Existence of the Coaxing Effect and Effects of Small Artificial Holes on Fatigue Strength of an Aluminum Alloy and 70-30 Brass

Y. MURAKAMI, Y. TAZUNOKI, and T. ENDO

In order to study the existence of the coaxing effect and the effects of small defects on the fatigue strength of an aluminum alloy and 70-30 brass, plain specimens and special holed specimens containing one or more very small drilled holes with diameters of 40, 50, 100, 200, and 500 μm were prepared. Contrary to commonly accepted knowledge, the existence of a distinct coaxing effect was confirmed in the fatigue test on 2017-T4 aluminum alloy. However, the coaxing effect was not confirmed in the fatigue test on 70-30 brass, though specimens with small artificial holes could contain non-propagating cracks at the fatigue limit. It was found that the appearance of the coaxing effect depends on the endurance at a higher stress level of small cracks initiated at a lower stress level. The very small drilled holes with diameters of 40 and 50 μm had no harmful effect on the fatigue strength of both the aluminum alloy and 70-30 brass; that is, the fatigue limits of specimens containing one or more drilled holes with diameters of 40 and 50 μm were identical with those of the plain specimens.

I. INTRODUCTION

It has been widely shown on the fatigue process of metals that slip bands are first induced by the shear component of cyclic stress, and then with the sufficient advance of cumulated slip bands microscopic cracks initiate along the slip bands or along the grain boundaries where the slip bands are blocked. Although these cracks have been comprehensively called stage-one cracks,[1] the sizes and the initiation process depend not only on the kinds of materials,[2] but also on the magnitude of stress. Namely, usually these cracks propagate beyond grain boundaries until they lead the specimen to fracture, while some cracks remain in the grains, or cease to propagate outside the grains. (Such microscopic non-propagating cracks in a plain specimen should no longer be called stage-one cracks, because they do not remain in the grains and they extend out of the plane of the slip bands.) Even when holes or notches in specimens are large enough to become fracture origins, the process of the initiation of a microscopic crack at the very small portion of holes or notches is essentially the same as the slip phenomenon in plain specimens.[3] When the size of the holes or defects is about the same order of magnitude as that of microscopic cracks introduced by the repetition of stress, it is expected that the cracks emanating from such holes or defects will behave in a manner similar to that of microscopic cracks initiated at other sites, which are not defective, for example, slip bands and grain boundaries. This happens because the crack formed along the slip bands and grain boundaries can be regarded as being mechanically equivalent to a traction-free zone such as holes or defects whose size is as large as the microcracks.

It is well known that at the fatigue limit of carbon steels, there exist microscopic non-propagating cracks on the surface of plain specimens.[4] The above-mentioned consideration leads us to expect that the existence of an artificial hole which is smaller than the size of microscopic non-propagating cracks will result in little or no decrease in the fatigue strength of the material. On the basis of this consideration, the authors have investigated and discussed the fatigue strength of specimens of various steels containing one or more very small holes with diameters ranging from 40 to 200 μm. The details are reported in References 5 through 9.

On the other hand, it is generally known that the fatigue phenomenon of non-ferrous metals such as aluminum and copper alloys are somewhat different from those of carbon steels. For example, it has been said that the knee point of an S-N curve and the coaxing effect do not appear in non-ferrous metals. Kommers[10] reported the existence of the coaxing effect in the fatigue tests of ingot iron and SAE1030 steel. However, in the discussion to Kommers' paper Stickley reported different results concerning the fatigue tests on wrought aluminum alloy. Sinclair[11] reported that the fatigue resistance of the unstrained ingot iron and the SAE1045 and 2340 steels was considerably increased by coaxing while the fatigue resistance of strained-and-aged ingot iron, 75S-T6 aluminum alloy, and 70-30 brass was not improved. Nisitani and Yamaguchi[12] reported the existence of a weak coaxing effect in only one case in the experiments on 70-30 brass. However, the exact meaning of these phenomena still seems ambiguous. Therefore, for investigating these phenomena more precisely, it is at least necessary to focus attention on the behavior of microcracks at and near the fatigue limit.

The objectives of the present work are (1) to investigate the behavior of microcracks emanating from one or more very small artificial holes in aluminum alloy and 70-30 brass specimens in comparison with microcracks of plain specimens and (2) also to study systematically (a) the existence of the fatigue limit in, or the clear knee point of, an S-N curve and (b) the coaxing effect, paying attention to the behavior of small cracks. It should be emphasized that the present work has the advantage of using specimens which contain very small artificial holes with 40 and 50 μm diameters, because these small holes restrict the location of the initiation of very small cracks within the holes' vicinity and these specimens help us to observe easily and in detail the behavior of very small cracks.

Y. MURAKAMI is Professor of Mechanics and Strength of Solids, Faculty of Engineering, Kyushu University, Higashi-ku, Fukuoka, 812 Japan. Y. TAZUNOKI is an Engineer with Hitachi Metal Company, Ltd. T. ENDO is a Professor with the Department of Mechanical Engineering, Kyushu Institute of Technology.

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II. MATERIALS, SHAPES, AND DIMENSIONS OF SPECIMENS AND EXPERIMENTAL PROCEDURE

Drawn bars of an aluminum alloy (the original diameter was 25 mm and the length was 4 m) and rolled plates of 70-30 brass (the thickness was 20 mm) were used for the fatigue tests. The chemical composition of these metals is shown in Table I. Seventy-thirty brass was annealed for 1 hour at 400 °C. The mechanical properties of the specimens before the fatigue test are shown in Table II. The grain size of 70-30 brass is 45 μm. The grain size of the aluminum alloy in transverse direction is about 89 μm and in longitudinal direction is about 3 to 5 mm. The grain size of the aluminum alloy was determined only approximately, because it is an anti-corrosive material and it was very difficult to expose the grain structure.

The shapes and dimensions of the specimens are shown in Figure 1. All specimens were electropolished. After the electropolishing one or more small artificial holes whose axis was normal to the specimen surface were made using a special drilling tool. The surface layer removed by the electropolishing was about 40 μm for 2017-T4 aluminum alloy and 100 μm for 70-30 brass per diameter of a specimen. Rotating-bending-fatigue testing machines of a uniform bending moment type were used.

Table I. Chemical Composition (Pct)

	Cu	Si	Fe	Mn	Mg	Zn	Cr	Pb
2017-T4	4.12	0.54	0.39	0.66	0.50	0.12	0.05	—
70-30 brass	68.9	—	0.02	—	—	30.9	—	0.18

Table II. Mechanical Properties (MPa, Pct)

	σ_s, $\sigma_{0.2}$	σ_B	σ_T	ψ
2017-T4	368.7	524.7	645.3	20.8
70-30 brass	103.0	318.7	1060.1	78.8

σ_s: yield stress, $\sigma_{0.2}$: 0.2 pct proof stress, σ_B: ultimate tensile strength, σ_T: true fracture strength, ψ: reduction of area.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. *Effect of Artificial Small Holes on the Fatigue Strength of Steels*

Before we discuss the fatigue behavior of the non-ferrous metals, *i.e.*, the aluminum alloy and 70-30 brass, the characteristics of the fatigue behavior of steels which were previously studied[5–9] are briefly summarized below. The length l_0 of the largest non-propagating crack observed on the surface of plain specimens at fatigue limit was about 100 μm for annealed low carbon steel[5] and 50 μm for annealed medium carbon steel.[5] From these results, it was predicted that the fatigue limit of holed specimens would be almost the same as that of plain specimens if the diameter of the hole was less than l_0. The results of fatigue tests on holed steel specimens were in good agreement with the prediction. The length l_0 of non-propagating cracks on the surface of the specimens of quenched ($H_v \cong 650$) and quenched-and-tempered ($H_v \cong 520$) medium carbon steels was very short (about 20 μm in both cases).[6] In such a case, even a small hole of 40 μm in diameter should be regarded as a fairly large defect in comparison with l_0. In this way, l_0 can be a measure for attaining high fatigue strength by controlling the size of defects in hard steels.[6]

From the above results, it may be said that harder steels or steels having high static strength are likely to have smaller values of l_0.

