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	ORIGINATOR'S REF. TP 96038 U		SECURITY CLASS. Unclassified

ORIGINATOR
National Aerospace Laboratory NLR, Amsterdam, The Netherlands

TITLE
Variability of fatigue crack growth properties for 2024-T3 aluminium alloy

PRESENTED AT

AUTHORS	DATE	pp	ref
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DESCRIPTORS

Aging (materials)
Aluminium alloys
Corrosion resistance
Crack propagation
Cyclic loads
Damage assessment
Environment effects
Fatigue tests
Mechanical properties
Speciment geometry

ABSTRACT
Discussions between D-BAA and the NLR have shown that significant variability in fatigue crack growth properties is possible for the industry standard damage tolerant aluminium alloy, 2024-T3 sheet. This is important for two reasons: (1) design assumptions and (2) comparisons of different candidate materials, such as 6013-T6, with 2024-T3. Another important topic is the possibility of changes in damage tolerance properties owing to long term natural ageing.
In this report a comparison was made between 2024-T3 aluminium alloy sheet crack growth obtained from two NASA reports (from 1958 and 1959) and an NLR report (from 1966) to examine batch to batch variability of fatigue crack growth rates. Two other NASA reports (from 1969 and 1988), which refer to test specimens from the same batch of material, were used to determine if there is any long term natural ageing effect on fatigue crack growth properties.
From the results it can be concluded that:
1. There is a significant effect of long term natural ageing on crack growth properties of 2024-T3.
2. Significant variability in fatigue crack growth properties is possible for different batches of 2024-T3.
3. The effect of long term ageing is less than or similar to the effect of batch-to-batch variation.
4. The effect of cycle frequency has to be considered even when tests are done in laboratory air.

NLR TECHNICAL PUBLICATION

TP 96038 U

VARIABILITY OF FATIGUE CRACK GROWTH PROPERTIES FOR 2024-T3 ALUMINIUM ALLOY

by

A. Oldersma and R.J.H. Wanhill

This investigation has been done as a contribution to topics of mutual interest to Daimler-Benz Aerospace Airbus and the NLR.

Division : Structures and Materials
Prepared : AO/ RJHW/
Approved : RJHW/

Completed : 960119
Order number : 543.003
Typ. : MM

Summary

Discussions between D-BAA and the NLR have shown that significant variability in fatigue crack growth properties is possible for the industry standard damage tolerant aluminium alloy, 2024-T3 sheet. This is important for two reasons: (1) design assumptions and (2) comparisons of different candidate materials, such as 6013-T6, with 2024-T3. Another important topic is the possibility of changes in damage tolerance properties owing to long term natural ageing.

In this report a comparison was made between 2024-T3 aluminum alloy sheet crack growth data obtained from two NASA reports (from 1958 and 1959) and an NLR report (from 1966) to examine batch to batch variability of fatigue crack growth rates. Two other NASA reports (from 1969 and 1988), which refer to test specimens from the same batch of material, were used to determine if there is any long term natural ageing effect on fatigue crack growth properties.

From the results it can be concluded that:

1. There is a significant effect of long term natural ageing on the crack growth properties of 2024-T3.
2. Significant variability in fatigue crack growth properties is possible for different batches of 2024-T3.
3. The effect of long term ageing is less than or similar to the effect of batch-to-batch variation.
4. The effect of cycle frequency has to be considered even when tests are done in laboratory air.

Contents

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1 Introduction

Discussions between D-BAA and the NLR have shown that significant variability in fatigue crack growth properties is possible for the industry standard damage tolerant aluminium alloy, 2024-T3 sheet. This is important for two reasons: (1) design assumptions and (2) comparisons of different candidate materials, such as 6013-T6, with 2024-T3. Another important topic is the possibility of changes in damage tolerance properties owing to long term natural ageing, which has already been demonstrated to be deleterious to corrosion resistance. With increasing age there is a trend towards more intergranular corrosion at the expense of general pitting.

2 Batch variability

Schijve [1] compared fatigue crack growth data of 2024-T3 Alclad sheet material from several manufacturers to examine batch-to-batch variation. The investigation also included differentbatches from the same manufacturer. Constant amplitude fatigue tests were carried out at the NLR with the same test conditions: specimen dimensions, cycle frequency, environment and testing machine. It was found that the variability between batches from the same manufacturer was similar to the variability between batches from different manufacturers.

In the investigation three stress amplitude levels were used with the same mean stress level, resulting in three different R-values: R = 0.037, R = 0.27, and R = 0.47. The results are shown in figure 1 (scatterbands) and listed in table 1. Each test series (same R,ΔK) contained 21 specimens. The standard deviation of the log(da/dn) values of each test series was calculated in order to describe the scatter in crack growth rates. The results are listed in table 2 and shown in figure 2. There is a tendency towards a higher standard deviation with increasing ΔK.

The Schijve results have also been compared with NASA (NACA) fatigue crack growth test data from the following reports [2, 3]:

- NACA TN 4394, prepared by McEvily, A.J. and Illg, W., September 1958.
- NASA TN D-52, prepared by McEvily, A.J. and Illg, W., October 1959.

The test conditions (specimen dimensions, cycle frequency and testing machine) for these tests differed from the NLR test conditions. The crack growth rate data are listed in tables 3 and 4. Figure 3 compares these data with the NLR data. Although tested at different frequencies and at slightly different R-values (0.033-0.02) the data from NACA TN 4394 fit into the scatterband for R = 0.037 from reference 1. The NASA TN D-52 data illustrate the effect of negative R-value (R = -1).

Taken as a whole, the crack growth results in figure 3 show that there is an effect of cycle frequency: lower frequencies result in slightly higher crack growth rates. This effect is discussed in the next section.

3 Frequency and thickness effects

3.1 Effect of frequency

The effect of cycle frequency is interrelated with the effect of atmospheric humidity. This is discussed in ref[4]. Figure 4 illustrates both effects and shows that reducing the frequency increased crack growth rates more in dry air than in wet air at low ΔK, but did the opposite at high ΔK. This figure also shows that the humidity effect decreases with decreasing frequency, i.e. at low frequencies there are only slight differences in crack growth rates in dry or wet air.

The data used in the present report are all from tests carried out in laboratory air. Although one might think that the humidity effect can therefore be neglected, figure 3 shows that there is still a frequency effect, which has to be taken into account when comparing crack growth rate data.

3.2 Effect of sheet thickness

Constant amplitude tests in normal and nominally dry air on plate and sheet materials demonstrate that crack growth rates tend to be higher in thicker section materials. (Note that specimen thickness, rather than sheet thickness, has a negligible influence for 2024-T3, but not for some materials, notably aluminium-lithium alloys.)

The data used in the present report are from test specimens with sheet thicknesses ranging from 2.0 to 2.6 mm. It is assumed that in this thickness range the thickness effect is negligible.

4 Long term variation

To investigate the effect of long term natural ageing, NASA fatigue crack growth test data for 2024-T3 sheet material were used from the following reports [5, 6]:

- NASA TN D-5390, prepared by Hudson, C.M., August 1969.
- AGARD report no.732, annex G, E.P. Phillips, 1988.

The long term natural ageing effect can be studied because the materials tested came from the same batch, which was manufactured before 1949.

The crack growth rate data are listed in tables 5 and 6. Figures 5-7 compare data for the same R, but tested in different decades. The crack growth rates for the Phillips 1988 data (ref[6]) were slightly higher than those for the Hudson 1969 data (Ref. 5) *at the same frequency*. Note, however, that figure 7 shows a frequency effect for the Hudson 1969 data (0.5 Hz versus 30 Hz), and that the Phillips 1988 data still are above the Hudson 1969 data even though the latter were obtained at a lower frequency (14 Hz versus 30 Hz).

5 Discussion

The batch-to-batch variation in crack growth is characterized by the scatterbands obtained from the data in reference 1 and shown in figure 1 for R = 0.037, R = 0.27 and R = 0.47. The scatterband representing R=0.47 is smaller, indicating a somewhat lower variability. This is also indicated by the calculated standard deviations, table 2 and figure 2.

Figures 8 and 9 show that the NASA 1969 and 1988 data (Refs. 5, 6) fit mostly in the scatterbands for the NLR 1966 data (Ref. 1) although there are slight differences in R values and cycle frequencies. This means that the effect of long term ageing on the NASA material is less than or similar to the effect of batch-to-batch variation. Nevertheless, both effects should be considered as significant, taking into account the log-log method of data presentation.

The frequency effect in laboratory air could not be studied over the total ΔK-range, since the test frequencies were generally adjusted to the applied stress amplitude. Therefore the low frequency data mostly relate to higher ΔK-values and the high frequency data to lower ΔK-values.

6 Conclusions

In this report a comparison was made between 2024-T3 aluminum alloy sheet crack growth data obtained from two NASA reports (from 1958 and 1959) and an NLR report (from 1966) to examine batch-to-batch variability of fatigue crack growth rates. Two other NASA reports (from 1969 and 1988), which refer to test specimens from the same batch of material, were used to determine if there is any long term natural ageing effect on fatigue crack growth properties.

From the results it can be concluded that:
1. There is a significant effect of long term natural ageing on the crack growth properties of 2024-T3.
2. Significant variability in fatigue crack growth properties is possible for different batches of 2024-T3.
3. The effect of long term ageing is less than or similar to the effect of batch to batch variation.
4. The effect of cycle frequency has to be considered even when tests are done in laboratory air.

