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AN INTEGRITY ANALYSIS OF WASHING-MACHINE HOLDERS

ANALIZA CELOVITOSTI NOSILCA KADI V PRALNEM STROJU

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This paper deals with a structure-integrity analysis of a holder designed to carry the cross of a washing machine. Premature fracture of the holder occurred during mechanical tests of the washing machine in the factory. In order to prevent fracture, the task was to determine the causes of the premature fracture of the holder and estimate the suitability of a new design of holder cross in the washing machine. The input data for the structure-integrity analysis were obtained from mechanical testing of the materials used. A stress-and-strain analysis of the holder's limit load was performed using finite-element modelling of the holder. Dynamic tests of holders with two different thicknesses were made on a servo-hydraulic machine in order to find dynamically the strength and endurance of the holder. The fracture behaviour of the holders is defined by the initiation and propagation of a crack. The determined behaviour confirmed that a new design of holders (with thickness t = 2.5 mm instead of t = 1.5 mm) reduces the stress concentration in the critical region. Consequently, the new holder, subjected to the same dynamic load, can last for more cycles until it breaks. The total number of cycles exceeded the requirements set for industrial testing.

Key words: structure-integrity assessment, fracture-toughness testing, high-cycle fatigue, washing-machine holder

V članku je predstavljena analiza celovitosti križnega nosilca kadi pralnega stroja. Predčasna porušitev nosilca je nastopila med mehanskim preizkušanjem pralnega stroja v podjetju. Z namenom, da se prepreči predčasna porušitev nosilca, so bili raziskani vzroki za porušitev in ocenjena je bila primernost nove zasnove nosilca križa kadi pralnega stroja. Vhodni podatki za oceno celovitosti so bili dobljeni na osnovi mehanskih preizkusov materialov. Napetostna in deformacijska analiza nosilca pri mejnem stanju obremenitve je bila opravljena z numeričnim modeliranjem in izračunom po metodi končnih elementov. Dinamični preizkusi dveh nosilcev z različnima debelinama ob enakem vpetju, kot je to v pralnem stroju, so bili opravljeni na servohidravličnem preizkuševalnem stroju. Na osnovi opravljenih preizkusov je bila določena dinamična trdnost in vzdržljivost nosilcev. Lomno vedenje nosilcev je bilo ocenjeno glede na lomno žilavost materiala med utrujenostno rastjo razpoke kot tudi glede na iniciacijo končnega, nestabilnega loma nosilca. Dobljeni rezultati potrjujejo, da nova zasnova nosilca z debelino t = 2,5 mm namesto t = 1,5 mm ob posledično spremenjenem polmeru zakrivljenosti zmanjša koncentracijo napetosti v kritičnem delu. Tako je pokazano, da novi nosilec pod enako obratovalno obremenitvijo prestane večje število ciklov do končne porušitve, kot je predpisano za preizkuse pri preverjanju kontrole kakovosti v podjetju.

Ključne besede: ocena celovitosti konstrukcij, preizkušanje lomne žilavosti, visokociklično utrujanje, nosilec kadi pralnega stroja

1 INTRODUCTION

Holders for carrying the cross of a washing machine's drum are dynamically loaded components, see **Figure 1**. The premature fracture of the holder can cause severe damage to other mechanical and electrical parts in the housing of the washing machine. Therefore, the integrity of the holder is essential for the safe and reliable service of the whole washing machine.

The mechanical testing of a washing machine with an eccentric load was performed in the factory. The results showed that the number of cycles without fracture or crack formation is insufficient for the quality-control requirements. A failure analysis and inspection of the fractured parts showed that the initial fracture occurred in the central holders of the cross, while the fracture of the outer holders occurred at the end, when the inner holder was already broken, see **Figure 2**. Therefore, the aim of this study was to carry out a stress-strain analysis and a structure-integrity analysis of the inner holders of a washing machine's drum.