B. *The Effects of Small Holes and the Coaxing Effect on the Fatigue Strength of 2017-T4 Aluminum Alloy*

Figure 3 shows S-N curves and the experimental results for the coaxing effect. The notations, U1 . . . U4, H40 and H100, in Figure 3 denote the specimens used in the coaxing effect test. The letter U denotes a plain specimen, and the letter H stands for a holed specimen. The number in the notation, for example 40 of H40, indicates the diameter of the artificial hole drilled on the surface of the specimen. As shown in Figure 2, the depth of the hole has the same dimension as the diameter. The fatigue limit σ_w of the plain specimens defined by the numbers of repetitions $N = 3 \times 10^7$ is 16.0 kgf/mm^2 (156.9 MPa). The fatigue

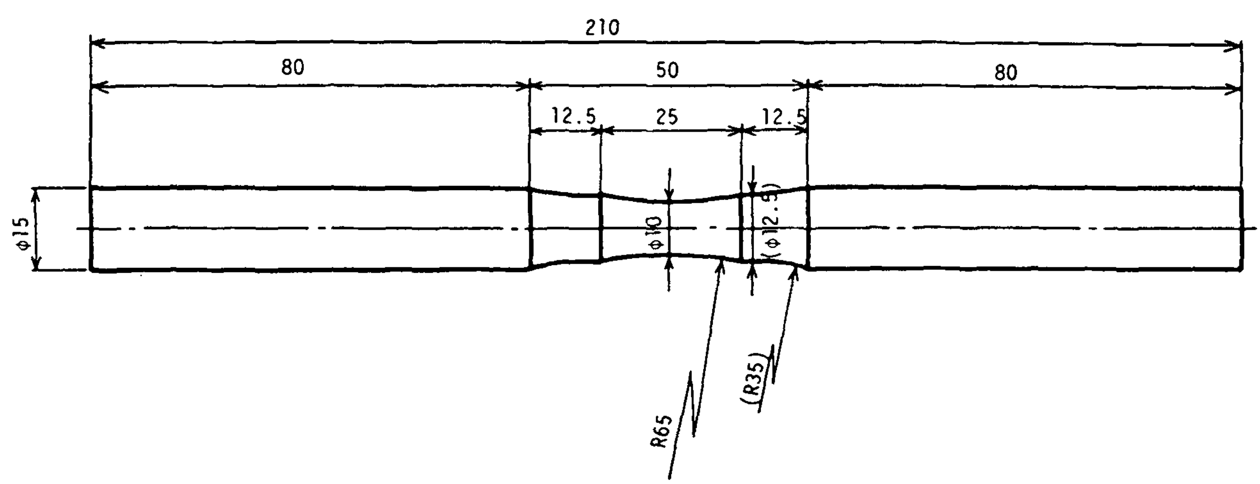


Fig. 1—Shape and dimensions of the specimen (mm).

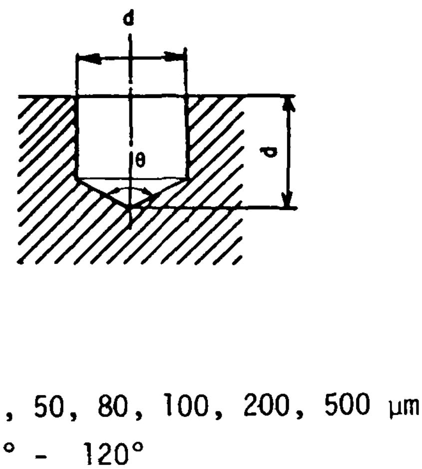


Fig. 2—Shape of a drilled hole.

Table III. Fatigue Limit Defined for $N = 3 \times 10^7$ (MPa)

Dia. of a Hole, μm	2017-T4	70-30 Brass
Plain specimen	156.9	122.6
40	156.9	122.6
100	147.1	117.7
200	122.6	107.9
500	—	98.1

limit of the holed specimens was defined by the stress under which a crack emanating from the edge of the hole endured for 10^7 cycles without increasing its length after ceasing propagation. The fatigue limits defined in this way are σ_w = 16.0, 15.0, and 12.5 kgf/mm^2 (156.9, 147.1, and 122.6 MPa) for the diameters of holes with d = 40, 100, and 200 μm. The fatigue limits are summarized in Table III with the data of 70-30 brass.

Figures 4 through 6 show the increase in the length of the crack in the coaxing effect tests, where the length is the sum of the diameter of a hole and the length of cracks emanating from the hole. Figure 4 shows the case of H200, where the initial stress amplitude σ_1 = 12.5 kgf/mm^2 (122.6 MPa) was repeated for 3×10^7 cycles and 3 pct of σ_1 was added step by step to the subsequent stress amplitude after making sure of the non-propagation of the crack. The letter N in the table included in the figure means the number of repetitions in each stress amplitude. Figure 6 shows the case of H100-1.

Comparing the results of Figures 4 through 6, it may be concluded that there is no definite difference in the behavior of crack extension between the non-propagating cracks of a plain specimen and those of a holed specimen. The commonly observed behavior is that cracks appear at the repetition of the first step of stress and that under the subsequent repetition of the increased stress they hardly propagate or cease to propagate after a small distance of propagation.

Figures 7 and 8 are the photographs of cracks observed at the points marked by A, B, *etc.* in Figures 5 and 6. These figures show clearly the behavior of non-propagation and propagation of cracks in the stress-increasing experiments. All cracks in Figures 7 and 8 eventually became critical cracks that led each specimen to final fracture after the subsequent increase in stress.

Plain specimens did not necessarily have non-propagating cracks like those which are shown in Figure 7. More properly speaking, few plain specimens had non-propagating cracks, and the numbers of cracks observed were only one or two to a specimen.

