

Numerical–Experimental Study of the Combined Influence of Hole- and Dent-Type Stress Concentrators on the Mechanical Properties of Structurally Similar Samples

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Abstract—The mutual influence of stress concentrators in the form of a dent (made by a hemispherical indenter 25 mm in diameter to a depth of the sheet thickness) and a hole 4 mm in diameter in a thin 1.5- or 3.0-mm-thick skin on the static strength and fatigue life of structurally similar samples made of a 1163AT aluminum alloy is studied. The presence of a dent does not decrease the static strength, while the strength decreases by ~8% regardless of the location of a hole with respect to a dent for combined dent + hole stress concentrators. The position of a hole relative to the center of a dent weakly affects the slope of a fatigue curve, whereas the displacement of a hole from the center to the edge of the dent leads to a decrease in the fatigue life.

Keywords: strength, fatigue, damage, dent, dent + hole, aluminum alloy

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INTRODUCTION

During the service life of the aircraft (aircraft), various kinds of damage can appear in the fuselage, wing, and plumage because of the strikes of flying birds, stones raised by an air jet from the surface of runways, and tools. In addition, damage can appear as a result of a collision with ground equipment, for example, if it is not properly maintained. Such damage related to the damage strike energy is combined into a general group, namely, foreign object damage (FOD), since it causes one of the most common types of damage and is one of the main causes of fatigue failure or a decrease in the strength of fuselage skin panels made of aluminum alloys [1–6].

The problem of a high degree of FOD has been studied quite comprehensively, since damage associated with a high strike energy poses an increased danger to aircraft. Significant damage, namely, holes, cracks, and/or dents, form on the panels of the skin subjected to such strikes (e.g., by birds) [7–10].

At a low impact energy, the damage is not catastrophic, mainly has the form of dents without a significant change in the configuration of a structure, but can affect the static and fatigue characteristics of the skin and, hence, the operation of the aircraft. The influence of stress concentrators of this type has been studied to a lesser extent than FOD with a high strike energy. Note work [11], in which the influence of

dents of different depths on the static and fatigue properties of an alloy was studied on 1.0- and 1.5-mm-thick skin samples made of a 2024T3 alloy. Even multiple dents weakly affect the static properties (compression, shear) and slightly increase the bearing capacity. However, the authors of [11] do not make clear conclusions about the effect of dents on fatigue properties. A dangerous place of the nucleation of fatigue cracks is represented by the edges of a dent, where bending stresses are high. The authors of [12, 13] considered the influence of stress concentrators in the form of dents of different shapes (spherical, conical, U-shaped) on the residual strength and the fatigue characteristics of 2-mm-thick samples made of a 2024T3 alloy. As was shown in those works, a dent can increase the rigidity of the plate (weakening was observed only in the case of uneven concentrator edges) during static compressive loading, and the appearance of the related bending of the plate outside the dent decreases the bearing capacity of the sample. Bending a plate outside a dent up to 2.5 mm does not affect the fatigue life, and a spherical dent decreases the fatigue life of samples according to a quadratic law as its depth increases. When studying the effect of a stress concentrator in the form of a dent on samples made of a 2198T851aluminum alloy with weld, the authors of [14] detected a decrease in the fatigue properties and found that, for a

Table 1. Description of the versions of SSSs* made of 1163AT alloy sheets with stress concentrators: dent (versions 1, 5) and dent + hole (versions 2–4, 6–8)

h , mm	d , mm	SSS	Hole position
1.5	1.5	1	Absent
		2	At the center of the dent (Fig. 1, hole 1)
		3	At the half radius of the dent (Fig. 1, hole 2)
		4	At the edge of the dent (Fig. 1, hole 3)
3.0	3.0	5	Absent
		6	At the center of the dent (Fig. 1, hole 1)
		7	At the half radius of the dent (Fig. 1, hole 2)
		8	At the edge of the dent (Fig. 1, hole 3)

* h is the dent thickness (equal to the sheet thickness) and δ is the dent depth.

dent, a point next to its edge at the flexure site serves as a crack nucleation site.

