Determination of fatigue crack propagation limit curves for high strength steels, and their applicability for structural elements having crack like defects

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Abstract There are different documents and standards containing fatigue crack propagation limit or design curves and rules for the prediction of crack growth. The research work aimed to characterise the fatigue crack propagation resistance of different steels using limit curves, based on statistical analysis of test results and fatigue crack propagation law, and to determine fatigue crack propagation limit curves for different structural steels and wide-spreading high strength steels, and their welded joints, under mode I and mixed mode I + II loading conditions. Experiments were performed on different (high strength) steels and partially their welded joints. The specimens were cut parallel and perpendicular to the characteristic directions of the materials; therefore the specimens represent the different possible locations of cracks in the base materials and welded joints. Fatigue crack growth experiments were performed by ΔK-decreasing and constant load amplitude methods. The evaluation process consists of six steps and by means of the evaluated and selected values a simplified method can be proposed for determination of fatigue crack propagation limit curves. The determined limit curves represent a compromise of rational risk and acceptable safety.

Keywords fatigue crack growth, limit curve, high strength steel, engineering critical assessment

1. Introduction

Reliability of a structural element having crack or crack-like defect under cyclic loading conditions is determined by the geometrical features of the structural element and the flaws, the loading conditions, as well as the material resistance to fatigue crack propagation. There are different documents [1-3], standards and recommendations [4-6] containing fatigue crack propagation limit or design curves and rules for the prediction of crack growth [6, 7]. The background of the fatigue crack propagation limit curves and the calculations consist of two basic parts: statistical analysis of numerous experiments (fatigue crack propagation tests) and fatigue crack propagation law, frequently the Paris-Erdogan law [8],

$$\frac{da}{dN} = C\Delta K^{n}, \tag{1}$$

where da/dN is the fatigue crack growth rate, ΔK is the stress intensity factor range, furthermore C and n are material constants.

The research work aimed

- to characterise the fatigue crack propagation resistance of different steels using limit curves [9], [10], based on statistical analysis of test results and the Paris-Erdogan law;
- determination of limit curves for different structural steels and wide-spreading high strength steels [11], and their welded joints, under mode I (tension) and mixed mode I + II (tension and shear) loading conditions.

2. Examinations

2.1. Materials and welding characteristics

The most important characteristics of the investigated structural steels and high strength steels, and used welding technologies are summarized in Table 1.

Table 1. Main characteristics of the investigated materials and used welding technologies

Steel type	Grade/Mark	Welding method	Shielding gas	Filler material
micro-alloyed	37C	gas metal arc	100 CO_2	VIH-2
low-alloyed DP	DP-25156	–	–	–
micro-alloyed	E420C	gas metal arc	80 Ar + 20 CO_2	Union K56
high strength TRIP	TRIP-28670	–	–	–
high strength	X80TM	gas metal arc	82 Ar + 18 CO_2	X-90 IG
high strength	QStE690TM	–	–	–
high strength	S960QL	under development (see 5. Conclusions, too)		
high strength	XABO 1100	–	–	–

The measured mechanical properties (R_y, R_m, A_5) and the therefrom calculated values (R_y/R_m, R_m*A_5) of the investigated base materials and weld metals are summarized in Table 2.

Table 2. Mechanical properties and characteristic calculated values of the investigated materials

Grade/Mark	R_y (1) N/mm^2	R_m N/mm^2	R_y/R_m –	A_5 %	R_m * A_5 N/mm^2 * %
37C base material	270	405	0,666	33,5	13567
VIH-2 weld metal	410-485	535-585	0,766-0,829	22,0-24,8	≥11770
DP-25156 base material	350-380	790-820	0,427-0,481	12,5-19,8 (2)	≥9875 (2)
E420C base material	450	595	0,756	30,7	18266
Union K56 weld metal	≥500	560-720	0,694-0,893	≥22,0	≥12320
TRIP-28670 base material	430-490	730-745	0,577-0,671	24,2-28,6 (2)	≥17666 (2)
X80TM base material	540	625	0,864	25,1	15687
QStE690TM alapanyag	780	850	0,918	18,3	15555
Böhler X90-IG weld metal	≥890	≥940	≈0,947	≥16,0	≥15040
S960QL base material	1007	1045	0,964	16,0	16112
XABO 1100 base material	1125	1339	0,840	11,0 (3)	14729 (3)

(1) R_y means R_{eH} or $R_{p0,2}$.
(2) For these material A_{80} instead of A_5.
(3) For these material A_{97} instead of A_5.