Figure 9 shows cracks which emanated from four holes (H40) drilled on an equal circumferential pitch on a circumferential contour line of one specimen. Although three holes had cracks during the repetition of stress from the first to the third step $\sigma_1 \rightarrow \sigma_3$ (see Figure 9 (a)), the last hole had a crack at the fourth step σ_4 for the first time, and this crack led the specimen to rapid final fracture. These four cracks which emanated from four small holes revealed the

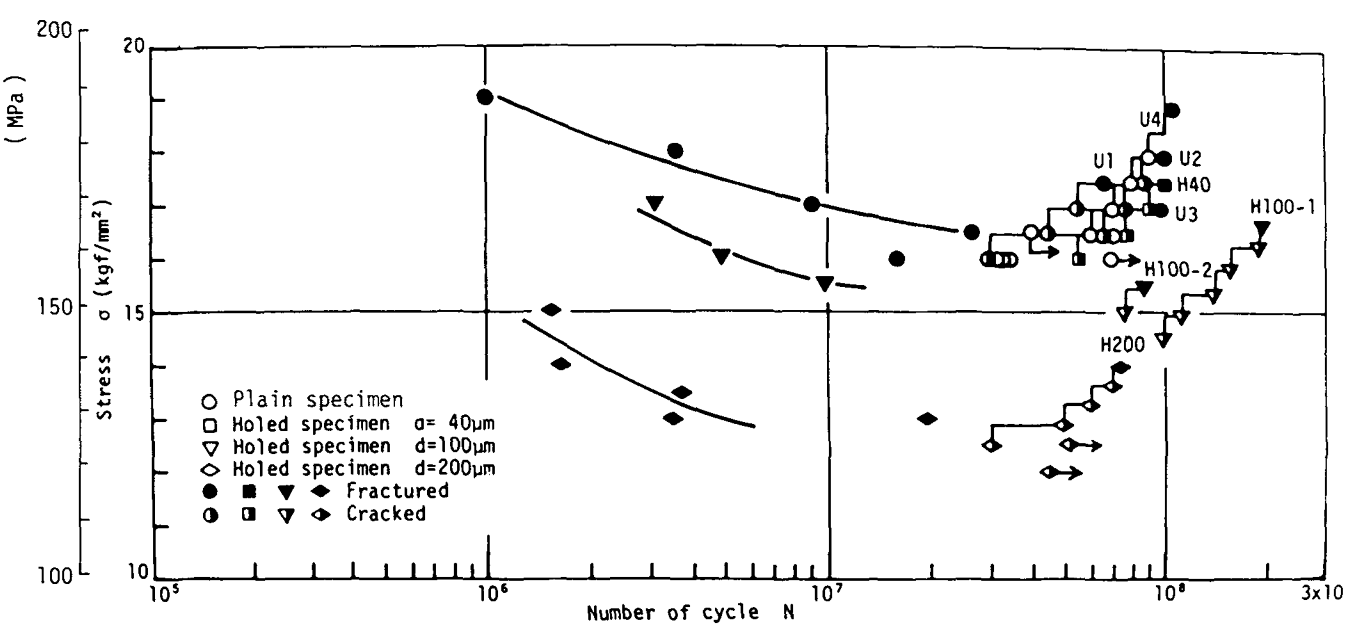


Fig. 3—The S-N curves of 2017-T4 Al-alloy and the results of the coaxing effect test (open marks indicate uncracked specimens or the shapes only indicate the type of a specimen).

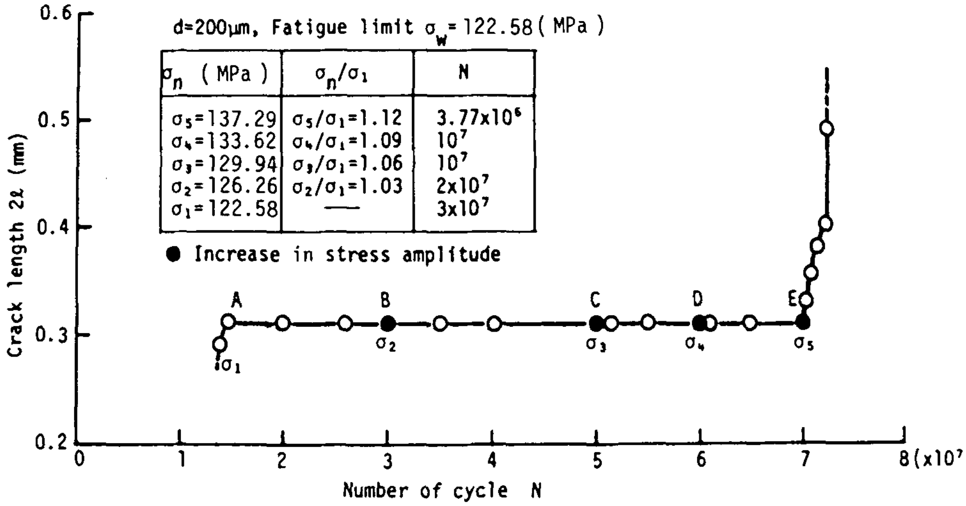


Fig. 4—Growth behavior of the crack emanating from a hole with a 200 μm diameter (holed specimen). The initial stress was σ_1 (= 12.5 kgf/mm^2; 122.6 MPa) and 3 pct of σ_1 was added step by step to the subsequent stress amplitude.

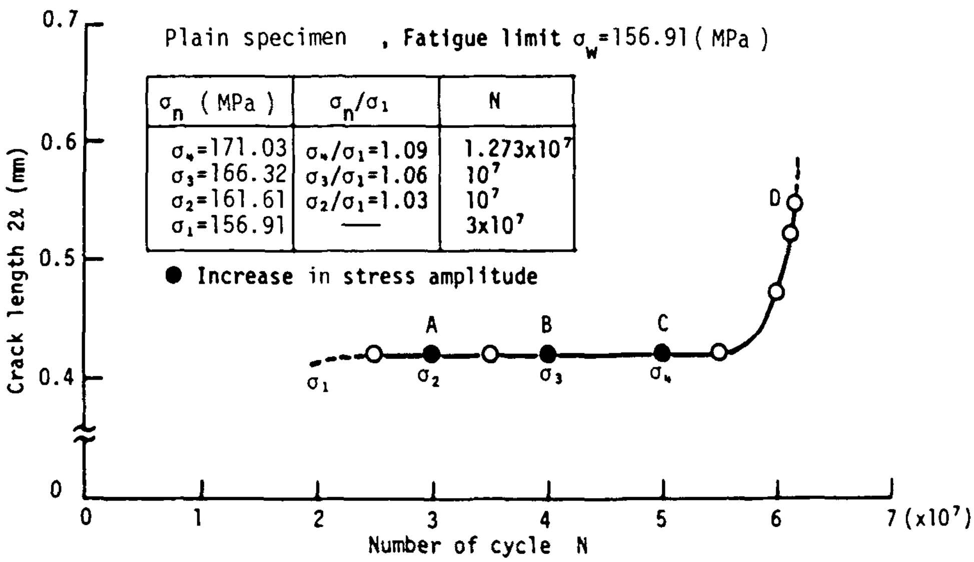


Fig. 5—Crack growth behavior in a plain specimen. The initial stress was σ_1 (16.0 kgf/mm^2; 156.9 MPa) and 3 pct of σ_1 was added step by step to the subsequent stress amplitude.

