Mechanisms of Fatigue Crack Initiation and Propagation in Hydropumps NP-89D of Aircraft Tu-154M of Cast Aluminum Alloy AL5.

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Keywords: Hydro pump, Cast aluminum alloy, Casting porosities, Fatigue cracks, Fractography, Fracture mechanisms, Meso-beach marks, Stress amplitude.

Abstract. The paper demonstrates results of quantitative fractographic analyses of in-service fatigued hydropumps NP-89D of cast AL5 Al-based alloy. The model that better describes microcracks threshold taken place from cast porosities is based on Vickers hardness of metal matrix and the $\sqrt{area}$ of defects (the «$\sqrt{area}$ model»). Crack growth period estimated by the result of meso-beach marks spacing measurements and stress equivalent calculated by the «$\sqrt{area}$ model» used to discuss causes of the in-service cracking of the pump casing. Shown that damping of self-oscillations with simultaneous decrease in an equivalent stress level of the hydrounit will allow increase operating time up to pump probable failure to more than 10^{10} individual cycles. It will lead to increase in the period of operation of casings without their fatigue cracking more than on two orders.

Introduction

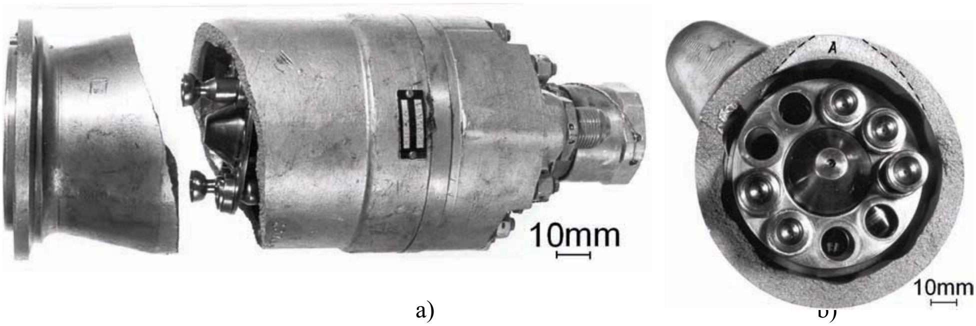
In service of aircrafts Tu-154M took place fatigue failures of the hydropumps NP-89D manufactured from the cast aluminum alloys AL5 [1]. This alloy has manufacturing procedure for aircraft components with low level of material stress-state, which permitted creation in their volumes of casting porosities.

Pump failures have discovered because of two reasons: internal destructions of pumps structural elements and fatigue cracking of their casings. A number of the constructive reasons were eliminated because of the new pump internal design that has allowed raising his reliability and durability in-service operation [2].

Failure of casings of hydropump NP-89D occurred only on engines of the first power plant (PP №1) and only by planes of a type Tu - 154M. Cracks passed through the section of the casing, shown on Fig. 1. Originally, attempt of the constructive decision of a problem and exception of in-operation casing failures for the account their amplification has been undertaken.

The accepted decision on necessity of replacement in operation of old pumps on amplified has not brought any results in general for the following reasons. In the bulletin entered into operation, replacement of all four pumps of an old design by necessities of carrying out of expenses new without a technical substantiation by this replacement was offered. Such position has left a problem not decided as cracking of hydrounits were rare and occurred only on «PP №1», and consequences of refusals were successfully parried by crews of planes without serious economic expenses.

Therefore, on engines «PP №1» airplanes Tu - 154M hydropumps with not the amplified casing that led to display in operation of refusals of hydro systems in the flight, similar to the event described above continued to be maintained. Moreover, acting in operation after repair of the airplane, amplified units also have started to collapse because of cracking from an internal surface, as well as not amplified casings.



a) b)

Fig. 1. Overview (a) of the fatigued hydropump NP-89D after in-service time 384 hours, as it followed from the documents, and (b) overview of the fracture surface. The fatigue fracture area shown dashed line and identified by “A”.