Fig. 1 shows the ultimate tensile strength vs. elongation (fracture strain) diagram [12] and the location of the investigated base materials based on the data can be found in Table 2.

2.2. Fatigue crack growth examinations

Compact tension (*CT*), three point bending (*TPB*) and single edge notched tension (*SENT*) specimens were tested for base materials and welded joints, while for testing of weld metal *TPB* type specimens were used. *CT* and *TPB* type specimens were cut from the sheets parallel and perpendicular to the rolling direction, so the directions of fatigue crack propagation were the same. For testing of weld metals cracks, which propagate parallel or perpendicular to the axis of the joint were also distinguished. Compact tension shear (*CTS*) specimens were used for tests under mixed mode I + II loading condition. The specimens were cut parallel to the rolling direction; the ratio of the two loading modes (I and II) was varied using a special specimen holder [13], so the cracks were propagated in different angles according to the rolling direction.
Tests were carried out according to the ASTM prescription [14] by an universal electro-hydraulic MTS testing machine. Experiments were performed by ΔK-decreasing and constant load amplitude methods, at room temperature, in air, following sinusoidal loading wave form. Stress ratio was constant ($R = 0,1$), and the crack propagation was registered by compliance and/or optical method.

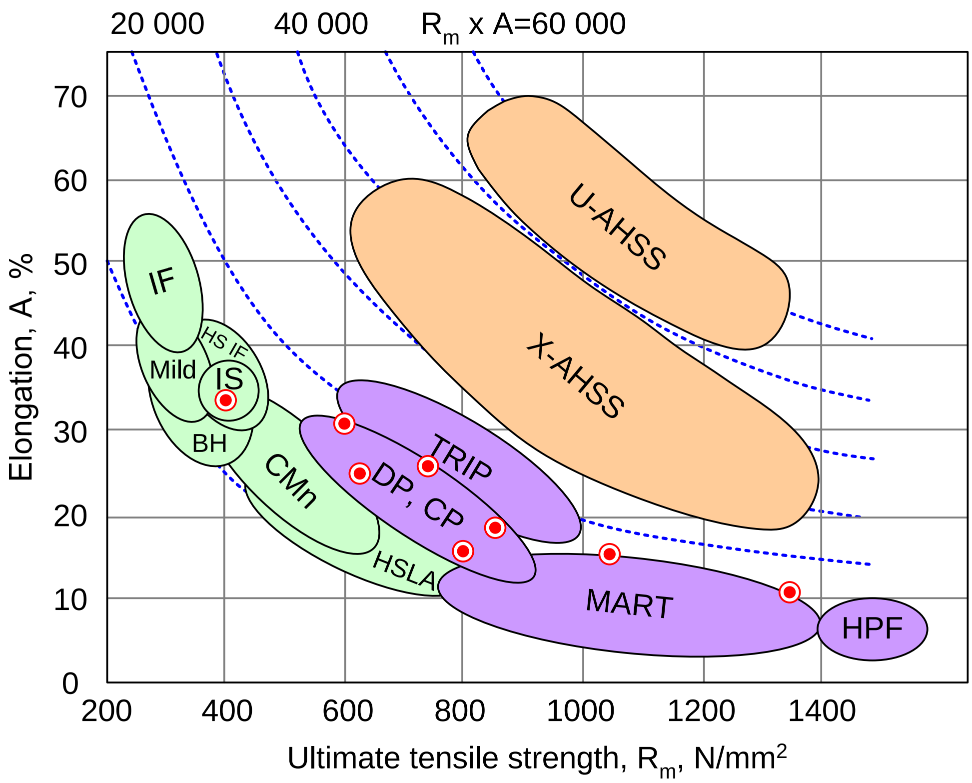

Figure 1. The investigated base materials in the ultimate tensile strength vs. elongation diagram

Fig. 2, Fig. 3 and Fig 4 show the calculated kinetic diagrams (fatigue crack propagation rate vs. stress intensity factor range curves) of tested DP-25156 and TRIP-28670 steels using *SENT* specimens, and S960QL steel using *TPB* specimens, respectively.