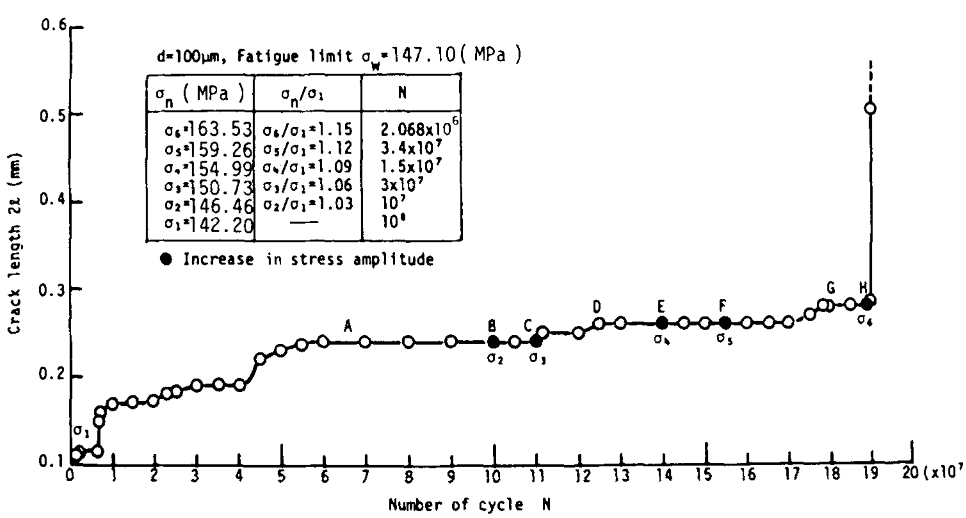
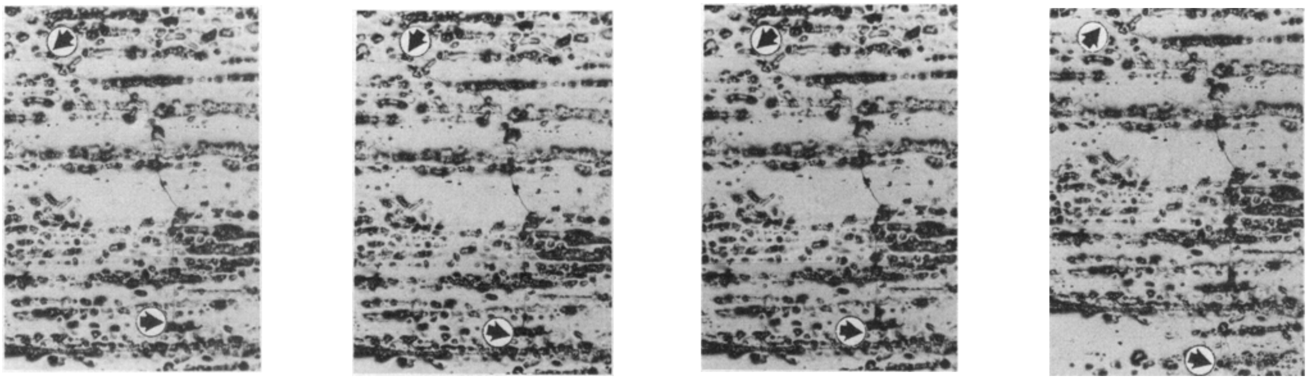


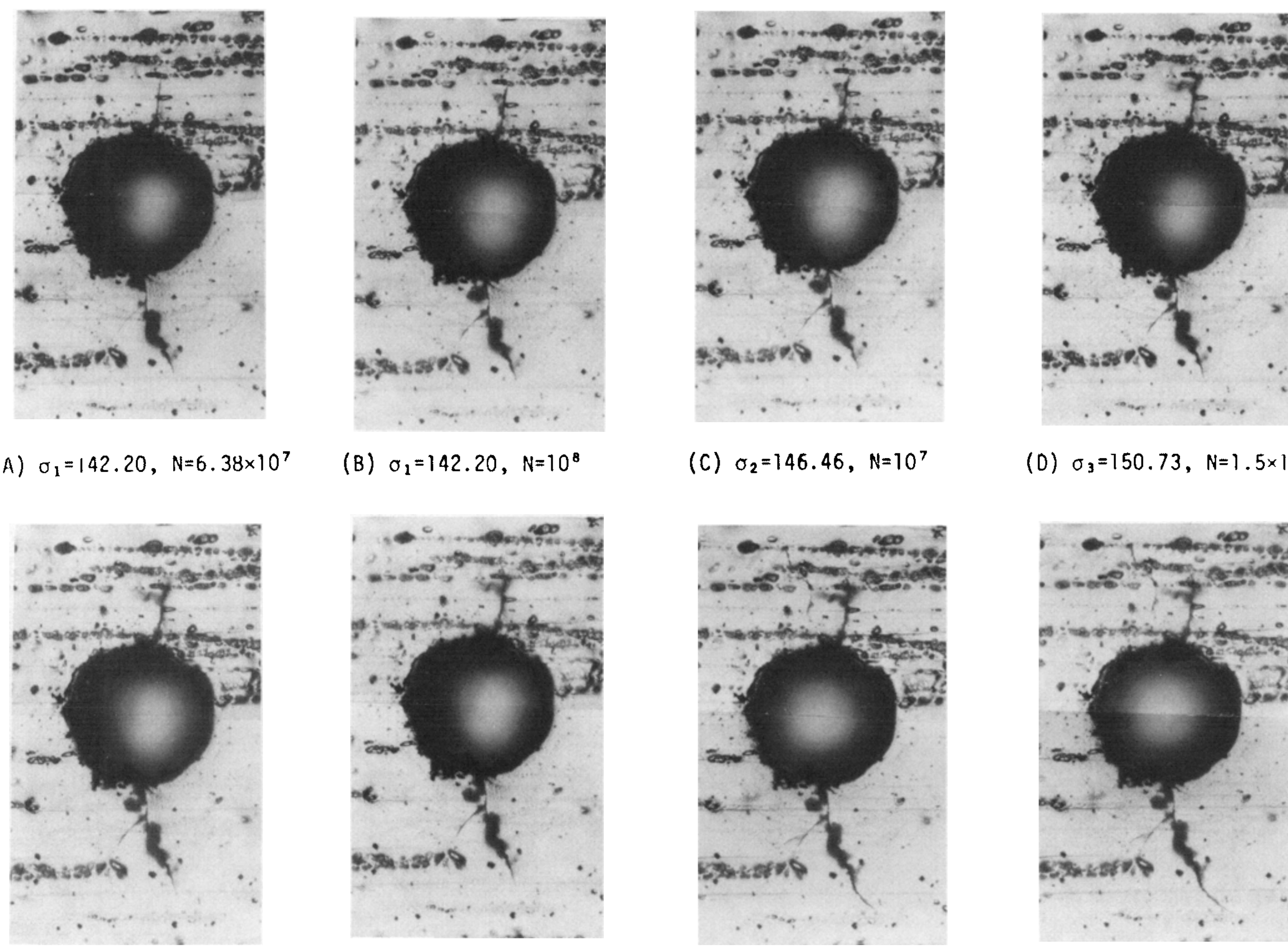
Fig. 6—Growth behavior of the crack emanating from a hole with a 100 μm diameter (holed specimen). The initial stress was σ_1 (= 14.5 kgf/mm^2; 142.2 MPa) and 3 pct of σ_1 was added step by step to the subsequent stress amplitude.