Taking into account the practical importance of the strength and fatigue properties of the aircraft skin material and the dependence of these properties on FOD, in this work we study the mutual influence on the static strength and life of the following two types of stress concentrators: holes 4 mm in diameter and dents in the form of a spherical segment 25 mm in diameter in a thin 1.5- or 3.0-mm-thick skin made of a 1163AT aluminum alloy.

EXPERIMENTAL

Structurally similar samples (SSSs) for investigations were made from 1.5- and 3.0-mm-thick sheets (in the transverse direction) of a 1163AT aluminum alloy. Table 1 gives eight SSS versions for studying the mutual influence of stress concentrators, and Fig. 1

shows the scheme of SSS with three positions on the dent of a hole-type stress concentrator (nos. 1–3) and a photograph of a tested SSS with a hole in position 1 and a fatigue crack.

A dent on an SSS was made by pressing a steel striker 25 mm in diameter to the depth equal to the skin thickness. Figure 2 shows the three-dimensional surfaces of 1.5- and 3.0-mm-thick SSSs with dents, which were scanned with a LEXT OLS 4100 (OLYMPUS, Japan) laser microscope (Table 1; versions 1, 5).

For versions 2–4 and 6–8 (see Table 1), SSSs, which modeled the mutual influence of concentrators in the form of a dent and a hole, were made as follows: a hole 4 mm in diameter was drilled, and indentation was then performed with a steel striker 25 mm in diameter to form a dent of depth δ , which was equal to the skin thickness in the hole area (Fig. 3).

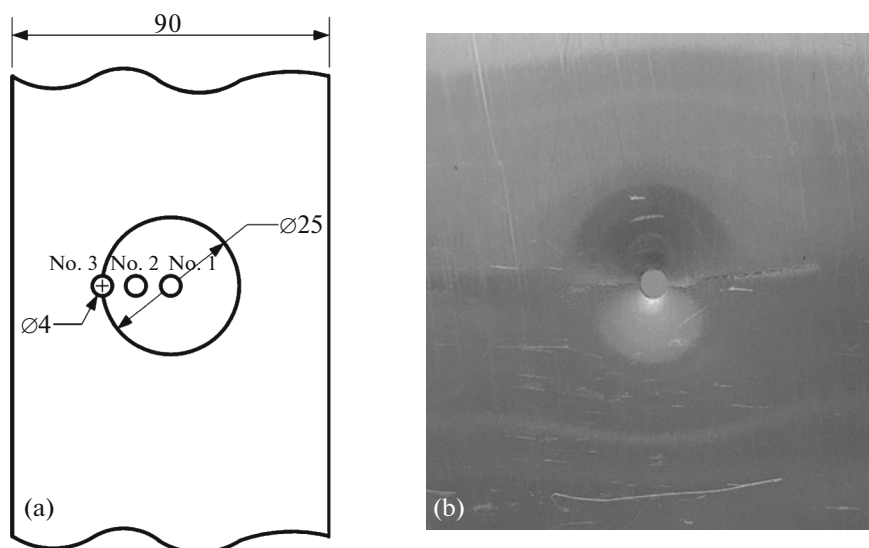


Fig. 1. (a) General scheme of SSS with various positions (1–3) of a hole-type stress concentrator and (b) photograph of a sample with a hole in position 1.