7 References

1. Schijve, J.; de Rijk, P., The fatigue crack propagation in 2024-T3 Alclad sheet materials from seven different manufacturers, National Aerospace Laboratory Report NLR M2162, Amsterdam, May 1966.
2. McEvily, A.J.; Illg, W., The rate of fatigue-crack propagation in two aluminium alloys, National Advisory Committee for Aeronautics Report NACA TN 4394, September 1958.
3. McEvily, A.J.; Illg, W., The rate of fatigue-crack propagation for two aluminium alloys under completely reversed loading, National Aeronautics and Space Administration Report NASA TN D-52, October 1959.
4. Wanhill, R.J.H., Environmental effects on fatigue of aluminium and titanium alloys, National Aerospace Laboratory NLR, Amsterdam, paper in "Corrosion fatigue of aircraft materials", AGARD Report N0.659,"Corrosion Fatigue of Aircraft Materials", April 1977.
5. Hudson, C.M., Effect of stress ratio on fatigue-crack growth in 7075-T6 and 2024-T3 aluminium-alloy specimens, National Aeronautics and Space Administration Report NASA TN D-5390, August 1969.
6. Phillips, E.P., Long-crack growth rate data -constant amplitude and FALSTAFF loading-, AGARD Report N0.732: "Short-Crack Growth Behaviour in an Aluminum Alloy- An AGARD Cooperative Test Programme", December 1988.

Table 1a   Overview of crack growth results from Schijve (Ref. 1)
R = 0.037

Report: NLR M2162 [1]
Material: 2024-T3 Alclad
frequency: 53 Hz
specimen width: 160 mm
sheet thickness: 2.0 mm
R = 0.037

	ΔK (MPa √m)															
	13.39	15.19	16.81	18.30	19.68	20.99	22.23	23.99	26.20	28.30	30.32	32.29	35.66	40.47	45.47	50.85
da/dn 10^{-6} m/cycle	0.1613	0.2632	0.2941	0.4545	0.5128	0.5714	1	1.2903	2	2.5	3.6364	6.6667	8.3333	20		
	0.1835	0.2222	0.2778	0.4348	0.4762	0.5882	1.1111	1.0811	1.8182	2.2222	4.4444	4	7.6923	14.286	33.333	
	0.1869	0.2222	0.25	0.3922	0.6452	0.7143	0.9524	1.2903	1.9048	2.5	3.6364	6.6667	7.6923	16.667	50.000	100.000
	0.1307	0.1015	0.1389	0.1563	0.2083	0.303	0.4545	0.4878	0.7692	1.4286	1.0256	2.3529	3.3333	7.1429	20.000	
	0.1538	0.1042	0.0901	0.2299	0.2299	0.241	0.4762	0.4706	0.6452	1.4286	1.3333	1.7391	12.5	50		
	0.0976	0.1282	0.1212	0.1739	0.2469	0.2817	0.3175	0.4706	0.7692	1	1.6	2.3529	3.125	7.6923	20.000	50.000
	0.1754	0.1923	0.3077	0.3774	0.3846	0.4878	0.7692	0.9756	1.3333	1.9048	2.5	3.3333	5.5556	12.5	50.000	
	0.2247	0.2105	0.2632	0.4	0.7692	0.7692	1.25	1.3333	2	4	4.4444	5.7143	8.3333	25	50.000	
	0.1724	0.2222	0.2222	0.2381	0.3125	0.4762	0.5263	1.0811	1.4815	2.3529	3.3333	4.4444	8.3333	14.286	100.000	
	0.1923	0.1923	0.4167	0.3226	0.4545	0.6667	0.5	0.8333	1.3333	1.9048	3.3333	3.0769	6.6667	14.286	50.000	
	0.1563	0.2326	0.1667	0.2381	0.241	0.339	0.625	0.8889	1.5385	2.2222	4	4	6.6667	20	100.000	
	0.1361	0.1724	0.1695	0.1342	0.2941	0.3509	0.5714	0.8163	1.5385	2.1053	2.8571	5	6.6667	20	20.000	
	0.1575	0.2667	0.2439	0.3279	0.3636	0.5556	0.7692	1.1111	1.8182	2.6667	3.3333	4.4444	8.3333	16.667	33.333	
	0.2083	0.2632	0.2985	0.3175	0.3571	0.4762	0.6897	0.9091	1.6	2.2222	4	4	7.1429	16.667	33.333	
	0.1818	0.2353	0.1961	0.3077	0.4255	0.5405	0.8	1.0256	2	2.2222	4	5	9.0909	20	50.000	
	0.2128	0.3125	0.4082	0.3333	0.5882	0.4082	0.6897	0.9091	1.0256	2.3529	2.5	4.4444	6.6667	14.286	20.000	
	0.241	0.3333	0.4082	0.5	0.5714	0.3704	0.5556	0.5479	0.9524	1.3793	2	3.3333	4.5455	10	14.286	20.000
	0.2469	0.4082	0.4167	0.4545	0.3571	0.4	0.7692	1.0256	1.1111	1.9048	3.0769	4	6.6667	12.5	16.667	50.000
	0.1563	0.2151	0.274	0.2778	0.3279	0.4878	0.6667	0.8889	1.4286	2.3529	2.6667	4.4444	6.25	12.5	25.000	50.000
	0.1626	0.1942	0.2353	0.2703	0.3571	0.4651	0.7407	0.8889	1.2903	2	3.3333	3.3333	7.6923	10	50.000	50.000
	0.1739	0.2857	0.2532	0.3509	0.4762	0.4348	0.625	0.7407	1.25	2.1053	3.6364	4	6.6667	16.667	25.000	50.000

Table 1b Overview of crack growth results from Schijve (Ref. 1)
R = 0.27

Report: NLR M2162 [1]
Material: 2024-T3 Alclad
frequency: 53 Hz
specimen width: 160 mm
sheet thickness: 2.0 mm
R = 0.27

	ΔK (MPa √m)																
	8.19	9.29	10.28	11.19	12.04	12.84	13.59	14.67	16.02	17.31	18.54	19.75	21.81	24.75	27.81	31.10	34.78
da/dn 10^{-6} m/cycle	0.0833	0.0833	0.1342	0.1212	0.1695	0.2083	0.2817	0.3540	0.4255	1.3333	0.5556	1.0256	1.8519	2.9412	5.0000	12.5000	33.3333
	0.0402	0.1379	0.1493	0.1504	0.2000	0.2500	0.2500	0.5263	0.5405	0.6061	0.9091	2.0000	1.6949	4.1667	6.6667	12.5000	33.3333
	0.0709	0.1053	0.1250	0.1493	0.1961	0.2381	0.2778	0.2759	0.5263	0.6452	0.9302	1.0526	1.6667	3.2258	5.5556	11.1111	33.3333
	0.0658	0.0667	0.1136	0.0917	0.1042	0.1639	0.1739	0.1633	0.2030	0.3361	0.3774	0.5405	0.6849	1.4085	2.4390	5.0000	16.6667
	0.0417	0.0647	0.0560	0.0877	0.1064	0.1227	0.1724	0.1544	0.2312	0.3150	0.3636	0.4348	0.7576	1.3889	2.9412	5.0000	12.5000
	0.0508	0.0800	0.0505	0.0617	0.0493	0.1163	0.1266	0.1208	0.2484	0.2073	0.2857	0.4000	0.7246	1.2821	2.2222	4.1667	11.1111
	0.0722	0.1099	0.1105	0.1653	0.1869	0.2469	0.2941	0.3448	0.4938	0.5128	0.7407	1.0811	1.6949	3.1250	5.8824	9.0909	25.0000
	0.0690	0.0858	0.1460	0.1418	0.1709	0.3704	0.3226	0.3101	0.4124	0.4706	0.8163	1.0256	1.1765	1.9608	4.3478	7.6923	20.0000
	0.0597	0.1667	0.1183	0.1709	0.1653	0.2857	0.2778	0.3704	0.4545	0.5882	0.8000	0.9091	1.1364	2.4390	4.3478	10.0000	25.0000
	0.0629	0.0980	0.1053	0.1075	0.2500	0.2632	0.2020	0.2286	0.3150	0.4124	0.5882	0.7692	1.1628	1.8519	3.3333	7.6923	25.0000
	0.0643	0.0957	0.0901	0.1316	0.1653	0.1626	0.2899	0.2381	0.3922	0.3150	0.6452	0.8511	1.3158	2.5641	4.0000	10.0000	25.0000
	0.0694	0.0800	0.1020	0.1351	0.1538	0.1887	0.2667	0.2920	0.3604	0.4878	0.7273	0.6780	1.1628	2.9412	4.5455	9.0909	25.0000
	0.0787	0.1117	0.1342	0.1538	0.1626	0.2353	0.2353	0.3053	0.3175	0.4651	0.6667	0.8163	1.6949	3.0303	5.5556	11.1111	25.0000
	0.0733	0.1163	0.1015	0.1093	0.1550	0.1471	0.2020	0.2062	0.3200	0.4348	0.6250	1.0000	1.5152	3.0303	5.8824	10.0000	50.0000
	0.0635	0.0725	0.1307	0.1408	0.1739	0.2198	0.1961	0.2703	0.3704	0.3704	0.8889	0.9302	1.3333	2.5000	4.3478	10.0000	25.0000
	0.1242	0.1333	0.1802	0.1786	0.3125	0.2817	0.3333	0.4301	0.4545	0.6061	0.6667	0.6667	1.1494	2.1277	4.3478	5.8824	11.1111
	0.0966	0.1653	0.1639	0.2532	0.2564	0.2857	0.3333	0.4167	0.4082	0.4545	0.5128	0.6667	1.1236	2.0408	4.3478	9.0909	14.2857
	0.1005	0.1130	0.1961	0.1980	0.3448	0.2564	0.4167	0.3448	0.3846	0.4494	0.5479	0.6452	0.9174	1.5385	3.8462	6.2500	14.2857
	0.0719	0.1099	0.1130	0.1274	0.1724	0.1923	0.2128	0.2899	0.4124	0.4762	0.7018	0.8889	1.2658	2.2727	4.1667	6.6667	16.6667
	0.0532	0.1058	0.1099	0.1538	0.2000	0.2532	0.3030	0.3540	0.4598	0.5797	0.7273	0.9091	1.2048	2.1277	3.5714	6.2500	10.0000
	0.0588	0.1053	0.1149	0.1550	0.1653	0.2083	0.2857	0.2667	0.3846	0.5000	0.6250	0.9091	1.1765	2.1739	3.7037	8.3333	16.6667