(A) σ_1=156.91, N=3×10^7 (B) σ_2=161.61, N=10^7 (C) σ_3=166.32, N=10^7 (D) σ_4=171.03, N=1.173×10^7

⟷ Axial direction 100μm

Fig. 7—The crack in a plain specimen. The initial stress was σ_1 (= 16.0 kgf/mm^2; 156.9 MPa) and 3 pct of σ_1 was added step by step to the subsequent stress amplitude (see Fig. 5).

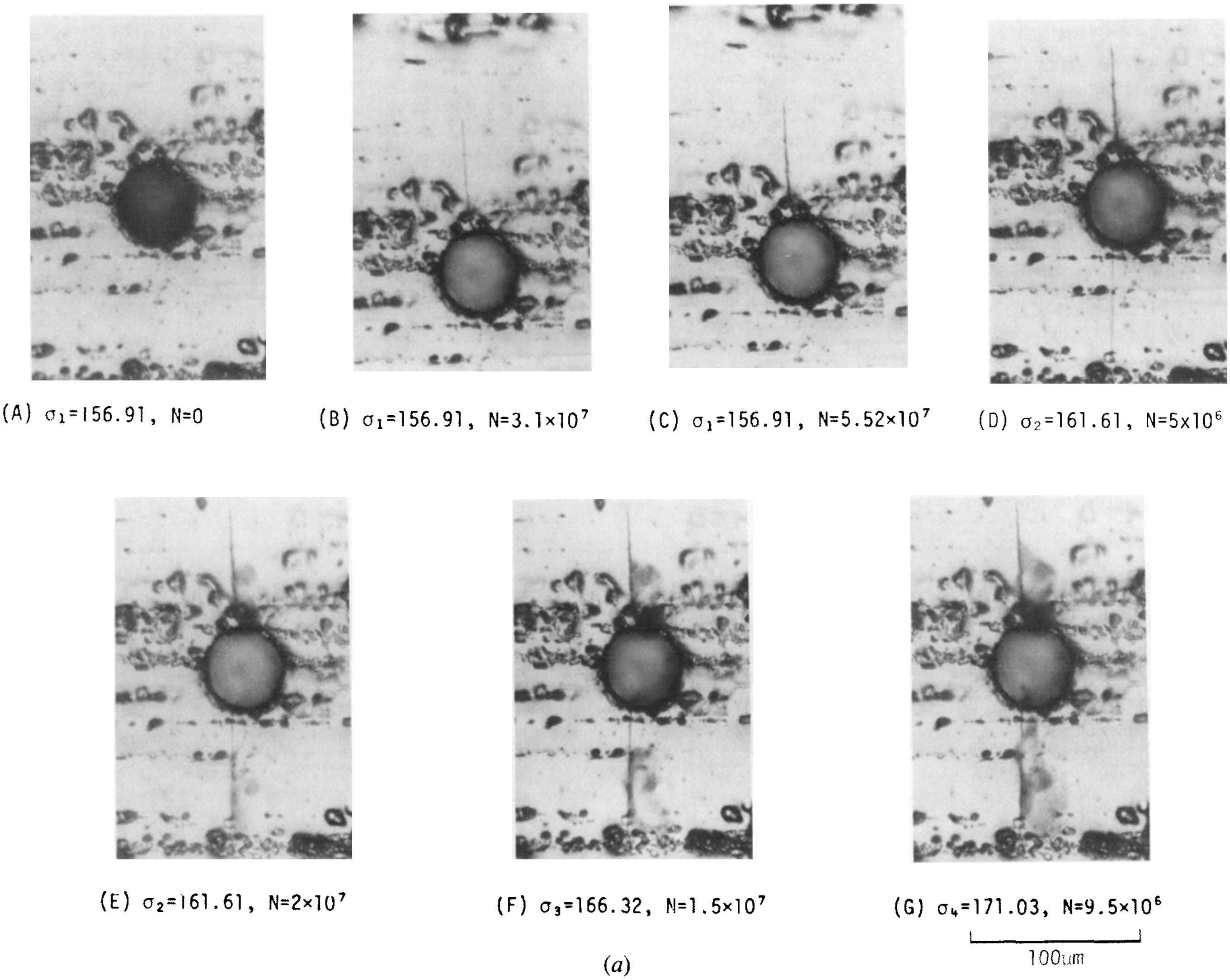


(A) σ_1=142.20, N=6.38×10^7 (B) σ_1=142.20, N=10^8 (C) σ_2=146.46, N=10^7 (D) σ_3=150.73, N=1.5×10^7

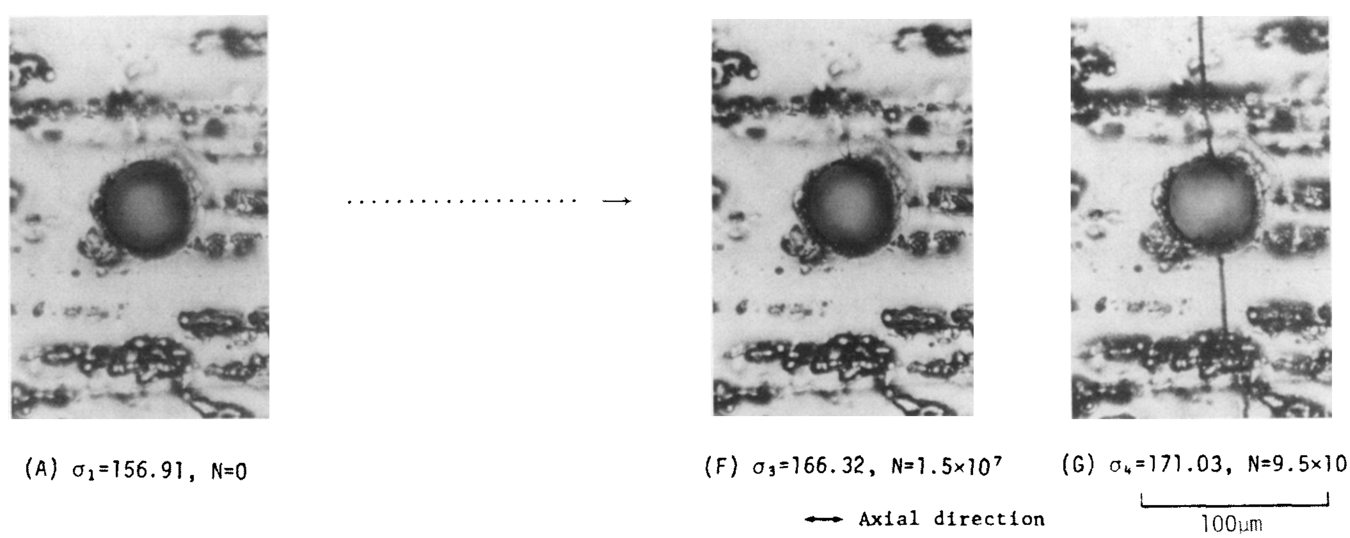
(E) σ_3=150.73, N=3×10^7 (F) σ_4=154.99, N=1.5×10^7 (G) σ_5=159.26, N=2×10^7 (H) σ_5=159.26, N=3.4×10^7

⟷ Axial direction 100μm

Fig. 8—The crack emanating from a hole with a 100 μm diameter. The initial stress was σ_1 (= 14.5 kgf/mm^2; 142.2 MPa) and 3 pct of σ_1 was added step by step to the subsequent stress amplitude (see Fig. 6).