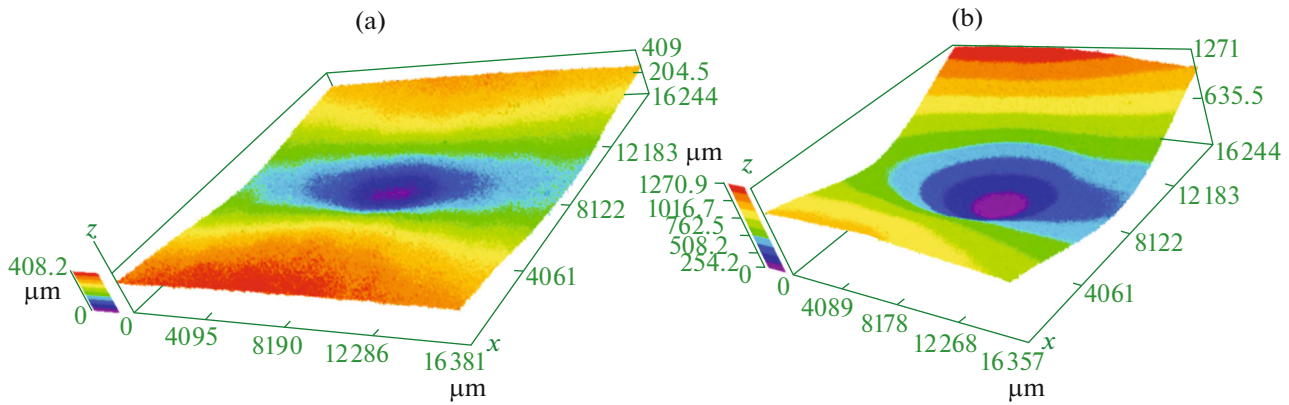


Fig. 2. 3D-scanned surface of the central part of a dent on SSS sheets (a) 1.5 and (b) 3.0 mm thick.

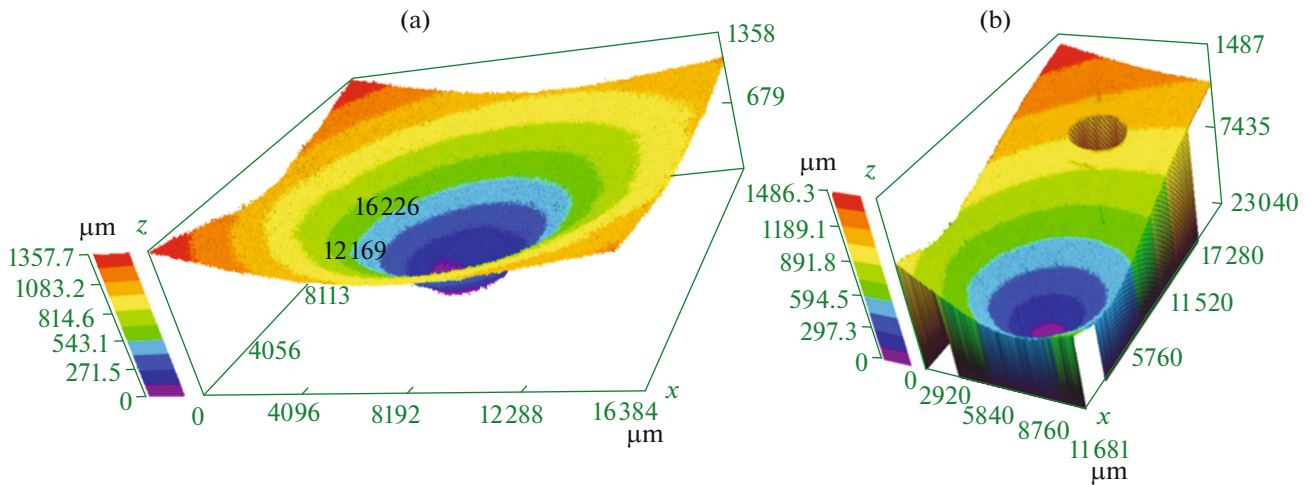


Fig. 3. 3D-scanned surface of the central part of a 1.5-mm-thick SSS with dent + hole stress concentrators: (a) centers of a hole and a dent coincide and (b) hole is located at the edge of the dent.

The static properties of SSS were determined by tension to failure. The tests were carried out on SSSs of all types to determine ultimate tensile stress σ_u^e . To determine the static sensitivity of the material to stress concentrators, we tested samples without any concentrators to determine ultimate tensile stress σ_u .

The life of the samples was determined using the number of cycles to failure at two stress levels, namely, 78 and 157 MPa, the stress ratio was $R_\sigma = 0$ (zero loading cycle), and the frequency was 5 Hz. The tests were carried out according to the scheme of repeated-variable tension under stress-controlled loading conditions according to a sinusoidal law [15].