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All this has demanded the careful analysis and a substantiation of the reasons of fatigue cracking of hydropump NP-89D because of casing failures after their new design.

Investigation procedure

The analysis was carried out in two directions. One group of pumps with a different operating time have selected for investigation regularities of fatigue cracks origination and propagation, Table 1. Several hydropumps subjected to fatigue tests on the hydraulic test-bench with imitation of various cyclic loading, reproducing in-service operation conditions of «PP №1» of the airplane Tu - 154M.

№	The pump number	Date of issue	Operating time, [Hours] / [Flights]	Type of the airplane	Type of «PP»	N_p, [cycle]
1	H009H112	14.09.2000	6013	Tu - 154M	№1	-
2	Н205Б97	18.06.02	717	- «-	- «-	100
3	Н202Б58	27.02.02	587	- «-	- «-	100
4	Н204Б74	11.02.02	1584	- «-	- «-	100
5	H301E7	15.01.93	2730	- «-	- «-	230
6	НП89-172	-	380/170	Tu - 154Б-2	№2	> 200

Table 1. Numbers of investigated hydropumps, their operating time on different types of airplanes and cracks growth period, N_p, from casting defects, reproduced from the fracture surface analyses.

In all cases studied, the material composition of AL5 aluminum based alloy was the same that recommended for the manufactured procedure: Si%; Fe%; Al remainder. The mechanical properties were – Ultimate tensile 340 MPa, 0.2% Offset strength 270 MPa.

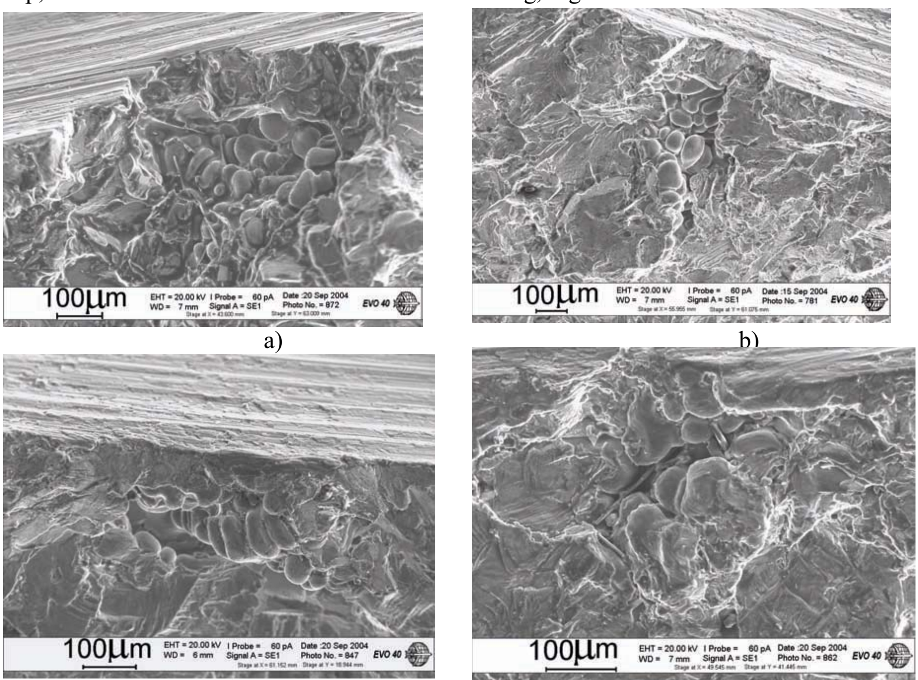
All areas with the fatigued material were cut from the hydropumps and fracture surfaces were opened for fractographic analyses. The fracture surface analysis was performed on the scanning electron microscope CDS-40 with resolution not less than 3nm.

The pumps tests have shown that at a combination of parameters of adjustment for the in-service pump and his modes of cyclic loading within the limits of existing norms there can be seen rare cases of hydroliquid pressure self-oscillations with high amplitude of 88 kg/cm2 of bi-modal type of vibrations. The main cyclic loading can takes place with frequency of 50Hz, and vibrations with frequency 450Hz covering of the main cyclic loading. This result gave possibility to introduce the hypothesis about the cause of hydropumps fatigue cracking.