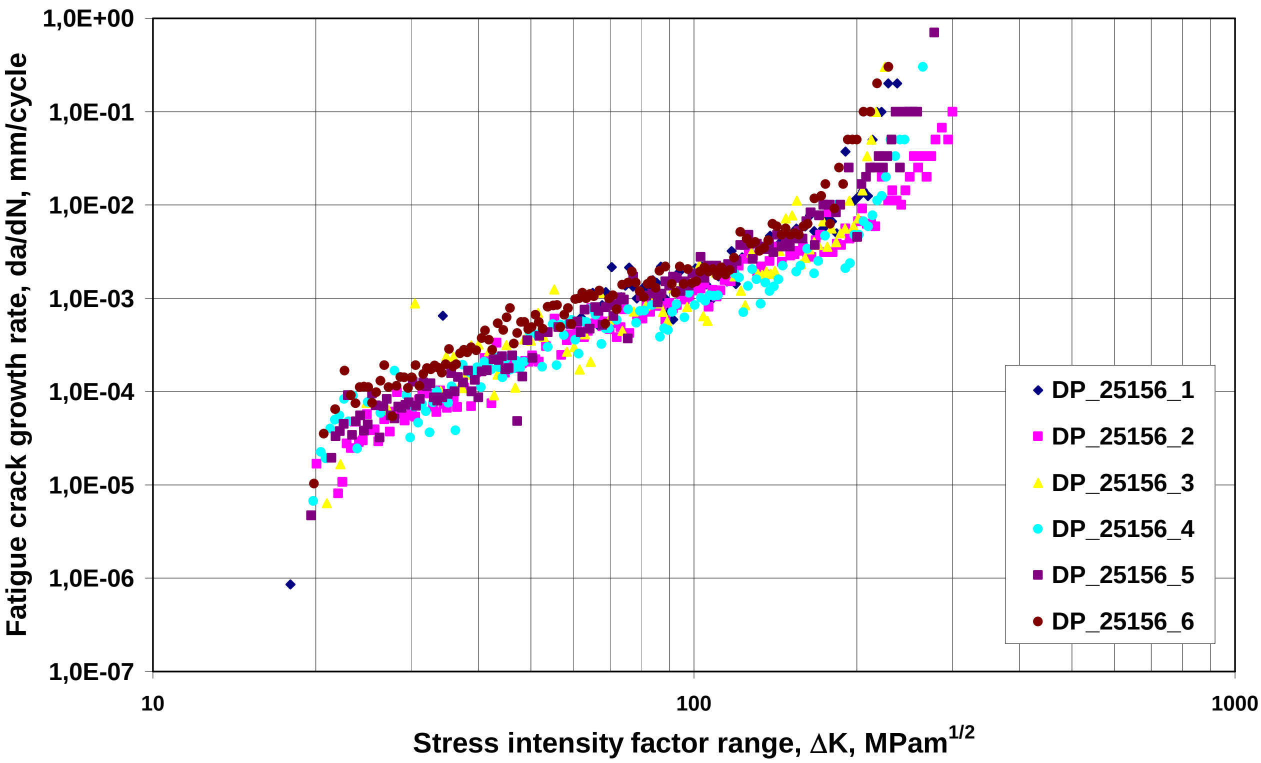

Figure 2. Kinetic diagrams of fatigue crack propagation from tested DP-25156 steel (*SENT* specimens)