SIMULATION

The position of a hole in different parts of a dent causes different stress concentrations in a sample. Stress concentration analysis was performed using a numerical simulation. For this purpose, finite element

models of SSS were developed according to the initial experiments. A sheet of the corresponding thickness (1.5 and 3.0 mm) with the following boundary conditions was simulated: the lower edge is fixed, and a load in the form of a distributed force is applied to the upper edge under limited motion along the axes except for the vertical z axis. The maximum stress was used to determine stress concentration factor K_t at a force of 1000 N. Figure 4 shows the normal stresses along the vertical z axis in the area of stress concentrators in a 3-mm-thick sheet (possible residual stresses were not taken into account).

The nominal stress is determined without taking into account geometry distortions using the formula

$$\sigma_{\text{nom}} = F/h(H - d), \tag{1}$$

where F is the applied force; h and H are the SSS thickness and width, respectively; and d is the hole diameter (for the case of a stress concentrator with only a dent $d = 0$).

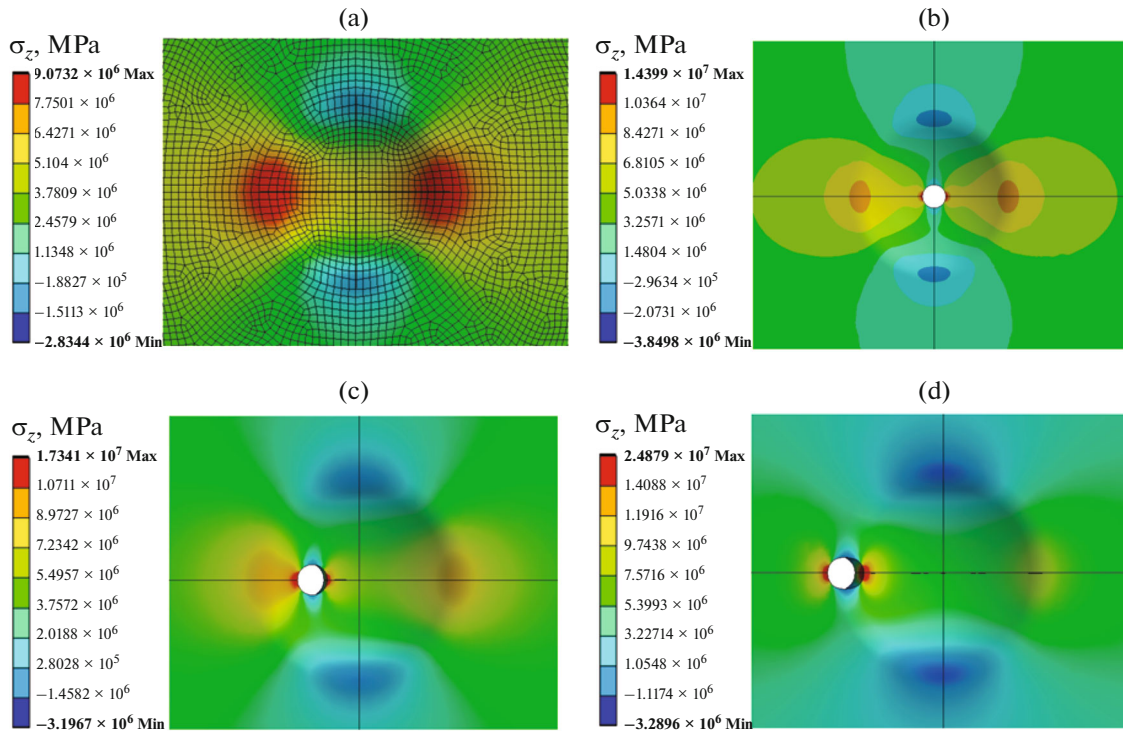


Fig. 4. Calculated normal stresses σ_z (MPa) for a 3-mm-thick SSS with the following stress concentrator: (a) dent, (b) dent + hole 1, (c) dent + hole 2, and (d) dent + hole 3.

For a 1.5-mm-thick sheet SSS and the stress concentration induced by a dent, the nominal stress is $\sigma_{\text{nom}} = 3.70$ MPa; in the combined case of dent + hole, we have $\sigma_{\text{nom}} = 3.88$ MPa. The corresponding data for a 3-mm-thick sheet SSS are 7.40 and 7.75 MPa.