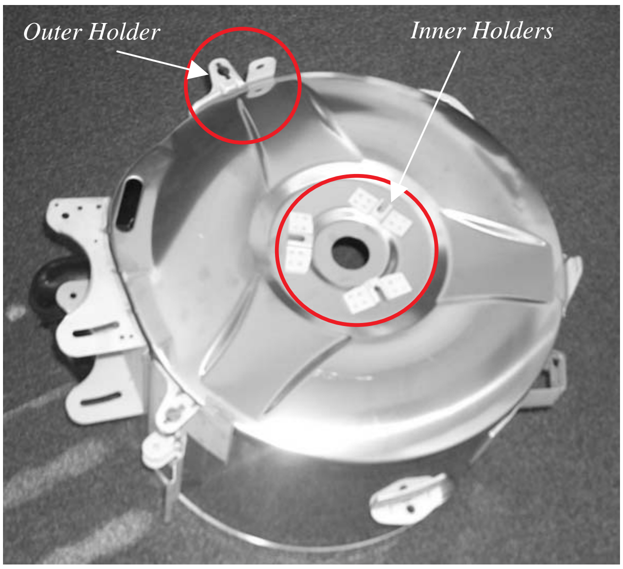

Figure 1: Holder cross welded on the drum of a washing machine
Slika 1: Križni nosilec kadi bobna pralnega stroja

Figure 2: Broken outer holder without fatigue-crack propagation
Slika 2: Zlomljeni zunanji nosilci brez vidne utrujenostne rasti razpoke

2 MECHANICAL PROPERTIES

The mechanical testing was performed on a steel sheet of the same material and the same thickness as used for the inner holders of the cross of the washing-machine drum. The nominal parent metal is DC03. The tensile mechanical properties were measured on flat tensile specimens with geometries according to the DIN10125 standard. The obtained mechanical properties are shown in **Table 1**.

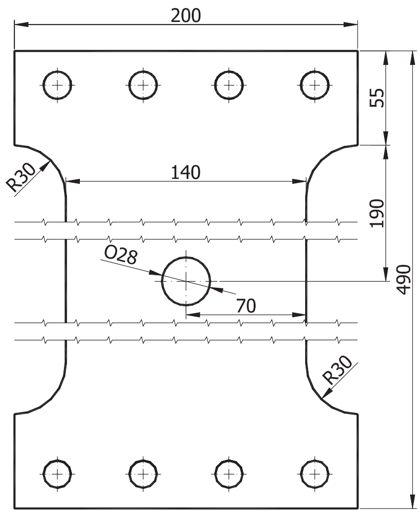

Figure 3: Middle-cracked tensile specimen (t = 2.5 mm)
Slika 3: Plošča s sredinsko razpoko ob izvrtini za natezni preizkus (t = 2,5 mm)

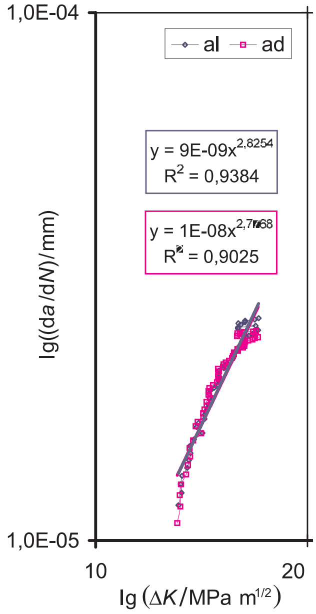

Figure 4: Results of fatigue-crack growth rate for left- and right-side measurements (specimens with t = 2.5mm)
Slika 4: Rezultati hitrosti utrujenostne rasti razpoke za meritev na levi in desni strani izvrtine v preizkušani plošči z debelino t = 2,5 mm

Fatigue-crack growth and fracture-mechanics testing were performed on a middle-cracked tensile specimen, M(T) [1], with the geometry shown in **Figure 3**. The initial notch of 0.5 mm in the hole was made with a razor blade. The growth of the fatigue crack was followed on both sides of the central hole. The fatigue loading of the sheets (t = 2.5mm) was performed in load control with a ratio $R = F_{min}/F_{max} = 0.21$ and frequency 20 Hz, F_{max} = 25.4 kN. The Paris-Erdogan relationship [2] was used to describe the fatigue-crack growth law, as shown in **Figure 4**.