(*a*)



(*b*)

Fig. 9—Behavior of cracks in the coaxing effect tests on a holed specimen of 2017-T4 Al-alloy containing four holes of 40 μm in diameter. (*a*) The crack emanating from the No. 1 hole, (*b*) the crack emanating from the No. 4 hole. (The crack initiated at the stress σ_4 and it led the specimen to final fracture.)

characteristics of the coaxing effect and the non-propagating behavior of cracks. Although three cracks which emanated from three holes (Nos. 1 to 3) under the increasing stress level $\sigma_1 \rightarrow \sigma_3$ continued to increase in size, they did not become the origin of the final fracture of the specimen. The crack that emanated from the No. 4 hole under the stress σ_4 did not show non-propagating behavior. These phenomena imply that the prior loading histories associated with the increase in stress amplitude and with the crack propagation may induce the mechanical or metallurgical conditions at the tip of Nos. 1 to 3 cracks which offer resistance to subsequent crack openings or strengthen the small zone of the crack tip.

It has been said that no coaxing effect exists in aluminum alloy.[10,11] However, it may be concluded from the above discussion and experimental results that a distinct coaxing effect is present in the fatigue of 2017-T4 aluminum alloy. Sinclair[11] pointed out that the coaxing effect in carbon steels was associated with the strengthening effects due to work hardening and strain aging. The authors are not sure whether a similar mechanism may or may not predominate in the coaxing effect in 2017-T4 aluminum alloy, because it is very difficult to explain the mechanism if we consider the experiments on 70-30 brass described in Section C.

C. *Effects of Small Holes on the Fatigue Strength of 70-30 Brass*

Figure 10 shows the S-N curve and the results of experiments of coaxing effects on 70-30 brass. The fatigue limit of plain specimen defined by the endurance of $N = 3 \times 10^7$ is $\sigma_w = 12.5$ kgf/mm^2 (122.6 MPa; see Table III). Although Nisitani and Yamaguchi[12] reported the existence of a weak coaxing effect in only one case in their experiments with a hole of 0.3 mm in diameter, we, as shown in Figure 10, could not confirm the existence of a definite coaxing effect in 70-30 brass in the present test. However, interesting behavior of small cracks was observed in the course of these experiments. This is explained with reference to Figures 11 through 13.

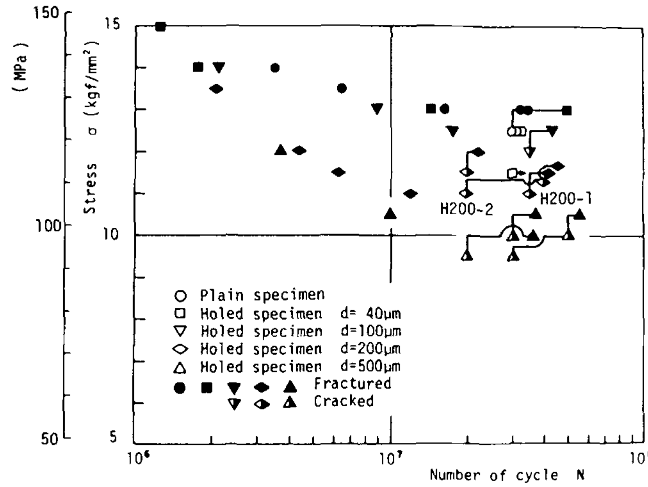


Fig. 10—The S-N curves of 70-30 brass and the results of the coaxing effect tests.

Figure 11 shows the behavior of a small crack which appeared because of the repetition of the stress of the fatigue limit (12.5 kgf/mm^2; 122.6 MPa). This crack showed the tendency of non-propagation at $\sigma = 12.5$ kgf/mm^2 (122.6 MPa), though it may have been transient behavior. As the stress was increased to 13.0 kgf/mm^2 (127.5 MPa), the crack started propagating.

Figure 12 shows the behavior of cracks emanating from the edge of a hole with a 40 μm diameter at $\sigma = 13.0$ kgf/mm^2 (127.5 MPa; 0.5 kgf/mm^2 (4.9 MPa) higher than the fatigue limit of the plain specimen). Although the cracks emanated in the early stage, they showed the tendency of non-propagation after $N \cong 10^6$. A crack which initiated at a place other than the edge of the hole led this specimen to final fracture at $N_f = 1.45 \times 10^7$. Since cracks larger than 40 μm (the diameter of the hole) initiate along slip bands at $\sigma_w = 12.5$ kgf/mm^2 (122.6 MPa; see Figure 11), they possibly become the origin of final fracture (the fatal crack) rather than the cracks emanating from the edge of the small holes, because the cracks which emanate from the holes

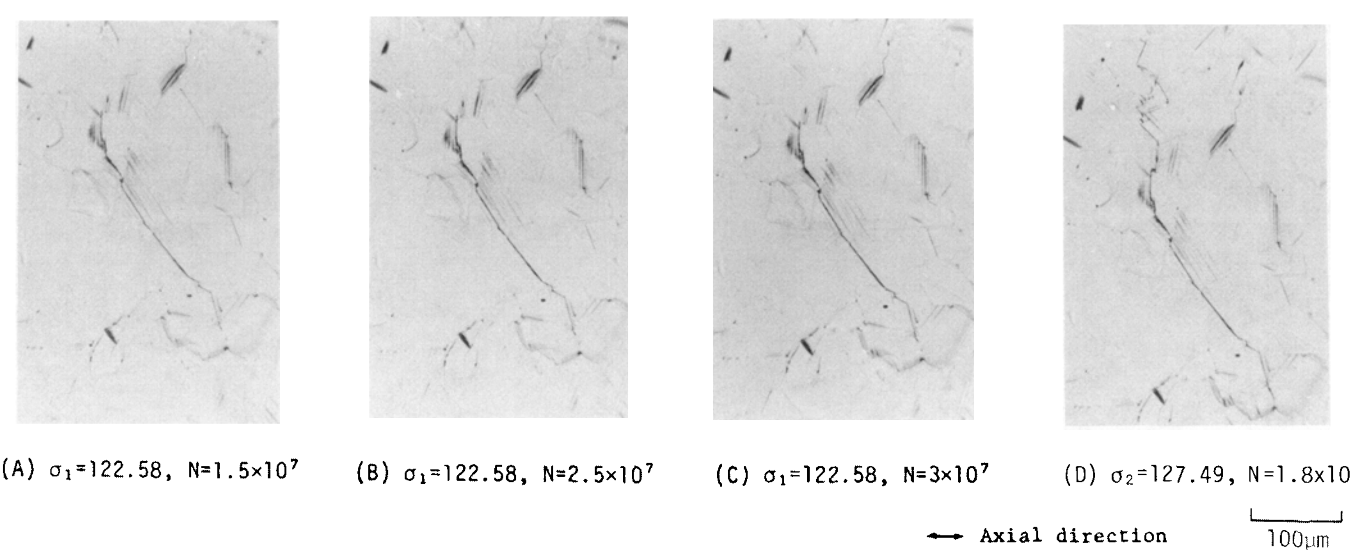


Fig. 11—Behavior of cracks in the plain specimen under stress increasing test (70-30 brass).