Presence of the bi-modal self-oscillations of hydroliquid pressure, in-service rare cases, separate units by the cyclic loading intensiveness and lead to that only some of them at operation in particular on «PP №1» of the airplane Tu - 154M subjected to such high-frequency cyclic loading and initiated their in-service fatigue cracking.

Results of investigation

Model of fatigue cracks origination and growth. Performed fractographic analyses of all fracture surfaces have shown that origin of fatigue cracks occurs from several casting defects such as ensemble of porosities, which are located on the short distance from an internal surface of a pump, or is direct about an internal surface of the casing, Fig. 2.



a) b) c) d)

Fig. 2. Cast porosities (a) - (d) placed at the different areas along the circumference of the internal surface of the pump casing. Areas (a), (b) with porosities disposition exactly at the surface, but areas (c), (d) with porosities placed subsurface, but near the internal surface.

Similar casting defects of a material are located on an internal surface of a pump near and far from a fracture surface. That is why, there was seen multi origination of fatigue cracks from defects in pumps during permitted in-service operation time for the first power plant (engine) only is placed on aircrafts Tu-154M.

Fracture surface analyses have shown that it is characterized striated features with pseudo-striations, which intersected meso-beach-marks (MBMs), Fig. 3. The revealed morphology of the fracture surface specifies development of pumps fatigue cracking under vibrations in the field of high-cycle-fatigue (HCF). In the direction of the fatigue crack growth from an internal surface «MBMs» have different intensity of their expression on different distance from the origin and tend small increase in spacing, Fig. 4. It specifies that difference between cyclic loads levels, which realize on a transitive regime of in-service operation from flight to flight, is not significant when there is «MBM» formation [1]. The revealed regularities of fatigue cracks origination and propagation in the direction through the casing wall have allowed calculate number of flight-cycles for crack growth period. In considered cases, duration of pumps operation during fatigue cracks propagation in hours has made 587, 717, 1584, 6013 and 2730 (See Table 1.).