The fracture-toughness measurement [3] was performed on cracked specimens with measurements of crack-mouth opening displacement (CMOD) in the specimen's symmetry loading line, as shown in **Figure**

Table 1: Obtained tensile mechanical properties for the parent material (DC03)
Tabela 1: Dobljeni rezultati za mehanske lastnosti za osnovni material (po oznaki DC03)

	Thickness, t = 2.0 mm		Thickness, t = 2.5 mm		Standard prescription
	01	02	01	02	
$(R_{0,005}/R_{p0,2})$/MPa	152/203	184/217	135/188	123/188	$R_{p0.2\ max}$ = 240
R_m/MPa	300	306	284	286	270-370
E/MPa	201012	202516	188284	159913	210000

Table 2: Obtained fracture-toughness values for parent material (DC03)
Tabela 2: Dobljeni rezultati za lomno žilavost za osnovni material (DC03)

t/mm	W/mm	a/mm	$\sigma_{p0.2}$/MPa	σ_y/MPa	$K_{I,i}$/MPa m$^{1/2}$	F_i/kN	$CTOD_{pl,m}$/mm	$CTOD_m$/mm	$K_{I,mat}$/MPa m$^{1/2}$
2.0	140	34.1	210	180	11.23	18.5	0.595	0.599	145.61
2.5	140	34.6	188	130	17.918	33.6	0.995	1.004	205.86

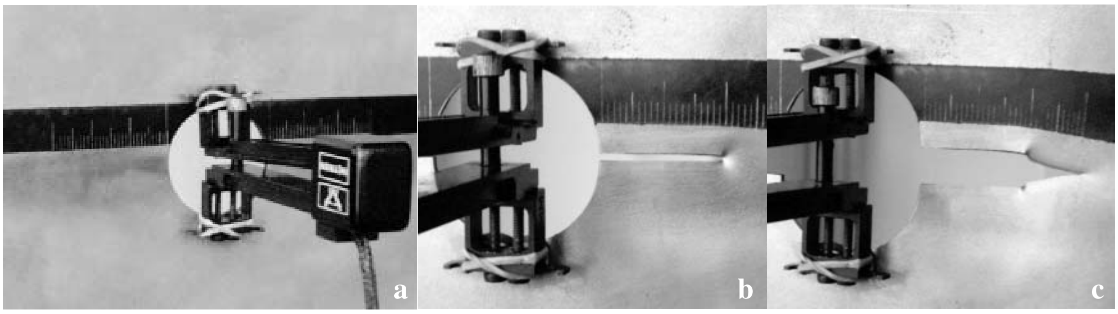

Figure 5: Measurement of CMOD values for middle-cracked tensile specimen (t = 2.5 mm); a) start of test b) stable crack initiation c) end of test
Slika 5: Meritev odpiranja ustja razpoke (ang. CMOD) med nateznim obremenjevanjem plošče s sredinsko razpoko (t = 2,5 mm); a) začetek preizkusa, b) začetek stabilne rasti, razpoke c) konec preizkusa

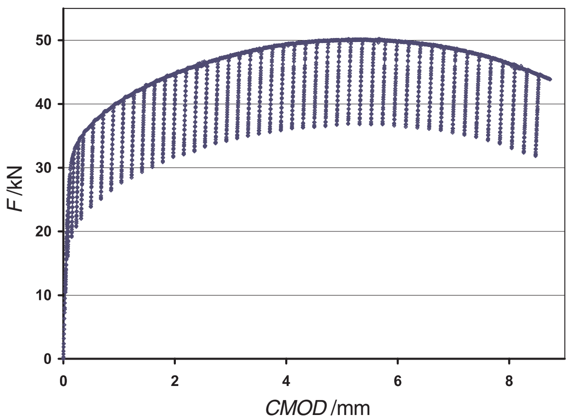

Figure 6: Measured data load vs. CMOD (t = 2.5 mm)
Slika 6: Izmerjeni podatki v odvisnosti obremenitve in odpranja ustja razpoke (t = 2,5 mm)

5. During the test compliance the unloading method was used to observe stable crack-growth extension. The recorded data are plotted in **Figure 6**. The results of the fracture mechanics testing are listed in **Table 2**.

3 TENSILE AND FATIGUE TEST

Tensile and fatigue tests were performed on the same holder (thickness and geometry) as was tested in the factory. The holder was welded with eight spot welds, as with the washing drum, but in the laboratory case this was on a pad for testing, as shown in **Figure 7**. The holder was tested statically with tensile pulling until fracture, as shown in **Figure 8**. A graph of load vs. stroke was recorded, as shown in **Figure 9**.