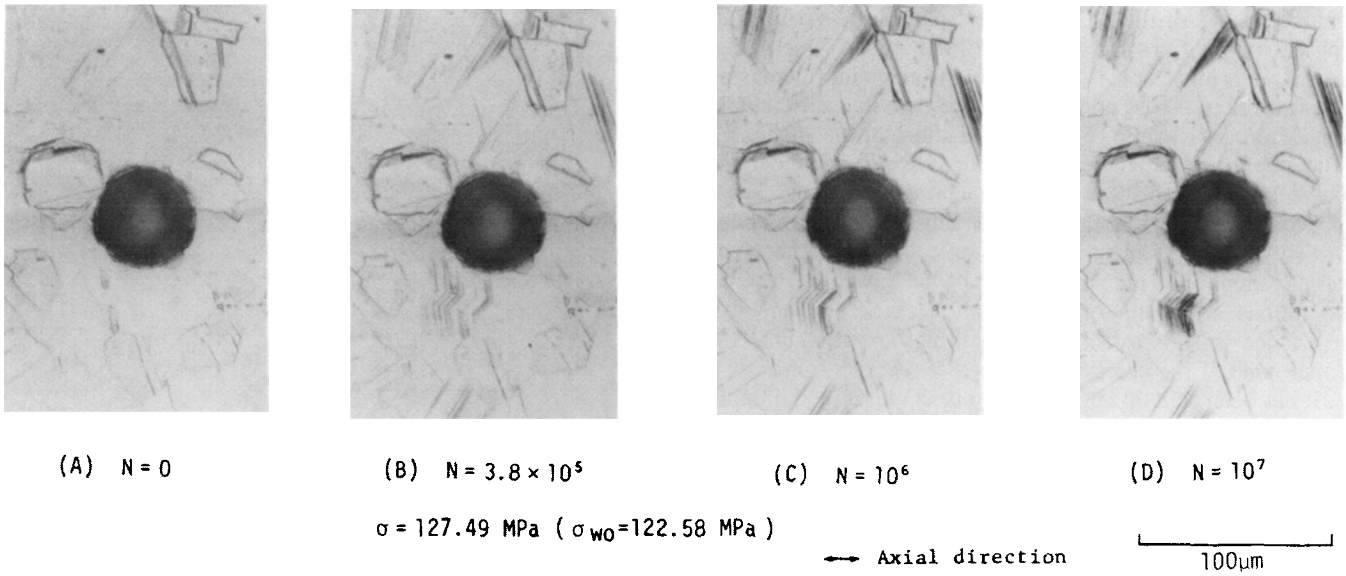


Fig. 12—Behavior of cracks emanating from a hole with a 40 μm diameter.

show the tendency of non-propagation. This may be the reason why holes with 40 and 50 μm diameters do not decrease the fatigue limit; this is shown in Figure 14. Thus, when we define the fatigue limit of 70-30 brass by the stress under which the specimen endures the cycles of repetitions $N = 3 \times 10^7$, the effects of small holes can be estimated in a way similar to those of carbon steels,[5-9] if we compare the dimensions of the holes with small cracks (which may propagate at $N > 3 \times 10^7$) of the plain specimen at the fatigue limit ($N = 3 \times 10^7$).

The existence of the coaxing effect was examined on the specimen with a hole of 200 μm in diameter, as shown in Figure 13. The cracks emanating from the edge of a hole ceased propagating at $\sigma = 11.0$ kgf/mm^2 (107.9 MPa), and this caused the appearance of the knee in the S-N curve (see Figure 10) similar to the case of the aluminum alloy previously described. By increasing the stress from $\sigma = 11.0$ to 11.5 kgf/mm^2 (107.9 to 112.8 MPa), the crack started propagating at the stress level, 11.5 kgf/mm^2 (112.8 MPa), and led the specimen to fracture (see (G) and (H) in Figure 13). On the other hand, a specimen which was subjected to the 3 pct stress increase test endured for $N = 3 \times 10^7$ at $\sigma_2 = 1.03\sigma_1$ and $\sigma_1 = 11.0$ kgf/mm^2 (107.9 MPa), and it fractured at σ_3 ($= 1.06\sigma_1$). However, considering that another specimen endured the stress $\sigma = 11.5$ kgf/mm^2 (112.8 MPa) for $N = 2 \times 10^7$, we cannot conclude the existence of any coaxing effect in 70-30 brass.

IV. SUMMARY AND CONCLUSIONS

It has been said that no definite coaxing effect and no definite knee point in the S-N curve exist in aluminum and copper alloys. In the present work, the existence of the

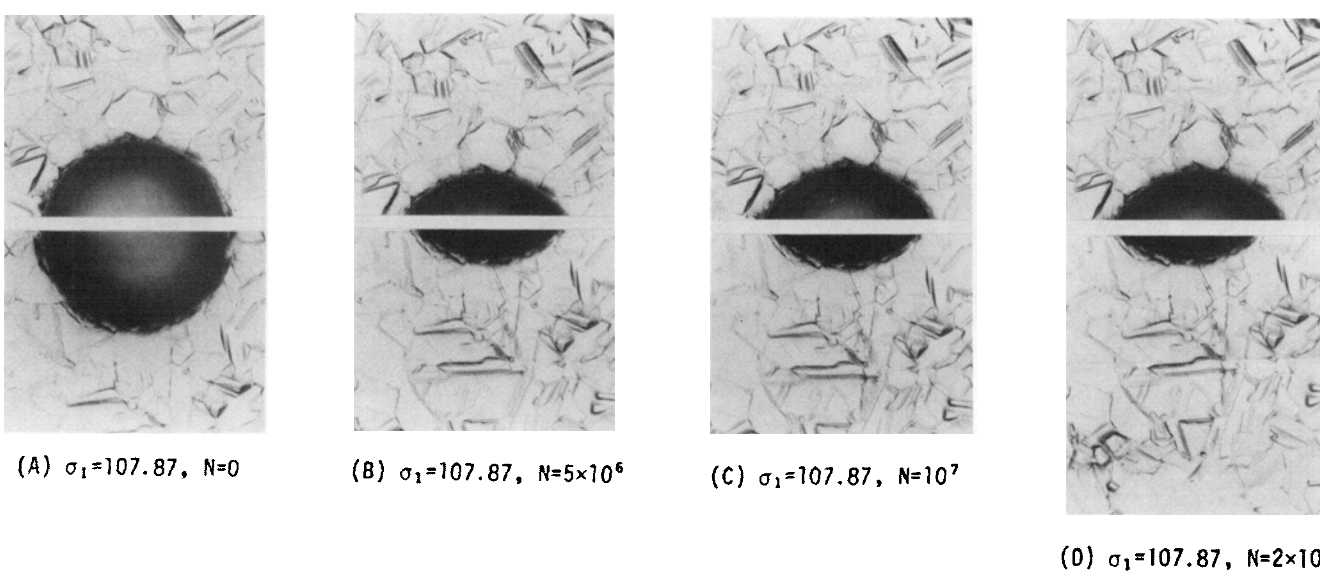


Fig. 13—Behavior of cracks emanating from a hole with a 200 μm diameter under stress increasing test (70-30 brass).