Table 1c Overview of crack growth results from Schijve (Ref. 1)
R = 0.47

Report: NLR M2162 [1]
Material: 2024-T3 Alclad
frequency: 53 Hz
specimen width: 160 mm
sheet thickness: 2.0 mm
R = 0.47

	ΔK (MPa √m)																	
	5.14	5.84	6.46	7.03	7.56	8.06	8.54	9.22	10.07	10.87	11.65	12.41	13.70	15.55	17.47	19.54	21.85	24.52
da/dn 10^{-6} m/cycle	0.0135	0.0267	0.0405	0.0464	0.0755	0.0755	0.0948	0.1187	0.1527	0.1860	0.2286	0.3604	0.4808	0.8197	1.2821	2.0833	3.7037	6.6667
	0.0150	0.0256	0.0377	0.0621	0.0510	0.1000	0.0948	0.1114	0.1471	0.1739	0.2548	0.3101	0.4651	0.8000	1.2658	1.8868	3.7037	6.6667
	0.0156	0.0235	0.0332	0.0714	0.0526	0.0952	0.0830	0.1170	0.1527	0.2041	0.2439	0.3008	0.4132	0.7692	1.2500	2.3810	3.2258	7.6923
	0.0102	0.0267	0.0344	0.0477	0.0485	0.0613	0.0758	0.0752	0.1036	0.1102	0.1303	0.1818	0.2174	0.4167	0.6410	0.8475	1.4925	4.3478
	0.0125	0.0275	0.0437	0.0443	0.0554	0.0714	0.0800	0.0891	0.1208	0.1278	0.1646	0.2198	0.2545	0.4348	0.6250	0.9259	1.3514	3.1250
	0.0092	0.0175	0.0444	0.0433	0.0457	0.0690	0.0664	0.0739	0.1050	0.1194	0.1460	0.2286	0.2208	0.3390	0.4785	0.6452	1.3889	2.7778
	0.0117	0.0248	0.0413	0.0575	0.0568	0.0735	0.1299	0.1075	0.1835	0.1869	0.2532	0.3478	0.4219	0.6024	0.9524	1.7241	3.3333	5.2631
	0.0129	0.0243	0.0727	0.0433	0.0604	0.0752	0.1005	0.1053	0.1429	0.2235	0.2353	0.2941	0.4082	0.7042	1.0526	1.7857	2.7778	5.8823
	0.0139	0.0310	0.0355	0.0556	0.0615	0.0909	0.0873	0.1036	0.1000	0.2151	0.2116	0.2759	0.3356	0.4717	0.8547	1.5152	2.5000	5.8823
	0.0138	0.0279	0.0358	0.0495	0.0615	0.0758	0.0712	0.1061	0.1320	0.1639	0.2162	0.2367	0.2994	0.5495	0.8772	1.5152	2.9412	5.2631
	0.0115	0.0282	0.0451	0.0673	0.0592	0.0833	0.0901	0.1176	0.1266	0.1980	0.1818	0.2667	0.3448	0.5682	0.8000	1.3889	2.3256	3.8462
	0.0165	0.0286	0.0376	0.0546	0.0602	0.0697	0.0980	0.1034	0.1294	0.1653	0.2235	0.2299	0.3534	0.5650	0.9346	1.4706	2.2727	4.5455
	0.0132	0.0318	0.0505	0.0580	0.0709	0.0909	0.0980	0.1299	0.1538	0.1674	0.1932	0.3448	0.3831	0.6250	1.0870	1.7857	2.7778	5.5556
	0.0100	0.0290	0.0370	0.0554	0.0637	0.0719	0.0926	0.1117	0.1307	0.1878	0.2105	0.2632	0.3676	0.6061	1.0101	1.4493	2.5000	4.3478
	0.0167	0.0388	0.0505	0.0588	0.0784	0.0837	0.1379	0.1231	0.1498	0.2186	0.2500	0.3333	0.3846	0.8621	1.0101	1.8182	2.9412	5.5556
	0.0111	0.0213	0.0542	0.0593	0.1036	0.1015	0.1183	0.1550	0.1527	0.2941	0.3333	0.3030	0.4505	0.6098	0.8772	1.3158	2.2222	4.0000
	0.0183	0.0293	0.0885	0.0694	0.1190	0.1087	0.1266	0.1498	0.1961	0.2797	0.3509	0.2899	0.4525	0.6757	0.9259	1.2048	2.8571	4.5455
	0.0154	0.0323	0.0613	0.0719	0.0840	0.1235	0.1176	0.1504	0.2083	0.2339	0.3279	0.3390	0.4425	0.6173	0.8696	1.0870	1.7857	3.1250
	0.0194	0.0324	0.0478	0.0592	0.0816	0.0976	0.0926	0.1143	0.1266	0.2030	0.2247	0.2367	0.3484	0.6452	0.9259	1.6393	2.5000	4.5455
	0.0169	0.0464	0.0501	0.0858	0.0823	0.1087	0.1333	0.1235	0.1587	0.2105	0.2703	0.3390	0.4255	0.7519	1.1236	2.0000	3.2258	7.6923
	0.0216	0.0444	0.0518	0.0515	0.0837	0.0889	0.1031	0.1183	0.1418	0.1869	0.2186	0.2778	0.3497	0.5988	0.8621	1.6667	2.9412	5.5556

Table 2 Calculated standard deviations of log (da/dn) as a function ΔK

Report: NLR M2162 [1]								
Material: 2024-T3 Alclad								
Frequency: 53 Hz.								
Specimen width: 160 mm								
sheet thickness: 2.0 mm								
R	ΔK (MPa√m)	std(log (da/dn))	R	ΔK (MPa√m)	std(log (da/dn))	R	ΔK (MPa√m)	std(log (da/dn))
0.037	13.39	0.0932	0.27	8.19	0.1162	0.47	5.14	0.0982
	15.19	0.1507		9.29	0.1143		5.84	0.0973
	16.81	0.1791		10.28	0.1408		6.46	0.1094
	18.30	0.1556		11.19	0.1322		7.03	0.0796
	19.68	0.1540		12.04	0.1760		7.56	0.1084
	20.99	0.1322		12.84	0.1270		8.06	0.0797
	22.23	0.1396		13.59	0.1208		8.54	0.0893
	23.99	0.1392		14.67	0.1551		9.22	0.0831
	26.20	0.1458		16.02	0.1128		10.07	0.0836
	28.30	0.1240		17.31	0.1569		10.87	0.1064
	30.32	0.1720		18.54	0.1334		11.65	0.1081
	32.29	0.1443		19.75	0.1506		12.41	0.0796
	35.66	0.1371		21.81	0.1226		13.70	0.0993
	40.47	0.1821		24.75	0.1358		15.55	0.1021
				27.81	0.1218		17.47	0.1043
				31.10	0.1367		19.54	0.1383
				34.78	0.1863		21.85	0.1293

Table 3 Crack growth results from McEvily and Illg (Ref. 2)

Report: NACA TN 4394 [2]					
Material: 2024-T3 bare					
frequency: see table					
specimen width: 305 mm					
sheet thickness: 2.6 mm					
ΔK	da/dn	R	ΔK	da/dn	R
MPa√m	10^{-6} m/cycle		MPa√m	10^{-6} m/cycle	
frequency 30 Hz			frequency 20 Hz		
6.09	0.0181	0.1	16.38	0.4536	0.04
7.21	0.0454		19.39	0.5292	
8.18	0.1155		21.99	0.5292	
9.05	0.0552		24.33	0.5773	
10.22	0.1210		27.47	0.7938	
11.60	0.1494		31.19	1.8143	
13.43	0.2117		36.11	3.1750	
15.58	0.3175		41.90	12.7000	
18.00	0.3810		48.39	10.1600	
frequency 30 Hz			frequency 20 Hz		
9.19	0.0948	0.07	19.78	0.7056	0.033
10.88	0.1411		23.41	0.9769	
12.34	0.1954		26.55	1.2700	
13.65	0.2309		29.37	2.1167	
15.41	0.3528		33.16	3.1750	
17.49	0.2920		37.65	6.3500	
20.26	0.4792		43.59	10.1600	
23.50	0.9769				
27.14	0.9071		frequency 0.33 Hz		
			26.57	2.4756	0.025
frequency 20 Hz			31.45	3.3687	
12.89	0.2153	0.05	35.67	7.1348	
15.25	0.2761		39.46	10.8547	
17.30	0.3256		44.55	15.8750	
19.13	0.3735		50.58	29.8824	
21.60	0.4379		58.57	84.6667	
24.53	0.6350				
28.40	1.1289		frequency 0.33 Hz		
32.96	2.4190		33.37	13.3684	0.02
38.06	5.8615		39.49	36.2857	
			44.79	105.8333	
			49.54	84.6667	
			55.94	362.8571	

Table 4 Crack growth results from McEvily and Illg (Ref. 3)