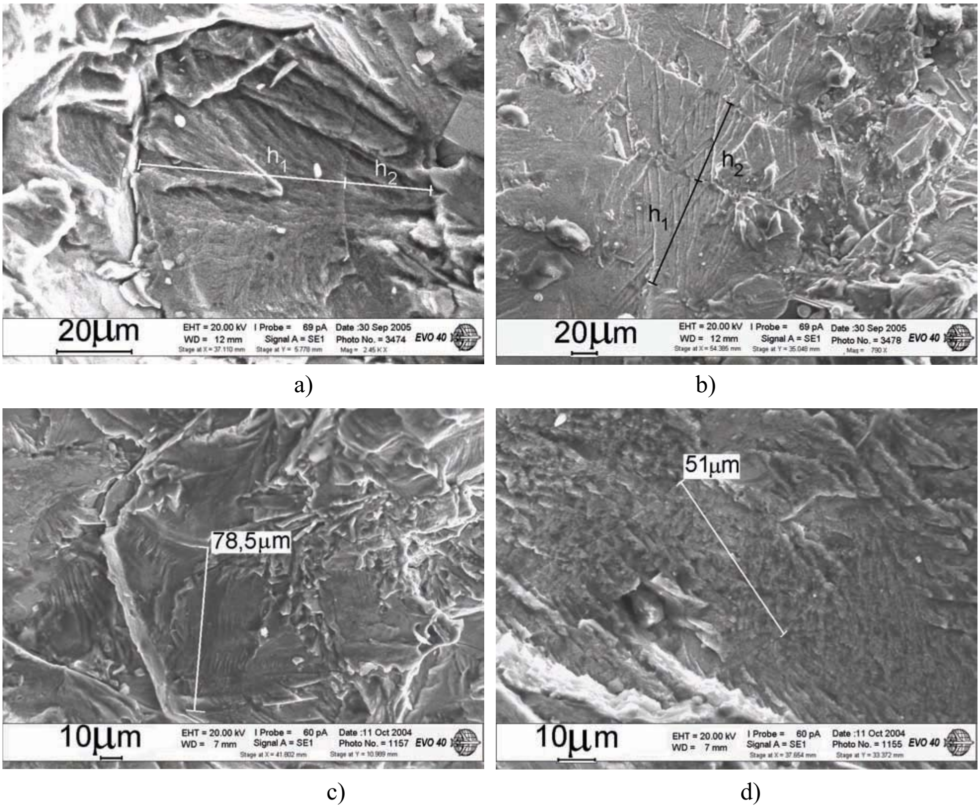


Fig. 3. Meso-beach marks with pseudo-striated pattern (a) - (d) discovered on the different distance from origins. Meso-beach marks spacing marked by, h_i, or spacing values indicated for the crack length at the distance near 8 mm.

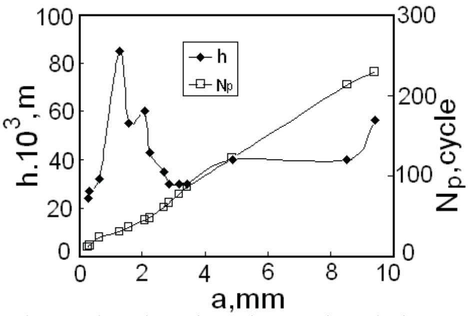


Fig. 4. Meso-beach marks spacing, *h*, and crack growth period, N_p, in versus crack length «a» in the direction from internal to external surface of the hydropump.

The minimal growth rate of a fatigue crack makes about 10^{-6} mm/cycle, as it follows from specimens test data of aluminum alloys in the regime of HCF [1]. The maximal in-flight increment of a fatigue crack, according to the lead measurements of a «MBMs» spacing (See Fig. 3), has made about 50μm = 5.10^{-2} mm. In result we can calculate number of cycles that have been spent during one flight for the fatigue crack propagation - $5.10\text{-}2/10^{-6}$ = 50000 cycles.

At the in-tests revealed frequency of cyclic loading 450 Hz, duration of acting of individual cyclic loads for casings in one flight makes 1.8min that correlated with near to 50000 cycles. At the same time, average duration of flight for all aircrafts of the type Tu - 154M is near to 2 hours. During this time, number of cycles for the frequency of 450Hz could be near to $7200\text{x}450=3.2\text{x}10^6$. From this consideration follows that the crack propagation under the cyclic loads with the high amplitude can takes in-service place only during transition regime of operation when self-oscillation of hydrofluid realizes.

Let be calculated number of cycles for operating time of 587, 717, 1584, 6013 and 2730 flights during fatigue crack propagation. The average value 2 hours takes place for one flight. Consequently, the following number of cycles has to be realized at the frequency 450 Hz - $0.57.10^6$, $0.71.10^6$, $1.58.10^6$, $6.12.10^6$, and $2.75.10^6$ cycles. For frequency of 50 Hz, the number of cycles will be on the order less for each pump.

Let us assume that at frequency 450 or 50 Hz continuous crack propagation occurs during one flight, all 2 hours, through all section of the casing, on thickness of his wall of 10mm. Then for 2 hours or 7200 seconds there should be average crack growth speed $10/7200=1.4.10^{-4}$ mm/s. Growth rate of a crack in cycles at the specified frequencies, as followed from the pump tests, will make $1.4.10\text{-}4/(450\text{-}50) = (0.3\text{-}2.8).10^{-5}$ mm /cycle. The revealed morphology of the fracture surface relief reflects development of a crack at speed more less than 10^{-5} mm/cycle. Consequently, the crack growth for one flight does not perform through all casing wall. It should be realized several flights after the crack origination from the internal surface of the casing.