The fatigue pull testing of both holders (with t = 1.5 mm and t = 2.5 mm) was performed with the same

Figure 7: Holder welded by spots on pad for testing
Slika 7: Nosilec, zavarjen s točkovnimi zvari na podlago za preizkušanje

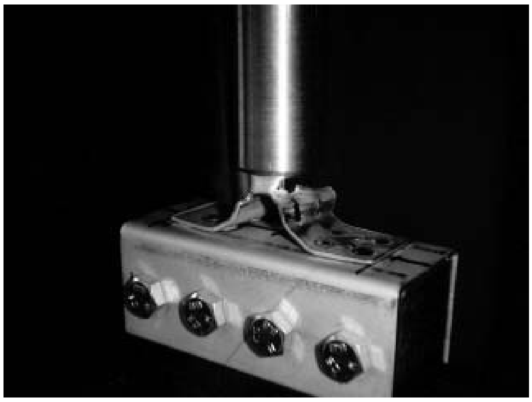

Figure 8: Static pulling test of holder
Slika 8: Statični trgalni preizkus nosilca, ki je zavarjen na podlago za preizkušanje

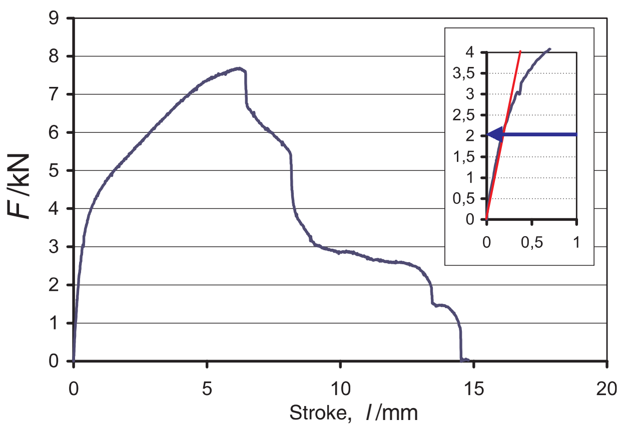

Figure 9: Load vs. stroke during static pulling test of holder
Slika 9: Obremenitev v odvisnosti od pomika, ki je posneta med statičnim trgalnim preizkusom nosilca

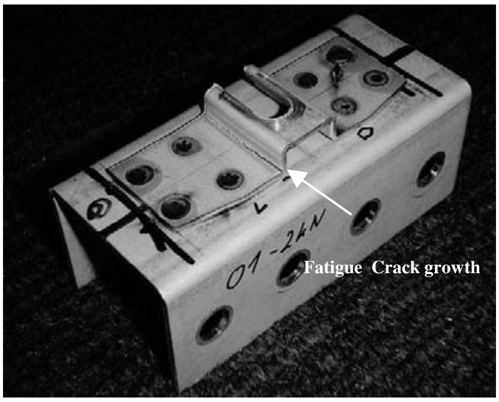

Figure 10: Fatigue crack at root region of holder (t = 1.5 mm)
Slika 10: Med dinamičnim utrujenostnim obremenjevanjem nosilca se je pojavila razpoka v kritičnem upognjenem delu nosilca (t = 1,5 mm)

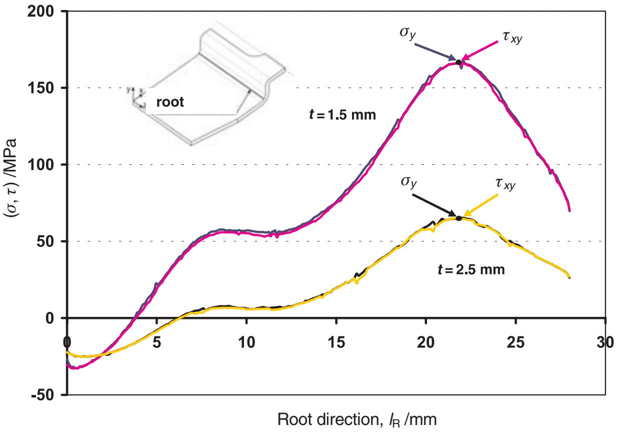

Figure 11: Maximum tensile and shear stress along the uncracked root of the holder calculated using the FEM
Slika 11: Porazdelitev osnih in strižnih napetosti vzdolž kritičnega upognjenega dela nosilca

equipment. Since the fatigue-behaviour analysis was performed only to compare two holders (different in thickness and root radius), the same fatigue load was chosen (F_{max} = 2 kN, R = –1). The fatigue crack appeared in the holder (t = 1.5 mm) in the expected region, like during the washing-machine test. The fatigue crack did not appear in the holder (t = 2.5 mm) after 1 million load cycles. As a result, a higher maximum fatigue load (F_{max} = 3.5 kN) was used and the fatigue crack appeared in same region, as shown in **Figure 10**.