Report: NASA TN D-52 [3]					
Material: 2024-T3 bare					
frequency: see table					
specimen width: 305 mm					
sheet thickness: 2.1 mm					
ΔK	da/dn	R	ΔK	da/dn	R
(MPa√m)	10^{-6} m/cycle		MPa√m)	10^{-6} m/cycle	
frequency 30 Hz			frequency 0.22 Hz		
8.19	0.0046	-1	27.27	0.3969	-1
9.70	0.0059		32.28	0.5853	
11.00	0.0121		36.61	0.8759	
12.16	0.0195		40.49	1.3656	
13.73	0.0254		45.72	2.0820	
15.59	0.0391		51.91	3.7353	
18.05	0.0696		60.11	5.4043	
20.95	0.1210		69.74	7.6970	
24.19	0.1905		80.55	12.2903	
27.79	0.3464		92.51	25.4000	
32.36	0.3528		107.72	47.0370	
38.10	0.5773				
frequency 30 Hz			frequency 0.15 Hz		
13.59	0.0273	-1	40.96	2.7729	-1
16.08	0.0651		48.48	3.8838	
18.24	0.0847		54.98	5.6444	
20.17	0.0977		60.81	9.0714	
22.78	0.1337		68.66	15.1190	
25.86	0.1752		77.96	29.1954	
29.94	0.2478		90.27	50.2970	
34.74	0.3629		104.74	127.0000	
40.13	0.5080		120.97	245.8065	
46.08	0.8467		138.93	508.0000	
53.66	1.6933		161.78	1154.5455	
frequency 20 Hz					
27.27	0.3780	-1			
32.28	0.4456				
36.61	0.6350				
40.49	0.8881				
45.72	1.5679				
51.91	2.5149				
60.11	4.6606				

Table 5a Crack growth results from Hudson (Ref. 5)
R = -1

Report: NASA TN D-5390 [5]					
Material: 2024-T3 bare					
frequency: see table					
specimen width: 305 mm					
thickness: 2.3 mm					
ΔK	da/dn	R	ΔK	da/dn	R
MPa√m	10^{-6} m/cycle		MPa√m	10^{-6} m/cycle	
frequency 0.5 Hz			frequency 13.7 Hz		
37.76	1.0855	-1	22.66	0.1435	-1
48.78	2.6458		29.27	0.2886	
57.78	6.3500		34.67	0.4618	
65.60	10.1600		39.36	0.6684	
72.65	16.9333				
79.15	25.4000				
85.22	31.7500				
90.98	50.8000				
96.48	63.5000				
frequency 0.5 Hz			frequency 13.7 Hz		
30.21	0.5237	-1	15.10	0.0423	-1
39.02	1.2390		19.51	0.0876	
46.22	2.1167		23.11	0.1588	
52.48	3.1750		26.24	0.2117	
58.12	5.0800		29.06	0.2540	
63.32	7.2571		31.66	0.2822	
68.18	10.1600		34.09	0.3629	
72.78	16.9333		36.39	0.5080	
77.19	16.9333		38.59	0.5080	
			frequency 13.7 Hz		
			14.56	0.0282	-1
			17.25	0.0508	
			19.59	0.0847	
			21.69	0.1016	
			23.63	0.1693	
			25.44	0.1693	
			27.16	0.1693	
			28.81	0.2540	
			31.16	0.3387	
			34.17	0.3387	

Table 5b Crack growth results from Hudson (Ref. 5)
R = 0

Report: NASA TN D-5390 [5]					
Material: 2024-T3 bare					
frequency: see table					
specimen width: 305 mm					
thickness: 2.3 mm					
ΔK	da/dn	R	ΔK	da/dn	R
MPa√m	10^{-6} m/cycle		MPa√m	10^{-6} m/cycle	
frequency 0.3 Hz			frequency 20 Hz		
22.66	0.9071	0	7.55	0.0179	0
29.27	2.3091		9.76	0.0706	
34.67	5.0800		11.56	0.1155	
39.36	8.4667		13.12	0.1588	
43.59	16.9333		14.53	0.2117	
47.49	16.9333		15.83	0.2309	
			17.04	0.2822	
			18.20	0.3175	
			19.30	0.4233	
			20.88	0.4233	
			22.89	0.6350	
			24.84	0.8467	
frequency 20 Hz			frequency 30 Hz		
15.10	0.2822	0	5.69	0.0042	0
19.51	0.4032		7.35	0.0149	
23.11	0.6048		8.71	0.0423	
26.24	1.0160		9.89	0.0635	
29.06	1.6933		10.95	0.0847	
31.66	3.1750		11.93	0.1270	
34.09	3.6286		12.85	0.1270	
36.39	8.4667		13.71	0.1270	
			14.54	0.2540	
frequency 20 Hz			15.73	0.1693	
11.27	0.1058	0	17.25	0.2540	
14.56	0.1881				
17.25	0.2822				
19.59	0.3908				
21.69	0.4618				
23.63	0.6350				
25.44	0.8467				
27.16	1.2700				
28.81	1.6933				
31.16	2.0320				

Table 5c Crack growth results from Hudson (Ref. 5)
R = 0.33

Report: NASA TN D-5390 [5]					
Material: 2024-T3 bare					
frequency: see table					
specimen width: 305 mm					
thickness: 2.3 mm					
ΔK	da/dn	R	ΔK	da/dn	R
MPa √m	10^{-6} m/cycle		MPa √m	10^{-6} m/cycle	
frequency 20 Hz			frequency 20 Hz		
15.10	0.4164	0.33	7.55	0.0423	0.33
19.51	0.9407		9.76	0.1155	
23.11	1.8143		11.56	0.1954	
26.24	3.6286		13.12	0.3791	
			14.53	0.1910	
frequency 20 Hz			15.83	0.5080	
11.27	0.2117	0.33	17.04	0.5080	
14.56	0.4032		18.20	0.5080	
17.25	0.5773		19.30	1.2700	
19.59	0.9071		20.88	1.0160	
21.69	1.2700		22.89	1.6933	
23.63	1.9538		24.84	2.5400	
25.44	2.5400				
27.16	3.6286		frequency 30 Hz		
28.81	4.2333		3.72	0.0046	0.33
			4.81	0.0110	
frequency 20 Hz			5.69	0.0212	
9.52	0.1239	0.33	6.47	0.0254	
12.30	0.2309		7.16	0.0508	
14.57	0.3387		7.80	0.0635	
16.54	0.5080		8.40	0.0847	
18.32	0.8467		8.97	0.0847	
19.96	0.8467		9.51	0.1270	
21.49	1.2700		10.29	0.1016	
22.94	1.6933		11.28	0.2540	
24.33	1.6933		12.24	0.2540	
			13.18	0.5080	

Table 5d Crack growth results from Hudson (Ref. 5)
R = 0.5

Report: NASA TN D-5390 [5]					
Material: 2024-T3 bare					
frequency: see table					
specimen width: 305 mm					
thickness: 2.3 mm					
ΔK	da/dn	R	ΔK	da/dn	R
MPa √m	10^{-6} m/cycle		MPa √M	10^{-6} m/cycle	
frequency 20 Hz			frequency 20 Hz		
11.27	0.2674	0.5	5.69	0.0154	0.5
14.56	0.5644		7.35	0.0529	
17.25	1.0160		8.71	0.1016	
19.59	1.6933		9.89	0.1494	
21.69	3.1750		10.95	0.1693	
23.63	6.3500		11.93	0.2540	
			12.85	0.2822	
frequency 20 Hz			13.71	0.2822	
9.41	0.1373	0.5	14.54	0.5080	
12.16	0.2822		15.73	0.5644	
14.40	0.5080		17.25	0.8467	
16.35	0.8194				
18.11	0.9769		frequency 30 Hz		
19.73	1.4111		3.72	0.0023	0.5
21.24	2.5400		4.81	0.0045	
22.68	2.3091		5.69	0.0127	
24.05	5.0800		6.47	0.0423	
			7.16	0.0508	
frequency 20 Hz			7.80	0.0635	
7.55	0.0876	0.5	8.40	0.0847	
9.76	0.1814		8.97	0.0847	
11.56	0.3175		9.51	0.1270	
13.12	0.4233		10.29	0.1693	
14.53	0.5080		11.28	0.1693	
15.83	0.6350				
17.04	0.8467				
18.20	1.2700				
19.30	1.2700				
20.88	2.5400				
22.89	5.0800				

Table 5e Crack growth results from Hudson (Ref. 5)
R = 0.7

Report: NASA TN D-5390 [5]					
Material: 2024-T3 bare					
frequency: see table					
specimen width: 305 mm					
thickness: 2.3 mm					
ΔK	da/dn	R	ΔK	da/dn	R
MPa√m	10^{-6} m/cycle		MPa√m	10^{-6} m/cycle	
frequency 13.7 Hz			frequency 13.7 Hz		
7.55	0.0498	0.7	3.94	0.0043	0.7
9.76	0.1588		5.09	0.0115	
11.56	0.4233		6.03	0.0318	
13.12	0.6350		6.85	0.0508	
			7.58	0.0847	
frequency 13.7 Hz			8.26	0.0847	
6.68	0.0302	0.7	8.89	0.1270	
8.62	0.1104		9.49	0.1270	
10.22	0.2117		10.07	0.2540	
11.60	0.3629		10.89	0.2540	
frequency 13.7 Hz			frequency 13.7 Hz		
5.25	0.0102	0.7	3.85	0.0025	0.7
6.79	0.0529		4.37	0.0051	
8.04	0.0977		4.84	0.0102	
9.13	0.1588		5.28	0.0181	
10.11	0.2117		5.68	0.0231	
11.01	0.2822		6.07	0.0363	
11.86	0.3629		6.43	0.0318	
12.66	0.6350		6.96	0.0847	
			7.63	0.1270	