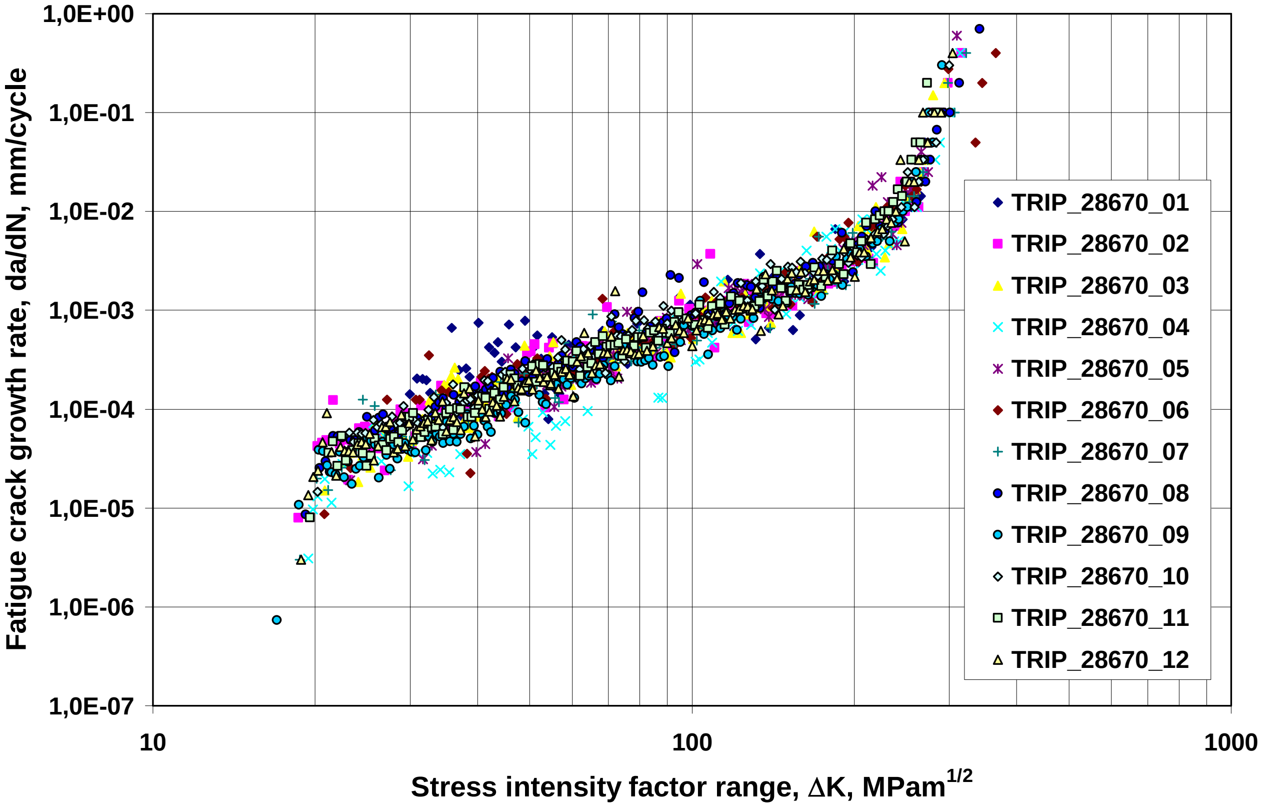

Figure 3. Kinetic diagrams of fatigue crack propagation from tested TRIP-28670 steel (*SENT* specimens)