At the average value of the crack growth rate 10^{-5} mm/cycle, materials fracture realizes in the HCF regime. In this case, the crack growth period N_p relates to the material durability N_f in the proportion of 1 % < N_p / N_f <10 % [1]. Supposing, that with frequency of 50 Hz carries out cyclic loading of casings for all flights of airplanes, we receive, that for the shortest period of in-service operation of 578 hours number of cycles will be about 108. It corresponds to the very-high-cycle-fatigue (VHCF) regime with parity N_p / N_f near to 0.26 % [3]. At frequency of 450 Hz, the number of cycles (not flights) up to the casing failure will be on the order more. However, it contradicts the fact that cracks in all casings originate from significant on size casting defects. In this case, aluminum alloys fracture attributes to the HCF regime when the crack growth period has the essentially greater contribution to durability than estimated value $N_p / N_f = 0.26$ or less.

Stress equivalent calculations. The performed above estimations of the fatigue crack growth period under cyclic loads with high frequency of 50 or 450 Hz show that casings failure in this realized situations could be take place in the VHCF regime for which the cyclic stress level in the casings wall should not exceed 60 MPa for the Al-based alloy [3]. The discussed critical value of the cyclic stress level have been discovered for tested specimens under bending and tension but under internal pressure the critical stress value will be less because this situation correlates with biaxial material tension. The stress equivalent value is less for material biaxial tension with the second tension stress component in accordance with the uniaxial tension or bending.

Different relations were introduced to estimate material strength and stress intensity factor of K_{th}. The model that better describes microcracks threshold for steel and cast irons is the one discussed by Murakami and Endo [4]. The model is based on Vickers hardness of metal matrix, «HV», and the «$\sqrt{area}$» of defects (the «$\sqrt{area}$ - model»). Investigations of AlSi7Mg cast alloy have shown that the hardness cannot be considered a significant parameter for Al alloy castings [5].

However, calculation of a stress level in a zone of origin of fatigue cracks from casting defects of a material has been lead under known formula [4]:

$$\sigma_{wm} = (1.41[HV + 120]) / ([area]^{1/2})^{1/6} . \qquad (1)$$

To calculate stress level by the Eq. (1), the area of the concentrator "area" = "A" (μm^2) and hardness of a material «HV» (kg/mm^2) have been measured. The area sizes distribution of the zones of casting defects for all investigated casings and calculated stress levels presented Table 2 and Fig.5. Three values of the area were taken: minimal (min), maximal (max), and average (mean). In addition, three values of material hardness were used: 71, 81 and 95, which also revealed as the minimal, average and maximal values in investigated cases.

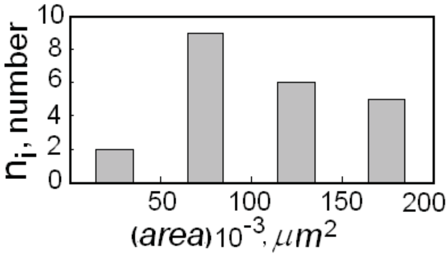


Fig. 5. Histogram of number, n_i, zones with material cast defects of indicated and measured «$area$», discovered in origins of fatigue fracture surfaces of investigated hydropumps after different in-service operation times.

Evidently that the crack initiation in pump casings took place under equivalent stress level in the range of 97-127MPa. The received results correspond to the observed fracture surface patterns and test results of casings in which their stress intensity was equivalent to in-service failed pumps in the HCF regime.

Hence, fatigue cracks initiation in casings in all cases occurred in the HCF regime from casting defects at short-term of in-flight acting vibrations with modulated fluctuations to frequency of 450 Hz. In this situation, at low growth rate of a crack its development occurs during sufficient time (or more than 100 flights, See Table 1) for introduction of the effective non-destructive of in-service inspection.