The fatigue-crack growth sensitivity was estimated for both holders by using fatigue-crack growth rate testing results, e.g., from **Figure 4** for t = 2.5 mm.

The range of the fatigue stress-intensity factor was determined using

$$\Delta K_{max} = K_{max} - K_{min} \quad (1)$$

since the loading ratio corresponds to the range of the fatigue stress-intensity factor is

$$\Delta K_{max} = 2K_{max} \quad (2)$$

A finite-element calculation shows that in the root region of the holder both tension stress and shear stress appear. The relevant maximum stress-intensity factor is

$$K_{max} = \sqrt{K_I^2 + K_{II}^2} \quad (3)$$

where K_I and K_{II} are determined using equations [6]:

$$K_I = \sigma\sqrt{\pi a} \quad (4)$$

where σ is the maximum tensile stress determined by FE analysis, a is the initial crack length in the holder (e.g., a = 1 mm).

$$K_{II} = (4.886\xi - 11.383\xi^2 + 28.198\xi^3 - 38.563\xi^4 + 20.555\xi^5)(\tau\sqrt{\pi a}) \quad (5)$$

τ is the maximum shear stress in the crack plane; it is also determined by FE analysis and ξ is the ratio between the crack length and the thickness.

Calculated values (**Table 3**) show that for the same tensile loading of the screw at the holder the SIFs are more than three times lower for the holder with thickness t = 2.5mm than for the holder with t = 1.5 mm.

4 NUMERICAL MODELLING

The numerical modelling and the calculation using the finite-element method was carried out for the inner holder. In order to determine the stress-strain profile along the crack propagation line in the holder a numerical analysis was performed, **Figure 12**. The stress-strain analysis in the direction perpendicular to the fatigue crack front was performed using Pro/Mechanica software (a module of the Pro/Engineer software). An additional contact surface on the 3D solid model was defined under the head's screw. The boundary conditions and the finite-element mesh with tetra-elements [5] is shown in **Figure 13**. The stress fields (von Mises) for the same applied pressure on the contact surface are shown in **Figure 14**. It is clear that the stress profile and the stress peak depend on the radius of the holder. The stress distribution along the fatigue-crack propagation line is shown in **Figure 15**, where the most critical value is

Table 3: Stress-intensity factor values for the holder
Tabela 3: Vrednosti faktorja intezivnosti napetosti v kritičnem upognjenem delu nosilca

Material data	Load	Stress intensity factors at holder						
t/mm	$K_{Im\ at}$/MPa m$^{1/2}$	ΔK_{crit}/MPa m$^{1/2}$	σ_y/MPa	τ/MPa	a/mm	K_I/MPa m$^{1/2}$	K_{II}/MPa m$^{1/2}$	ΔK_{max}/MPa m$^{1/2}$
1.5	145.61	291.22	165	165	1.0	9.24	15.19	35.56
2.5	205.86	411.72	65	65	1.0	3.64	4.23	11.16

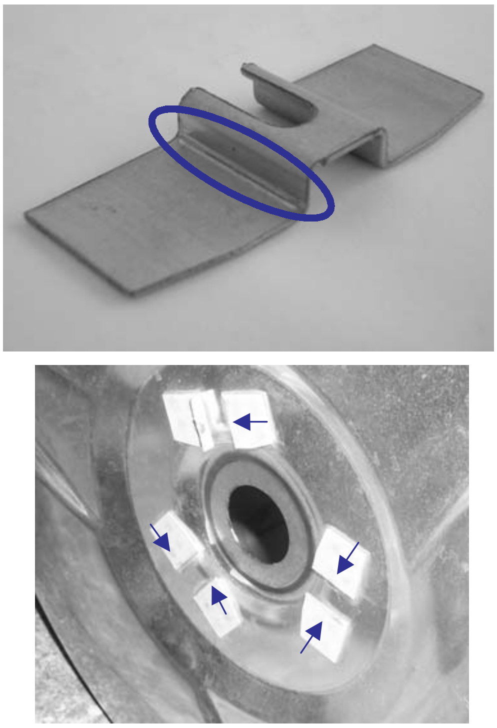

Figure 12: Critical path for fatigue-crack growth on the inner holder
Slika 12: Napredovanje utrujenostne razpoke vzdolž kritičnega dela nosilca