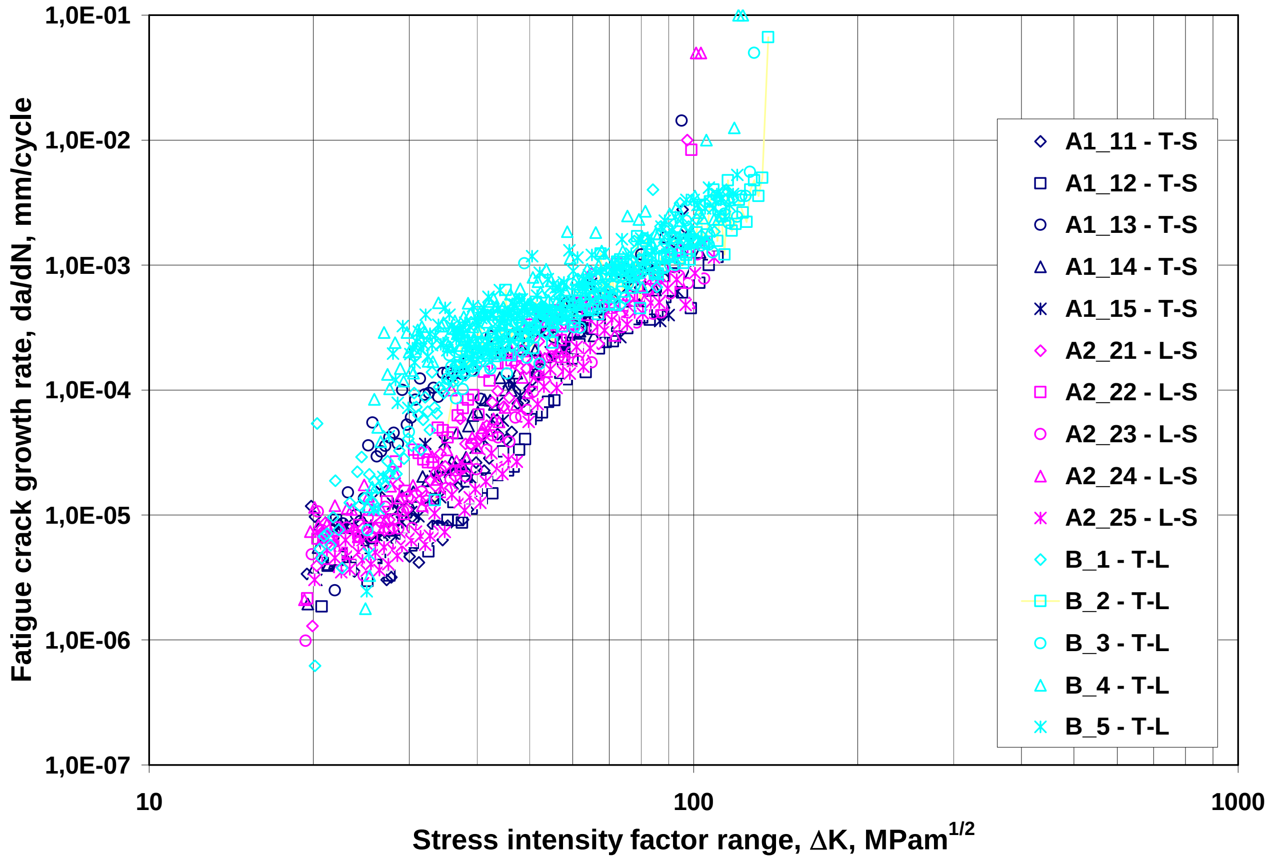

Figure 4. Kinetic diagrams of fatigue crack propagation from tested S690QL steel (*TPB* specimens)

3. Determination of fatigue design limit curves

The determination of the fatigue design limit curves consists of six steps.

First step: determination of measuring values. Values of threshold stress intensity factor range (ΔK_{th}) and two parameters of Paris-Erdogan law (C and n) were calculated according to ASTM prescriptions [14]. Fatigue crack propagation rate was determined by secant method or seven point incremental polynomial method. Values of fatigue fracture toughness (ΔK_{fc}) were calculated from crack size determined on the fracture surface of the specimens by the means of stereo-microscope.

Second step: sorting measured values into statistical samples. On the basis of calculated test results, mathematical-statistical samples were examined for each testing groups. As its method, Wilcoxon-probe was applied [15], furthermore statistical parameters (average, standard deviation and standard deviation coefficient) of the samples were calculated. Standard deviation coefficients (standard deviation/average) of the samples were generally less than *0,2*, which means reliable and reproducible testing and data processing methods. Table 3 summarizes the mathematical-statistical samples and their characteristics of experimental results on S690QL steel, as an example.

Table 3. Mathematical-statistical samples and their characteristics of experimental results on S690QL steel

Orientation	Element number of the sample	Parameter	Unit	Average	Standard deviation	Standard deviation coefficient
T-S	5	n	–	3,959	0,946	0,2390
L-S	5			3,735	0,273	0,0731
T-S and L-S	10			3,847	0,667	0,1734
T-L	5			2,441	0,615	0,2519
T-S	5	ΔK_{fc}	$MPam^{1/2}$	100,22	6,685	0,0667
L-S	5			102,68	4,574	0,0446
T-S and L-S	10			101,45	5,553	0,0547
L-T	5			125,11	8,385	0,0670

Third step: selection of the distribution function. Afterwards it was examined, what kind of distribution functions can be used for describing the samples. For this aim Shapiro-Wilk, Kolmogorov, Kolmogorov-Smirnov and χ^2 statistical probes were used at a level of significance $\varepsilon = 0,05$ [15-17]. It was concluded, that three parameter Weibull-distribution is the only function suitable for describing all the samples.