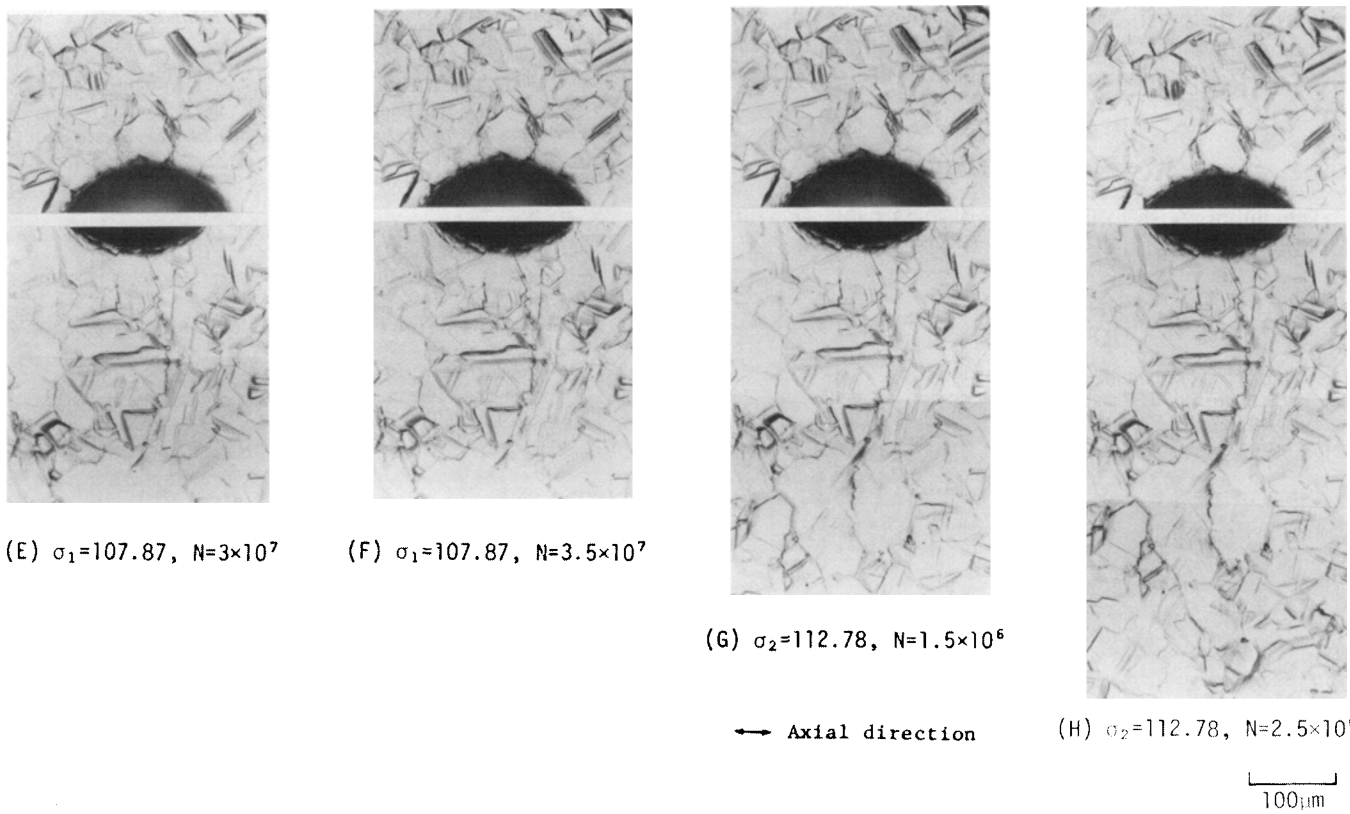


Fig. 13 — Behavior of cracks emanating from a hole with a 200 μm diameter under stress increasing test (70-30 brass).

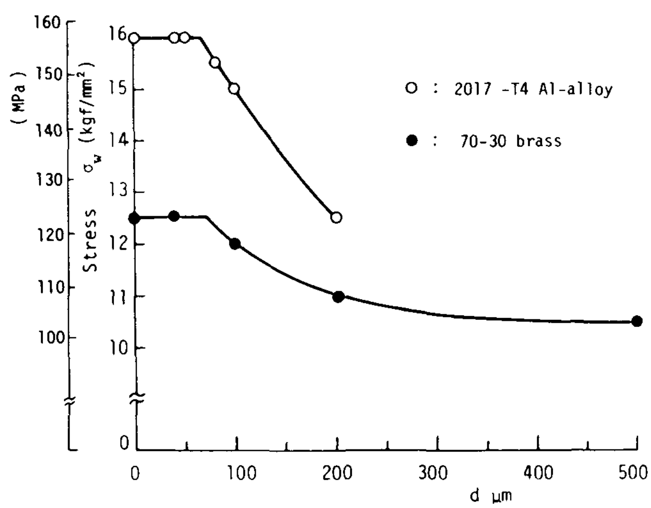


Fig. 14 — Relationship between fatigue limit and diameter of a hole d (μm) (2017-T4 Al-alloy and 70-30 brass).

coaxing effect in 2017-T4 aluminum alloy and 70-30 brass was investigated, with attention paid to the behavior of small cracks.

In addition to plain specimens, specimens that contained one or more very small artificial holes (drilled holes with diameter ranging from 40 to 200 μm) were used in order to restrict the location of crack initiation. We should always notice the behavior of the critical crack when we discuss the effects of a certain factor of fatigue strength. From this viewpoint, it is important that these holed specimens were helpful in the observation of the critical crack which led the specimens to final fracture.

The results obtained are summarized as follows:

1. The existence of a distinct coaxing effect was confirmed in the fatigue of 2017-T4 aluminum alloy. This new conclusion is different from commonly accepted knowledge. The details of the results of the observations follow. Cracks appear at the first step of stress and they do not propagate or propagate a short distance and stop at the subsequent steps of increased stress. This observation implies that the insistence that the specimen used might happen to be strong due to the statistics factors of the material cannot be accepted. This observation also indicates that how the cracks which initiated at the first step of stress can endure the subsequently increased stresses is of primary importance in the discussion of the coaxing effect.
2. The existence of the coaxing effect was not confirmed in the fatigue tests of 70-30 brass, though specimens with small artificial holes can contain non-propagating cracks at the fatigue limit. This conclusion is the same as that derived by Sinclair.[11]
3. The artificially drilled holes which were a little smaller than cracks observed at fatigue limit stresses on the surface of plain specimens did not lower the fatigue limit of 70-30 brass (defined for $N = 3 \times 10^7$). The same viewpoint cannot be directly applied to 2017-T4 aluminum alloy, because few non-propagating cracks and slip bands were observed at the fatigue limit of plain specimens. However, the cracks emanating from holes with 40 and

$50\ \mu m$ diameters ceased to propagate, and the holes eventually did not result in a reduction of the fatigue limit of 2017-T4 aluminum alloy (Figure 14).

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