with stainless steel parts and nickel alloy parts have sufficient, but yet relatively low strength and brittle fracture pattern.

The flange is brazed in vacuum created in a cavity between the inner and outer walls, under an increased pressure of the shielding gas, argon, in the machine working cavity int order to compress the walls together. The inner wall has ribs on the tops of which Mn-base braze strips are attached with the help of spot welding during the assembly for brazing.

An experimental operation with brazing the flanges in two machines with various degrees of medium vacuum in the brazing cavity has been carried out in order to check the influence of the vacuum degree and homogenizing annealing after brazing to increase the brazed joint strength using Mn-base braze. These are HR-64x80VC (10^{-2} mm of mercury vacuum) and VCA (10^{-1} mm of mercury vacuum) machines.

After homogenizing annealing and standard heat treatment (cold treatment and tempering) metallographic specimen to study the brazed joint quality, as well as samples for tensile strength tests have been cut out from the flange brazed joints.

Metallographic study of the brazed seam showed no defects in both flanges . The brazed seams have a thickness of ~ 50 μm and are formed with double fillets (Figure 2).

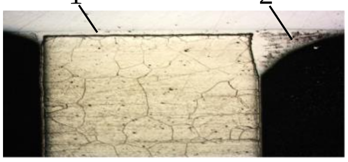

Figure 2. Flange brazed joint
1 - brazed seam; 2 - fillet

The test results have demonstrated that the tensile strength of flange samples brazed with subsequent homogenizing annealing in both machines with various degrees of vacuum is sufficiently high and exceeds the strength of brazed joints without homogenizing annealing by approximately 1,5 times. The fracture surface of brazed seams is matt, typical for ductile fracture. The fractures show no defects (Figure 3).

Figure 3. Brazed seam fracture

4. Regarding the rate of temperature variation in the course of brazing

4.1 Temperature distribution in structural elements

In order to determine the approach to select the rate of brazing temperature variation during heating and cooling, a theoretical analytical treatment of the non-stationary temperature distribution in the structural elements during brazing has been carried out, assuming that the heating is performed via a radiant heat flux, as it is implemented in the brazing machines in NPO Energomash, JSC [3].

A heat transfer model for an unlimited plate with a linear temperature variation over time on one plate surface (in our case it is the wall outer surface) and with no heat flow on the other surface (wall inner surface), as implemented in the process of heating for brazing, has been taken as the analytical model.

The heating rate and wall thickness have been varied in a range corresponding to the existing brazing practice, particularly, the rate has been varied from 0,1 to 1 K/s and the wall thickness - from 5 to 40 mm.

The following characteristics have been received as the result:

- difference of temperatures across the entire wall thickness upon attainment of the brazing temperature by the outer surface;
- wall thickness warm-up time;
- rate of wall outer surface heating due to the incident radiant flux and wall thickness value;

The obtained results have shown that the heating rate is inversely related to the wall thickness. Based on this we can get an idea of the wall heating nature with sections of various thicknesses. Indeed, the wall thin part will heat up faster than the thick one that will result in a temperature gradient between them. Consequently, conditions for thermal stresses will occur that will increase manifold under certain conditions (low material plasticity, stress concentrators) and result in crack formation.

The obtained calculated data of the temperature distribution in the structure in the course of brazing allow selecting optimal brazing conditions and finding design solutions to reduce the probability of structural failure due to the thermal stresses.

4.2 Solution to the problem of crack formation in the guide vanes of the turbo-pump unit pump

The obtained data have been used to solve the problem of crack formation during brazing of the guide vanes of the turbo-pump unit pump (Figure 4). An assumption on the thermal stresses in the housing material due to the difference of temperatures between the nozzle and the header during brazing has been made as the reason for crack formation. The presence of the stress concentrator in the form of a surface transitional section with a small bending radius in the area of the nozzle interface with the header enhances this effect. Attention has been also paid to the following feature related to the presence of soaking in the brazing temperature conditions, both during heating and cooling stages.