Fourth step: calculation of the parameters of the distribution functions. Parameters of three parameter Weibull-distribution function were calculated for all the samples:

$$F(x) = 1 - \exp\left[-\left(\frac{x - N_0}{\beta}\right)^{1/\alpha}\right] \tag{2}$$

where N_0 is the threshold parameter, α is the shape parameter and β is the scale parameter of the three parameter Weibull distribution function.

Fifth step: selection of the characteristic values of the distribution functions. Based on the calculated distribution functions, considering their influencing effect on life-time, characteristic values of ΔK_{th}, n and ΔK_{fc}, were selected. With the help of these values a reliable method can be proposed for determination of fatigue crack propagation limit curves:

- the threshold stress intensity factor range, ΔK_{th}, is that value which belongs to the *95 %*

probability of the Weibull-distribution function;
- the exponent of the Paris-Erdogan law, *n*, is that value belonging the *5 %* probability of Weibull-distribution function;
- the Paris-Erdogan constant, *C*, is calculated on the basis of the correlation between *C* and *n*;
- the critical value of the stress intensity factor range or fatigue fracture toughness, ΔK_{fc}, is that value which belongs to the *5 %* probability of the Weibull-distribution function.

Sixth step: calculation of the parameters of the fatigue crack propagation limit curves. Simplified method was used for the calculation of the design curves, based on simple crack growth law, using the above mentioned five steps. The details of the curves can be found in the Table 4. and on Fig. 5.

Table 4. Details of determined fatigue crack propagation limit curves (simple law)

Grade/Mark	ΔK_{th}	n	C	ΔK_{fc}
	$MPam^{1/2}$	$MPam^{1/2}$ and mm/cycle		$MPam^{1/2}$
37C base material	10,4	2,98	8,22E-09	53
37C welded joint	– (1), (2)	3,16	2,42E-09	70
DP-25156 base material	–	2,02	1,68E-07	95
E420C base material	8,0	2,26	9,78E-08	92
E420C welded joint	– (1), (3)	2,74	1,16E-08	101
TRIP-28670 base material	–	1,84	3,06E-07	250
X80TM base material	–	1,78	3,74E-07	129
X80TM welded joint	– (1)	1,86	3,13E-07	–
QStE690TM base material	–	1,82	3,27E-07	–
QStE690TM base material (4), (5)	–	2,15	1,09E-07	–
S960QL base material	–	1,80	3,50E-07	94
XABO 1100 base material	–	1,76	4,00E-07	104

(1) It can be derived from data concerning to the base metal after the evaluation of characteristic and assessment of magnitude of residual stresses.
(2) Average value of *16* tests under compressive residual stress: $\Delta K_{th} = 16,9\ MPam^{1/2}$.
(3) Average value of *4* tests under compressive residual stress: $\Delta K_{th} = 16,3\ MPam^{1/2}$.
(4) Under mixed mode I + II (tension and shear) loading condition.
(5) ΔK should be replaced by ΔK_{eff}.

4. Discussion

For the investigated steels and their welded joints both the tendency of threshold stress intensity factor range (ΔK_{th}) and the tendency of the Paris-Erdogan exponent (*n*) decrease with the increase of the strength of material; while the tendency of fatigue fracture toughness (ΔK_{fc}) has not unambiguous dependence on the strength of material.

For the investigated steels both the Paris-Erdogan exponent (*n*) and the fatigue fracture toughness (ΔK_{fc}) for welded joints are higher than those of base materials.

The proposed method is suitable for determination of fatigue crack propagation design curves under mixed mode I + II (tension and shear) loading condition, too. For this case stress intensity factor range (ΔK) should be replaced by effective stress intensity factor range (ΔK_{eff}).