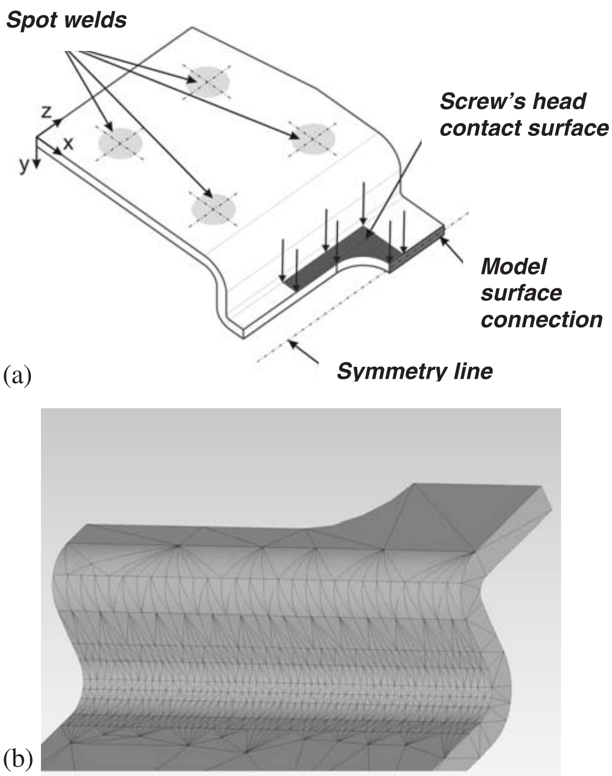

Figure 13: Boundary conditions and finite-element mesh with tetra-elements; a) boundary condition, loading and symmetry line; b) detail of mesh with tetra elements
Slika 13: Robni pogoji in umreženje nosilca za izračun po metodi končnih elementov; a) robni pogoji, obremenitev in simetrijska ravnina za numerični izračun, b) detajl mreže s tetraedrskimi elementi

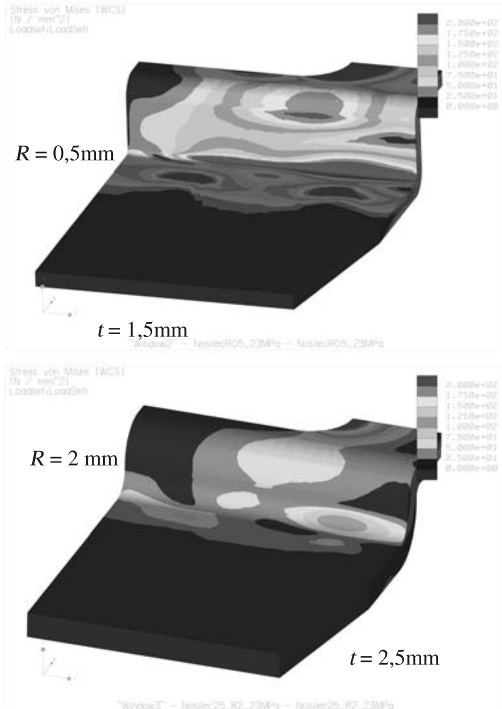

Figure 14: Calculated stress (von Mises) at the surface of the numerical model
Slika 14: Izračunane primerjalne napetosti (von Mises) na površini numeričnega modela

achieved for the model with thickness t = 1.5 mm and root radius R = 0.5 mm. It is obvious that the specimen with t = 2.5 mm and root radius R = 2 mm has the lowest stress values along the fatigue-crack growth path.