Stress concentrators are characterized by a stress concentration factor, which is the ratio of the maxi-

imum calculated stress σ_{max} to the nominal stress for each calculation case,

$$K_t = \sigma_{\text{max}} / \sigma_{\text{nom}} \quad (2)$$

RESULTS AND DISCUSSION

Table 2 presents the stress concentration factors calculated for the versions under study and the experimentally determined sensitivity of the material to stress concentrators, which is estimated in relation to the ultimate tensile stress of a sample with a concentrator (σ_u^c) to the ultimate tensile stress for a sample without any concentrators (σ_u).

The nominal ultimate tensile stress of a sample with a concentrator is calculated by the formula

$$\sigma_u^c = F_{\text{max}} / h(H - d), \quad (3)$$

where F_{max} is the maximum force at which the sample was destroyed.

Table 2 gives the experimentally obtained static sensitivity of a 1163AT alloy to stress concentrators for the SSSs under study. Its dependence on the stress concentration factor is graphically shown in Fig. 5.

The introduction of a dent leads to an increase in the stress concentration by 1.2–1.3 times for the position of a hole at its center (Fig. 1, position 1) and by 1.5 times for position 2. The most critical position of a hole is at the edge of the dent, where the distortion of

Table 2. Estimated static sensitivity* of a 1163AT alloy to stress concentrators

h , mm	Type of stress concentrator**	K_t	σ_u^c / σ_u
1.5	Dent 25 × 1.5 mm in diameter	2.49	1.05
	Dent + hole 1	3.57	0.93
	Dent + hole 2	4.44	0.91
	Dent + hole 3	6.23	0.92
3.0	Dent 25 × 3.0 mm in diameter	2.45	1.11
	Dent + hole 1	3.71	0.93
	Dent + hole 2	4.47	0.92
	Dent + hole 3	6.42	0.92

* Sheet of thickness $h = 1.5$ or 3.0 mm made of 1163AT aluminum alloy.

** Combined effect of stress concentrators: dent 25 mm in diameter and 1.5 or 3.0 mm in depth and a hole in three positions relative to the center of the dent.

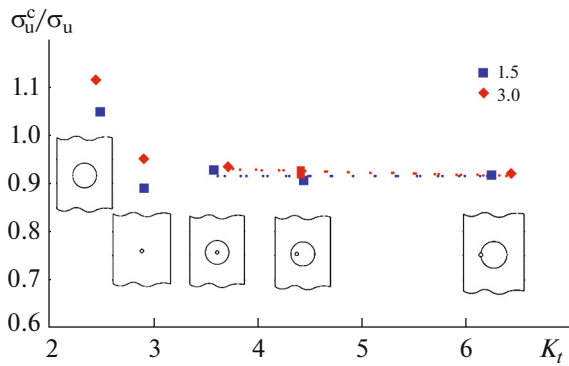


Fig. 5. Static sensitivity of a 1163AT alloy vs. the stress concentration factor.

its geometry (see Fig. 4a) is superimposed on the stress concentration at the hole (Fig. 4d). As a result, K_t can increase by 2.1–2.2 times compared to the stress induced by a simple hole. However, the sensitivity coefficient of the material to the stress concentrator in this case nonlinearly depends on the stress concentration factor (lowest strength results were obtained for hole position 2 on the dent). For a 1163AT alloy, static insensitivity to a dent-type stress concentrator is observed (even a noticeable increase in the load-bearing capacity of SSS is detected). The residual stress induced at the edges of the dent, which introduces hardening into the structure, exerts an effect.

In addition, it is worth noting the insensitivity of aluminum–beryllium alloys to concentrators up to certain values of K_t . For example, the following data are given for an ABM1 alloy (transverse direction of sample cutting) in [16, 17]. The sensitivity coefficient is 1.01 for $K_t = 2.44$, 0.994 for $K_t = 2.5$, and 1.0 for $K_t = 2.57$. At the same time, a decrease in the static strength, i.e., the opposite effect, is observed for a D16 alloy: for $K_t = 2.44$, the sensitivity coefficient is 0.949; for $K_t = 2.5$, it is 0.931; and for $K_t = 2.57$, 0.922 (transverse direction of sample cutting).