Table 6a Crack growth results from Philips (Ref. 6)
R = -1

Report: AGARD-R-732 [6]		
Material: 2024-T3 bare		
frequency: 15 Hz		
specimen width: 50.8 mm		
sheet thickness: 2.3 mm		
ΔK	da/dn	R
MPa√m	10^{-6} m/cycle	
11.7	0.0105	-1
11.74	0.0151	
12.63	0.0279	
12.68	0.031	
13.56	0.0366	
13.64	0.0376	
14.53	0.0437	
14.62	0.0457	
16	0.065	
16.11	0.0668	
17.61	0.0925	
17.76	0.0983	
19.42	0.101	
19.63	0.137	
21.41	0.191	
21.68	0.178	
23.53	0.218	
23.85	0.217	
25.85	0.246	
26.24	0.223	
28.41	0.386	
28.87	0.386	
31.26	0.528	
31.84	0.546	
34.41	0.678	
35.14	0.709	
37.84	0.874	
38.72	0.795	
41.7	1.59	
42.81	1.98	
12.68	0.0107	
13.11	0.0138	
13.75	0.0176	
14.45	0.0366	

Table 6b Crack growth results from Philips (Ref. 6)
R = 0.5 and R = 0

Report: AGARD-R-732 [6]					
Material: 2024-T3 bare					
frequency: 15 Hz					
specimen width: 50.8 mm					
sheet thickness: 2.3 mm					
ΔK	da/dn	R	ΔK	da/dn	R
MPa√m	10^{-6} m/cycle		MPa√m	10^{-6} m/cycle	
4.66	0.0121	0.5	6.67	0.0154	0
5.22	0.0156		6.87	0.0142	
4.99	0.018		6.87	0.021	
4.63	0.0116		7.24	0.0305	
4.85	0.0195		7.25	0.0284	
4.84	0.0178		8.04	0.0417	
5.39	0.0215		8.07	0.0498	
5.35	0.0212		9.29	0.0686	
5.62	0.0248		9.32	0.0714	
5.58	0.0279		9.67	0.0879	
6.23	0.0424		9.72	0.0787	
6.2	0.0483		10.68	0.145	
6.53	0.0556		10.73	0.145	
6.5	0.045		11.08	0.159	
7.1	0.115		11.13	0.16	
7.04	0.0612		12.19	0.175	
7.82	0.0874		12.26	0.205	
7.8	0.0892		12.65	0.198	
8.67	0.132		12.75	0.188	
8.61	0.108		14.01	0.257	
9.1	0.138		14.12	0.257	
9.02	0.18		14.62	0.318	
10.68	0.272		14.76	0.307	
10.62	0.226		16.07	0.338	
11.2	0.297		16.24	0.401	
11.09	0.318		16.67	0.434	
12.5	0.381		16.9	0.424	
12.35	0.366		18.43	0.541	
13.17	0.508		18.69	0.521	
13.06	0.587		19.22	0.544	
			19.56	0.655	
			21.16	1.02	
			21.6	0.98	
			21.94	0.726	
			22.34	0.422	
			24.41	2.64	
			24.87	3.12	
			25.69	1.93	
			26.43	2.49	

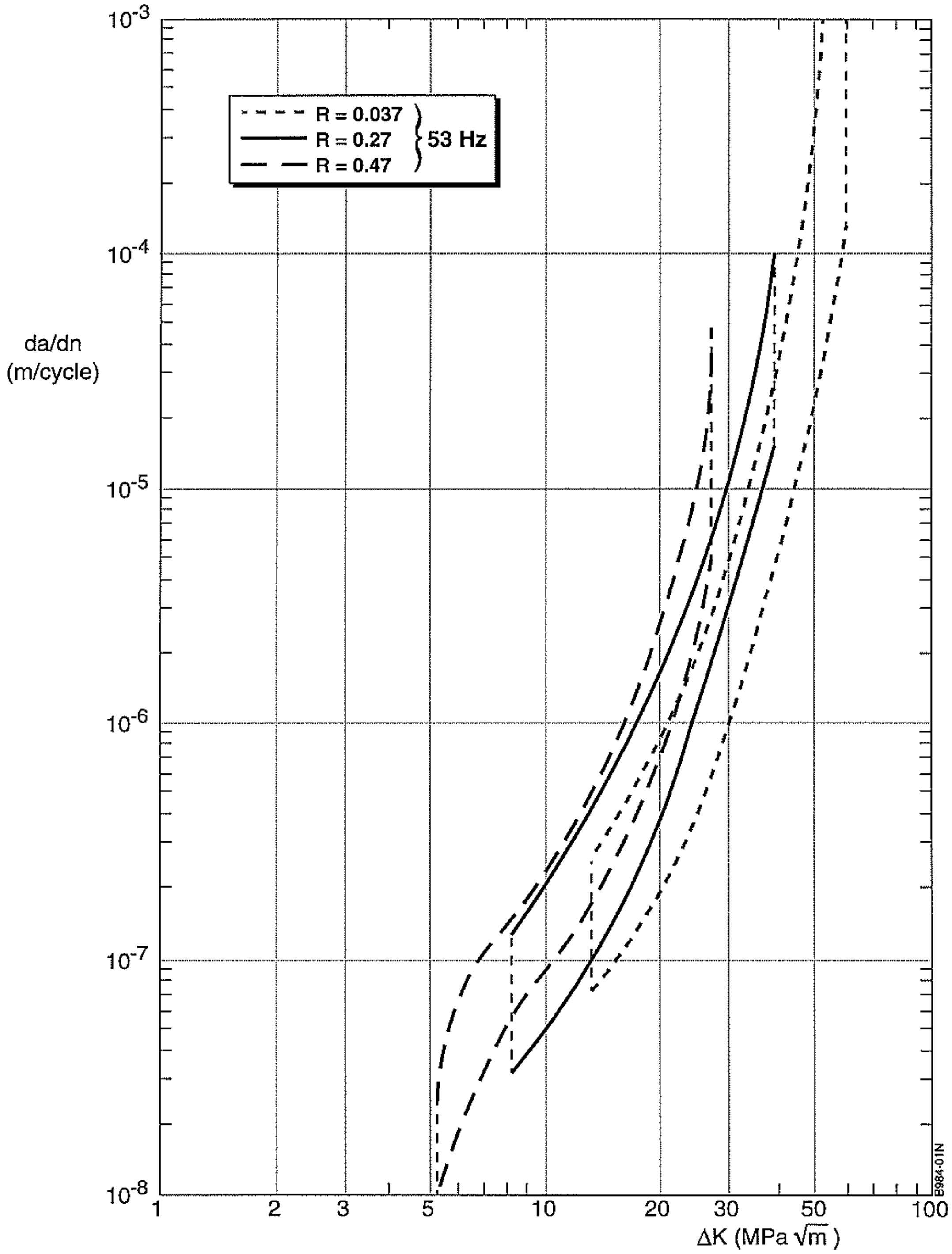

Fig. 1 Constant amplitude fatigue crack growth rate scatterbands representing material batch variability [Ref. 1]

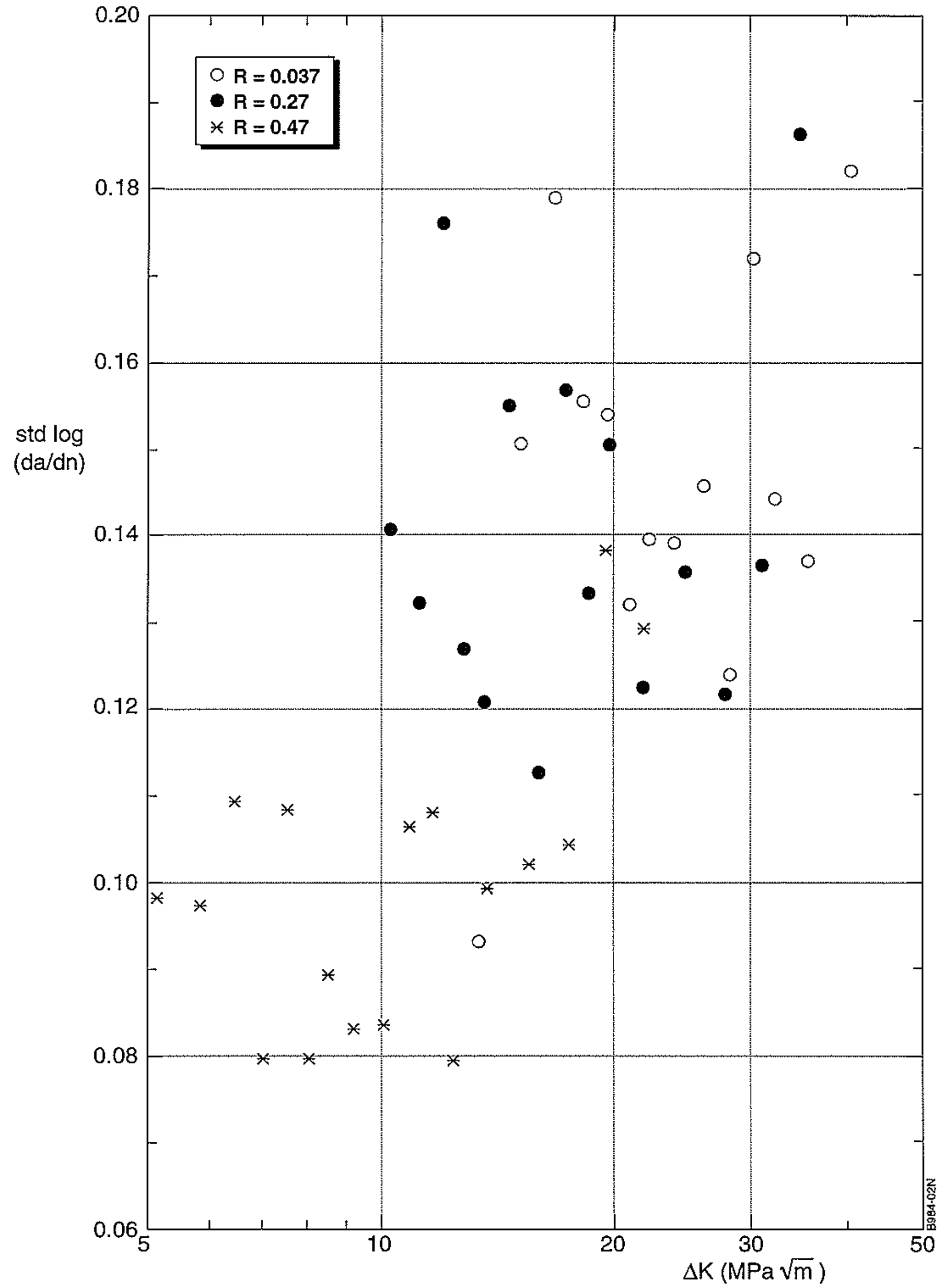

Fig. 2 Batch variability as function of ΔK [Ref. 1]