Figure 4. Guide vanes of the turbo-pump unit pump:
1 - housing (header); 2 - inner wall;
3 - housing (header nozzle)

Such soaking is provided to equalize the temperature between the brazed parts that have different weight. However, the soaking assumes a relative jump from the heating rate set by the brazing method to zero rate (constant temperature). In this case, the structural element with smaller weight is heated faster before the soaking, and during soaking its temperature will be approaching the temperature of the element with greater weight and, thus, a steplike temperature excess of the element with a smaller weight over the element with a larger weight takes place.

Additional thermocouples in addition to the standard ones were installed on several assembly units to identify the temperature difference in the structural elements. With the help of these thermocouples it was really possible to register the presence of the steplike temperature difference between the nozzle and the header within the soaking temperature ranges . Subsequent strength calculations have demonstrated the presence of tensile stresses [4].

In accordance with the calculation results it has been decided to exclude soaking from the brazing cycle during heating and cooling in order to reduce stresses, having left the same brazing time that led to a significant decrease of both heating and cooling rates. In the result of the measures taken, the crack formation in the guide vanes was no longer observed.

4.3. Solution to the problem of dry joints in the booster pump unit rotor

The decrease of the heating rate was also required for another liquid rocket engine structural element - the booster pump unit rotor, upon brazing of the rotor shroud blades (Figure 5), however, for a different reason. This was due to a specific feature determining the main difficulties of selecting the rotor brazing conditions that consist in the fact that the material of the both braced parts is (steel of a transitional class with structural transformations upon its temperature variation defining a significantly nonmonotonic dependence of the linear thermal expansion coefficient from temperature.

Following the standard rise with the temperature increase to 600^{o}C, it then drops sharply to a minimum at 700 ^{o} C, then the rise repeats with the subsequent temperature increase.

Thus, as the temperature increases, the part increases in size, then decreases, then increases again that may be interpreted as the distortion "hole".

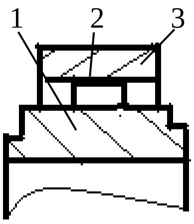

Figure 5. Booster pump unit rotor: 1 - rotor with blades; 2 - braze; 3 - shroud

This results in the fact that in case of the difference of the brazed rotor parts temperature and mismatch of the distortion "holes" there is a danger of their counter thermal deformation that may lead to the shroud plastic deformation with subsequent unacceptable increase of the brazed clearance upon the brazed parts temperature equalizing at the brazing temperature.

To obtain high-quality brazing of parts made of such material, it is required to provide the temperature difference between them not exceeding a certain maximum permissible value that may only be selected by test.

Based on the shroud - rotor thermal interaction analysis results [5], a conclusion has been made that following requirements have to be unconditionally followed. Firstly: slow rate of the rotor initial heating ensuring the lowest possible temperature difference between the shroud and rotor. Secondly: introduction of soaking for equalizing the brazed parts temperature before they enter the "hole" by the coefficient α, as the factors ensuring the shroud plastic deformation absence.

The appropriateness of the above described thermophysical scenario of the shroud - rotor interaction has been confirmed by subsequent successful and sound rotor brazing.

5. Conclusions

The following conclusions may be made as the result:

1. Homogenizing annealing of the engine gimbal flange made after brazing with Mn-base braze under the conditions of various medium vacuum values enables significant increase of the strength of the brazed joint produced without homogenizing annealing.
2. The conducted analytical and experimental studies on the temperature distribution in the structural elements during brazing allowed to exclude the excessive thermal stresses in the guide vanes of the turbo-pump unit pump, thus avoiding crack formation in it during brazing that was achieved by means of the slow heating and cooling, as well as excluding soaking in the course of brazing.
3. Based on the thermophysical design analysis, the booster pumping unit rotor brazing conditions have been defined as follows: decrease of the heating rate and introduction of soaking that allowed to ensure defect-free rotor brazing.

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