As can be seen from the results, the presence of two stress concentrators hole + dent does not exert a mutual effect on the sensitivity depending on the position, which can be due to induced hardening (residual stresses along the edges of the dent). In other words, the distortion of the hole geometry and the increase in the concentration are blocked by the growth of residual stresses toward the edge of the dent.

Figure 6 depicts the results of durability tests of SSS samples with a dent and a hole for its different locations.

Table 3 gives the results on fatigue life. As can be seen, an increase in the stress concentration leads to a significant decrease in the fatigue life. The position of a hole at the edge of the dent is most dangerous (Fig. 1, hole 3).

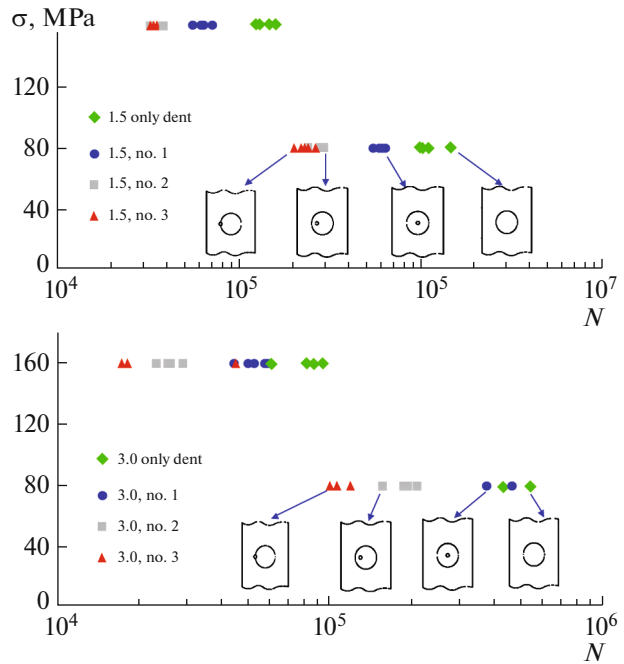


Fig. 6. Results of durability tests for an SSS made of an alloy sheet (a) 1.5 or (b) 3.0 mm thick for various positions of stress concentrators.

The position of a hole at the edge of the dent leads to the maximum drop in the fatigue life of SSS. The number of cycles to failure at $\sigma = 78$ MPa for the 1.5- and 3-mm-thick SSSs decreases by 2.6 and 3.7 times, respectively, depending on the position of a hole, when it is shifted to the edge of the dent (position 3). At $\sigma = 157$ MPa, the number of cycles to failure for the 1.5- and 3-mm-thick SSSs decreases by 1.8 and 2.3 times, respectively, when a hole is shifted from the center of the dent to its edge.

Table 3. Data for constructing a fatigue curve of an SSS made from an alloy 1163AT sheet with concentrators of various types

h , mm	Type of stress concentrator	K_t	Fatigue curve $N\sigma^m = 10^C$	
			m	C
1.5	Dent	2.49	2.98	11.69
	Dent + hole 1	3.57	3.26	11.95
	Dent + hole 2	4.44	2.90	10.92
	Dent + hole 3	6.23	2.76	10.59
3.0	Dent	2.45	2.61	10.61
	Dent + hole 1	3.71	2.93	11.16
	Dent + hole 2	4.47	2.83	10.64
	Dent + hole 3	6.42	2.32	9.44

CONCLUSIONS

(1) The combined effect of dent + hole stress concentrators on the mechanical properties of SSSs was studied numerically and experimentally. The static strength and durability of SSSs with stress concentrators of various types were experimentally determined.

(2) The presence of a dent in a 1163AT alloy sheet was found not to decrease the static strength, while the strength decreased by up to 8% regardless of the location of a hole with respect to a dent for combined dent + hole stress concentrators.

(3) The position of a hole relative to the center of the dent weakly affects the slope of a fatigue curve, whereas the displacement of a hole from the center to the edge of the dent leads to a decrease in the fatigue life.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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