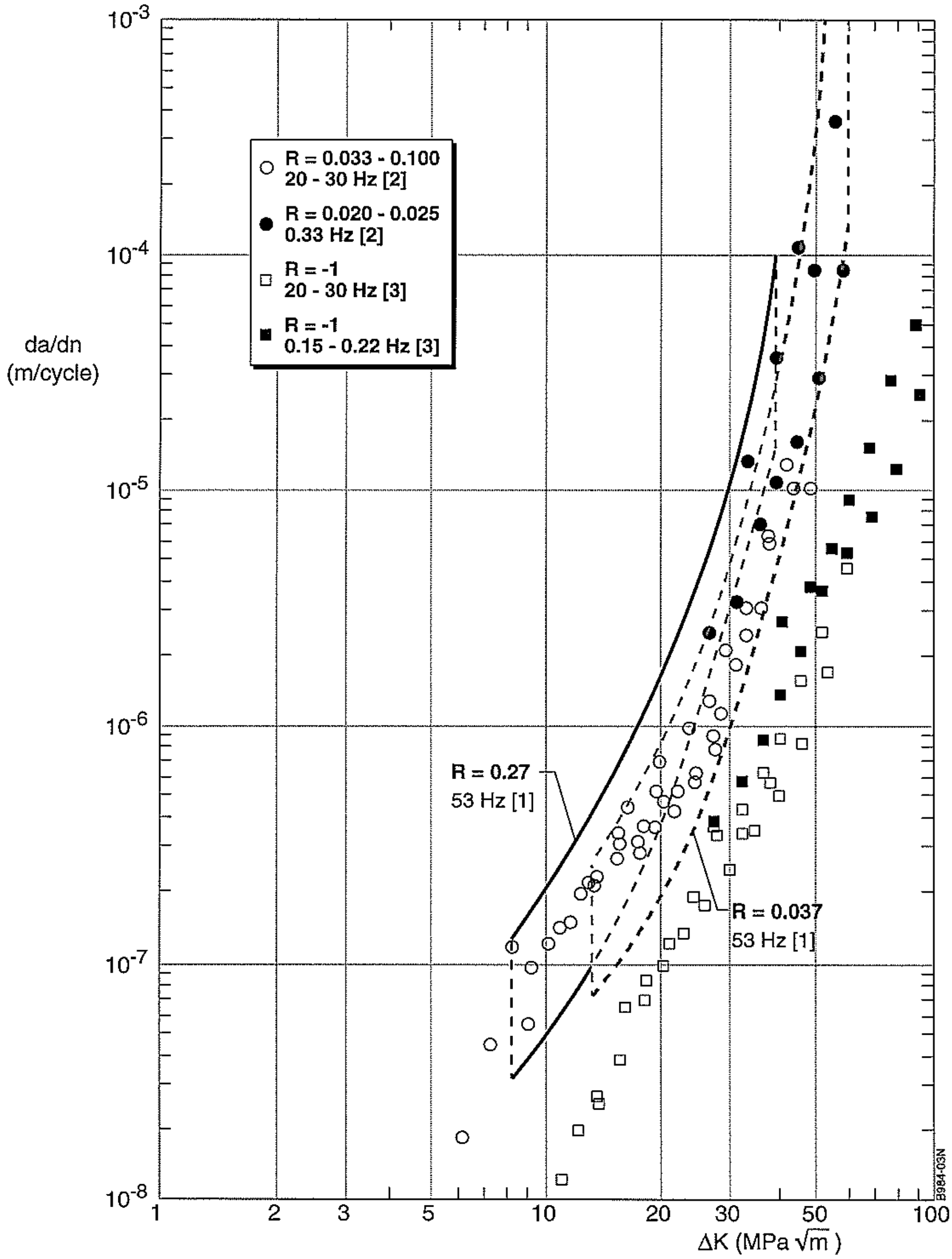

Fig. 3 Constant amplitude fatigue crack growth results from McEvily and Illg [Refs. 2, 3] compared with two of the scatterbands from figure 1

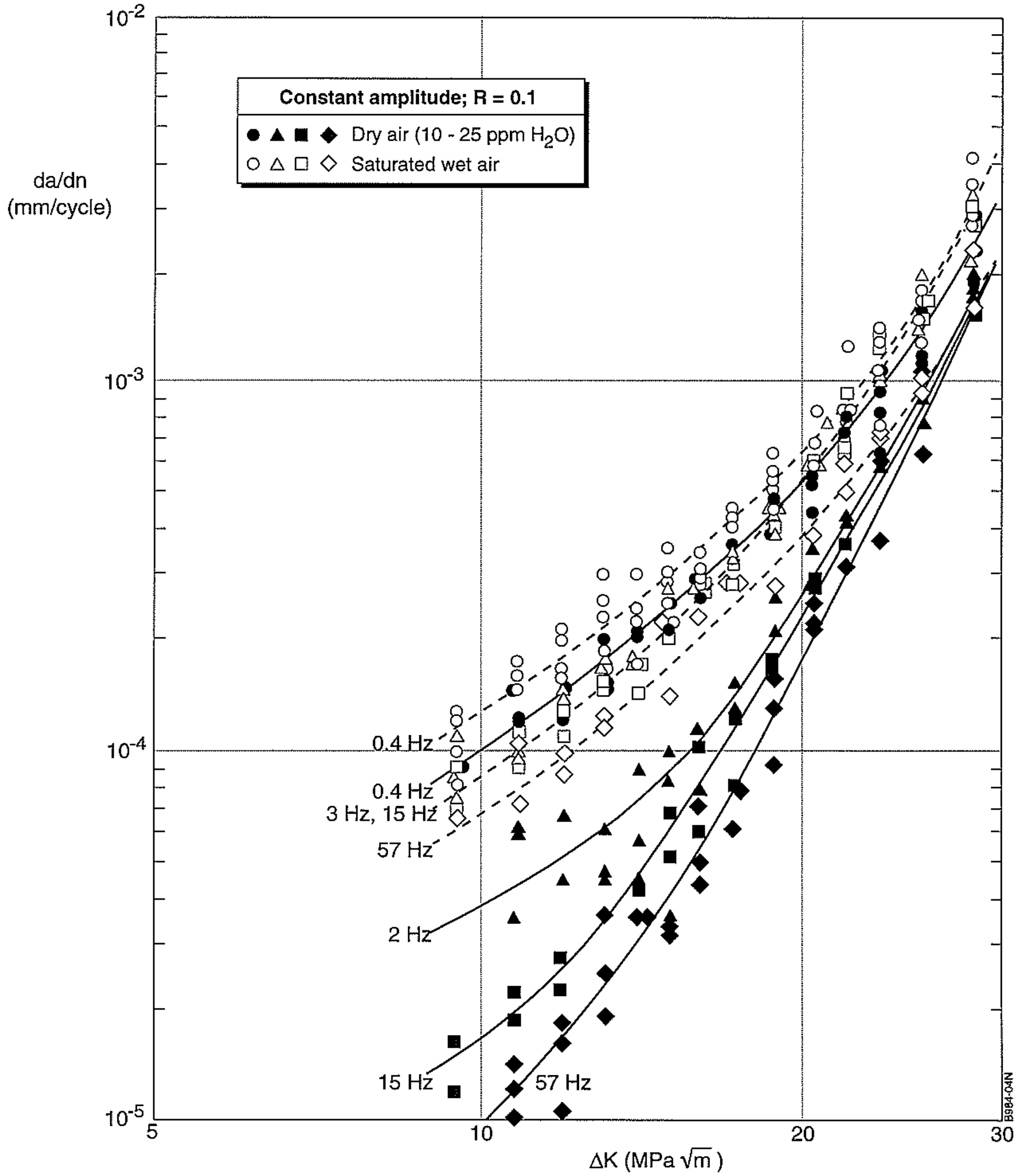

Fig. 4 Frequency effects on 1 mm 2024-T3 Alclad sheet [Ref. 4]