5 DETERMINATION OF THE FAILURE LOAD

Determining the fatigue load of the holder that appears in the washing machine during the test is difficult. It was only known that a fatigue crack appeared and the entire holder was broken when the critical

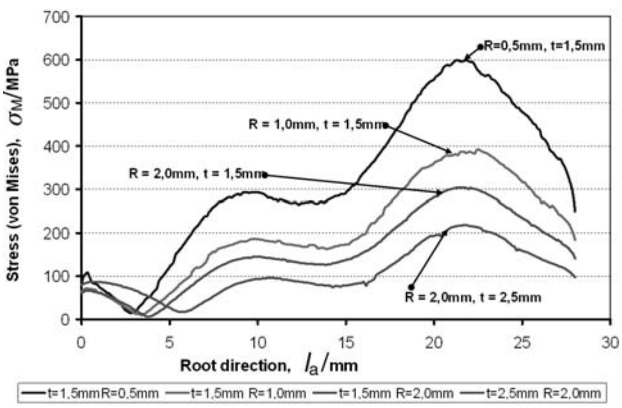

Figure 15: Distribution of stresses (von Mises) along the crack path in the root of the holder
Slika 15: Porazdelitev napetosti (von Mises) vzdolž upognjenega dela, v katerem je napredovala razpoka

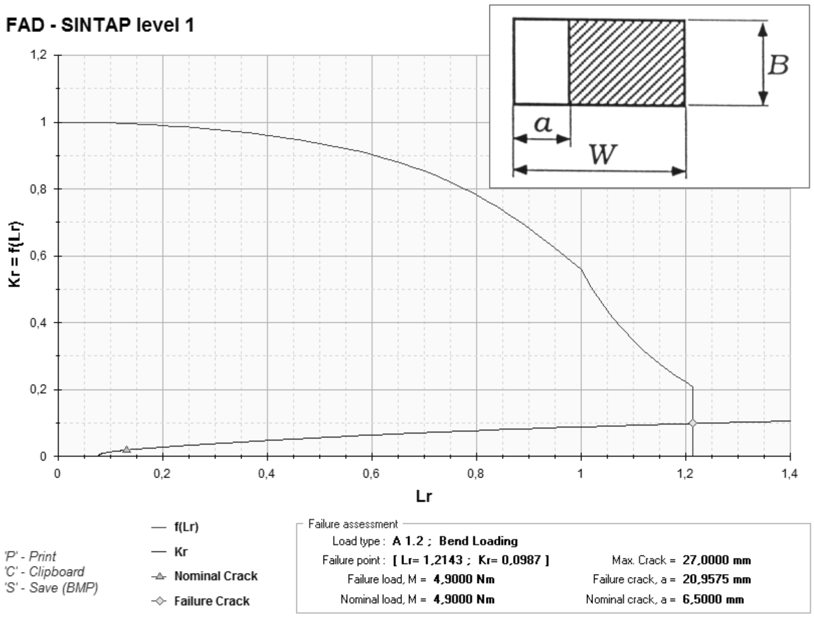

Figure 16: Determination of critical loading of washing machine's holder
Slika 16: Določitev kritične obremenitve križnega nosilca kadi pralnega stroja po postopku SINTAP

fatigue-crack length was achieved after a certain number of cycles. In this case the number of cycles contains an initiation stage and a fatigue-crack propagation stage. The longest critical crack length in the holder tested in the factory was measured in the fractured surface of the holder (a_{crit} = 20.9 mm).

The difference between the fatigue-crack surface and the final ductile failure was obvious. In order to determine the failure load the SINTAP procedure (level 1) was performed by using our own software [6,7]. The calculation shows that the final failure of a single holder appeared at the moment M_{crit} = 4.9 N m. The result is shown in **Figure 16**; it corresponds to a tensile load in the screw of 198 N. **Figure 16** shows that failure occurred with significant plasticity of the non-fractured ligament of the holder. This confirms the assumption that failure occurs under plane-stress conditions. The failure occurred at a low stress-intensity factor value (low loading ratio, K_r).

6 CONCLUSION

The inner holder of a washing machine is a critical part. This holder is subjected to dynamic loading with $R = -1$. The critical part of the holder is the root region, which is deformed with a different radius, depending on the thickness of the metal sheet. In the first prototype of the washing machine the holder had a thickness of t = 1.5 mm and a root radius of R = 0.5 mm. The premature fracture of the holder occurred in the factory. The replacement holder had a thickness t = 2.5 mm and a root radius R = 2 mm. In the paper the analyses of the stress concentration were performed in order to determine the fatigue durability of the holder. On the basis of the experimental results of the material testing, the fatigue and fracture mechanics parameters and also the finite-element analysis of the critical part of holder, it is possible to assess the SIF, and on the basis of the critical crack length in the holder the failure load that occurred in the holder during the washing-machine testing in the company.

However, the new holder subjected to the same dynamic load can survive a larger number of cycles until failure, where the total number of cycles exceeds the industrial testing requirements.

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