The «area», [μm^2]		HV	σ_{wm}, [MPa]
Min	35000	71	113
		81	119
		95	127
Mean (average)	103000	71	103
		81	108
		95	116
Max	209000	71	97
		81	102
		95	109

Table 2. Parameters of casting defects, values of material hardness «*HV*» by Vickers, and level of stresses in cases of units, σ_{wm}, received because of calculations by the formula (1)

Discussion

Maintenance of safe operation of vessels under internal pressure with introduced in material casting defects is connected to a substantiation of the fact, that only by planes Tu - 154M display fatigue cracks development in pumps up to the critical depth through the wall at their existing resource. Stress level estimations have shown that the casing wall subjected to high stress-state that determined cause of the in-service material cracking. The role of casting defects of a material in crack origination is essential. They influenced material stress-state in area of crack origination but dominant role in earlier fractures of pump casings especially on the "PP №1" of the plane Tu - 154Б-2 plays the high level of material stress-state in the casing wall.

While in-service, there was one case of the casing fatigue cracking of the pump NP89-172 on "PP №1" of the plane Tu - 154Б-2 (See item 6 of Table 1). It especially was necessary, to estimate the possibility of in-service safety operation of "PP №1" when fatigue cracking is probable. That is why, the fractographic analysis has performed for the reason on which individual event with in-service fatigue cracking of pump NP89-172 has taken place by the plane Tu - 154Б-2.

Fracture surface analyses of the pump have shown that the surface features of origins and areas in the direction of the fatigue crack growth are similar to that revealed earlier in investigated pumps operated on planes of a series Tu - 154. There were several origins of fatigue cracking have taken place at the internal surface. The length of a fatigue crack along an internal surface has made 65 mm (See Fig. 1). The final fast fracture of the casting taken place after the crack propagation through a wall at its length of 18 mm by the external surface.

Fracture surface analyses on the scanning electron microscope have shown that the «MBMs» spacing increases in the direction of the crack development along a small axis of a semi-elliptical crack front. There was «MBMs» spacing about 5 microns at the fracture origin, and at the opposite (external) party of a wall - about 9 microns. This implies that essential increase of «MBMs» spacing on depth of a crack did not occur. The law of crack growth in a wall of the pump distinguished from earlier investigated pumps where «MBM» spacing reached 40 microns on the maximum depth of a crack.

Operating time of the hydropump, it agrees to the data of the passport, has made only 384 hours that corresponds on average duration of flight of the plane Tu - 154Б-2 to 170 flights since it was new (item 6 of Table 2). If to take the maximal «MBMs» spacing of 9 microns at external wall of the pump, the crack increment will make near to 1.53 mm for 170 flights. It specifies that, at the moment of registrations operation time in "passport" of this hydropump as on a product of the first category, there already was available a crack depth not less than 8.47мм in a casing wall with thickness of 10 mm. However, the state of the casing with fatigue crack cannot be realized during manufacturing procedure. That is why fracture (propagation of a crack on approximately all section of the unit) in the considered case has taken place for the first time during operation time in the plane Tu - 154Б-2. The pump has been put aboard the plane Tu -154Б-2 with fatigue crack already available in it, which «has been brought up», while in service the unit by the other plane. It was wrong information about operation time of hydropump because of "false" passports.

Therefore, revealed destructions should be attributed, as it has been specified earlier [1], to a high tension of units at their high-frequency cyclic loading when insignificant increase of stress concentration on a surface of the unit occurs to an output of casting defects to fast origination of fatigue cracks. Damping of self-oscillations with simultaneous decrease in an equivalent stress level of the hydrounit will allow increase operating time up to pump failure to more than 1010 individual cycles. It will lead to increase in the period of operation of casings without their fatigue cracking more than on two orders.

Summary

Even occurrence of resonant fluctuations under external cyclic loads influence is accompanied by long (for some number of flights) development of fatigue cracks from defects in fatigued in service hydropumps. Therefore, in pumps casings, at the correct periodic in-service inspection, revealing fatigue cracks before their full cracking on all thickness of a casings wall is possible. Such non-destructive testing of casings introduced for civil aircrafts to increase reliability of in-service operated hydro systems. It was recommended to introduce periodical non-destructive tests at further use of pumps for engines of «PP №1» planes Tu - 154M on other engines and other planes. The number of flights for the recommended inspection interval was determined by the described above quantitative fractographic analysis.

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