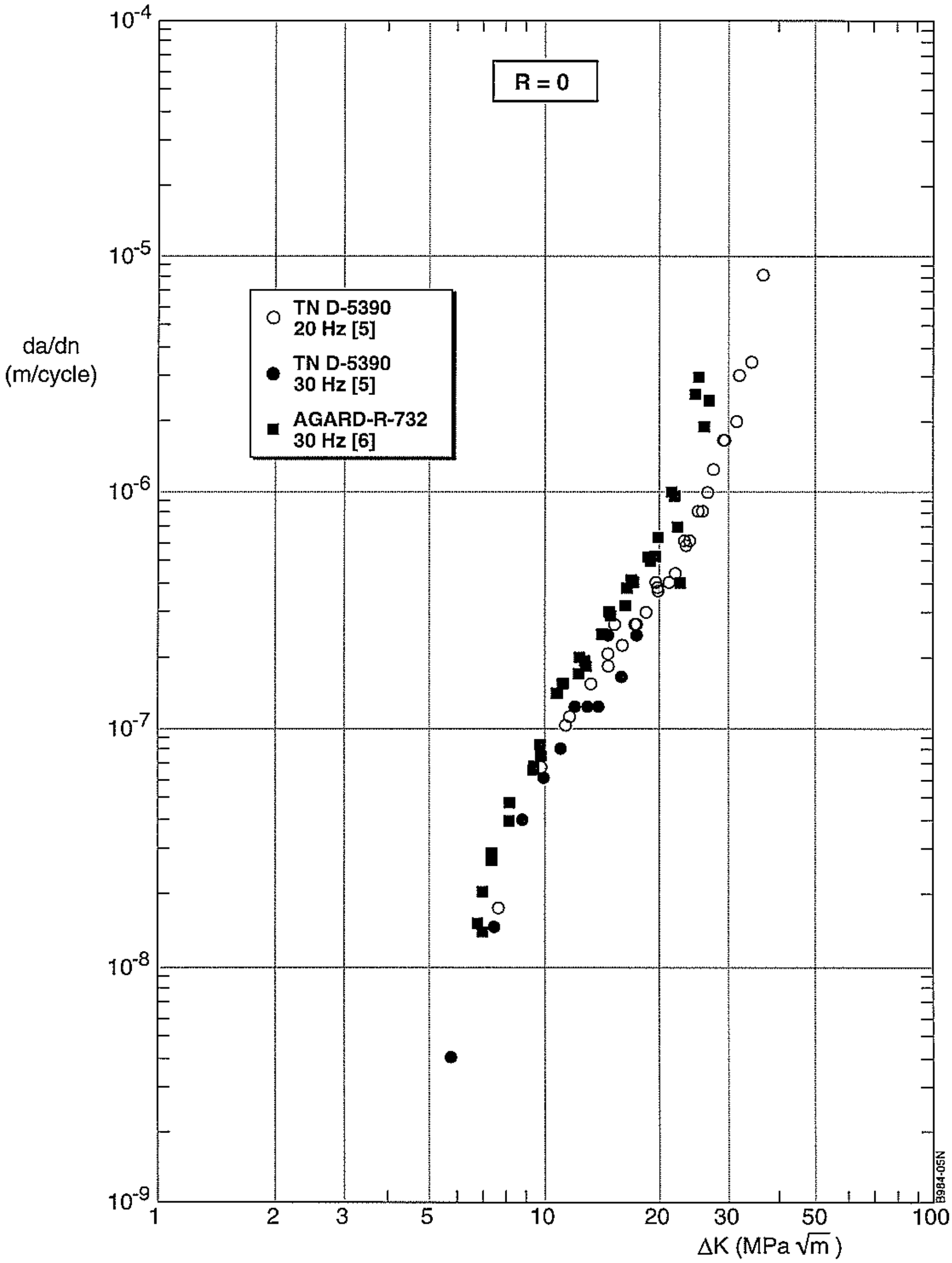

Fig. 5 Comparison of constant amplitude fatigue crack growth rates for R = 0

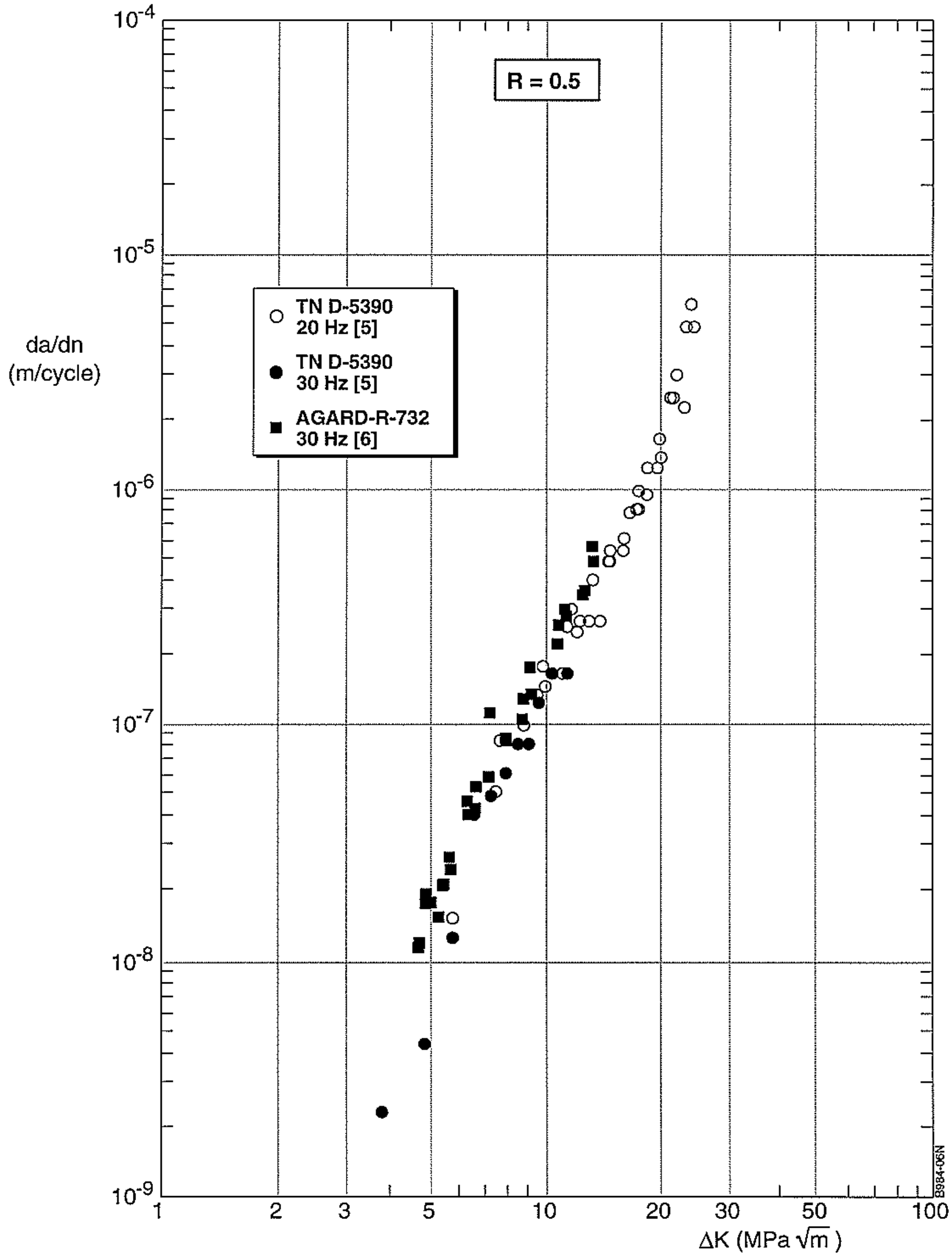

Fig. 6 Comparison of constant amplitude fatigue crack growth rates for R = 0.5

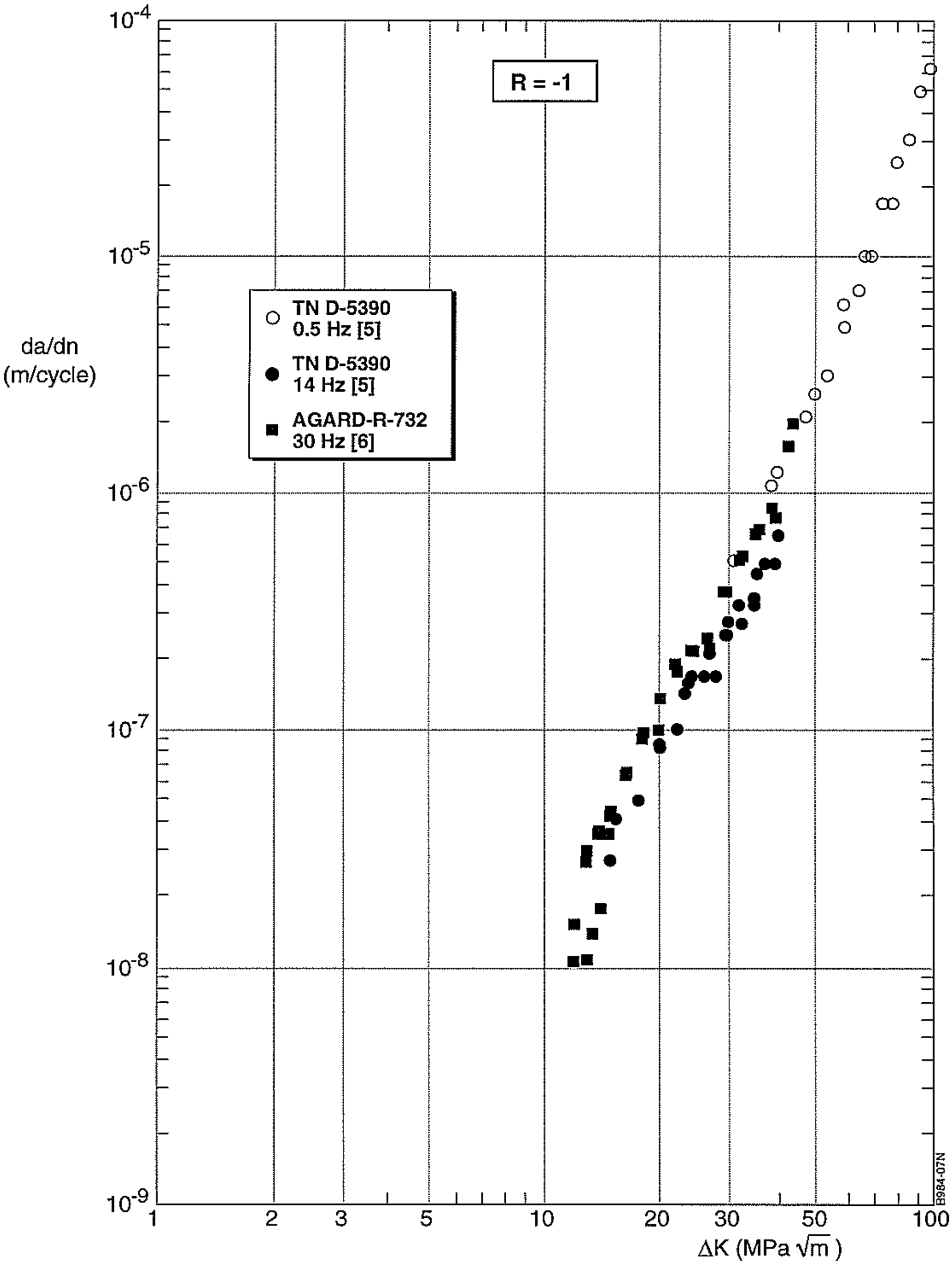

Fig. 7 Comparison of constant amplitude fatigue crack growth rates for R = -1

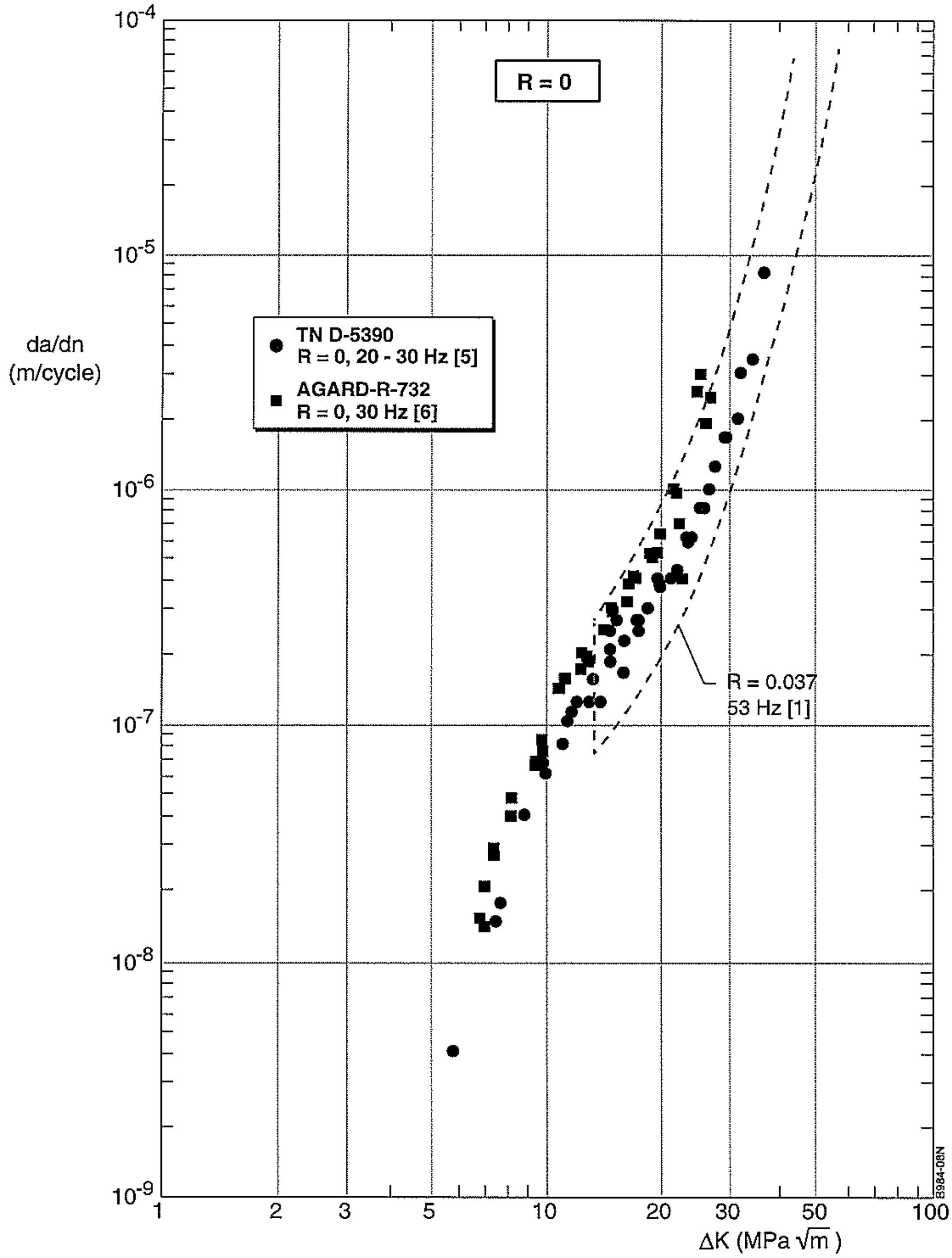

Fig. 8 Comparison of crack growth rates for R = 0 and a scatterband representing crack growth data for R = 0.037

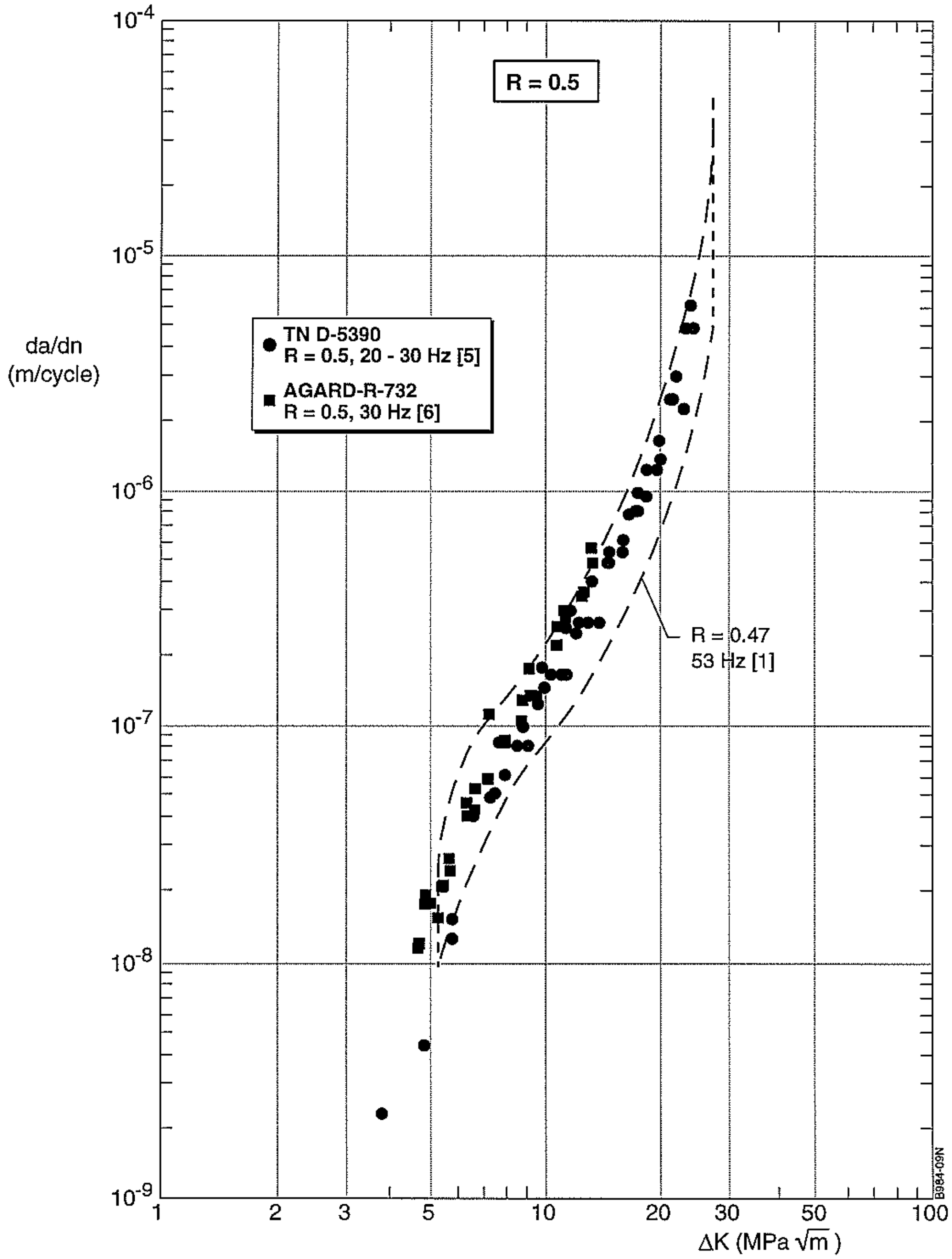

Fig. 9 Comparison of crack growth rates for R = 0.5 and a scatterband representing crack growth data for R = 0.47