The design curves of welded joints in the near threshold region are open. On the one hand, if the threshold stress intensity factor range value (ΔK_{th}) is not known, values can be found in the literature (e.g. [18]) are usable. On the other hand, the threshold stress intensity factor range, ΔK_{th}, must be reduce by tensile residual stress field and may be increase by compressive residual stress field (e.g. welding residual stresses).

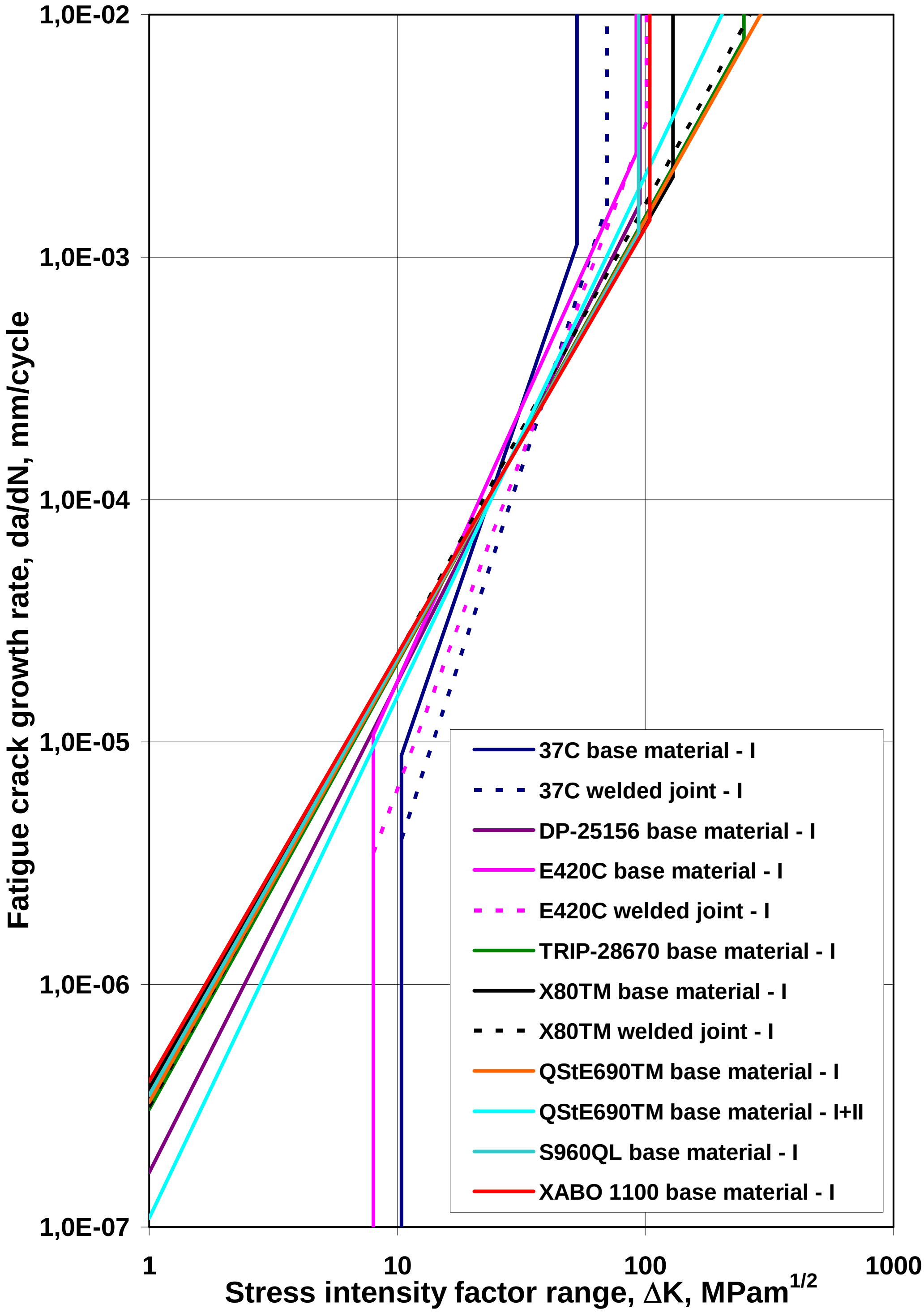

Figure 5. Fatigue design limit curves for the investigated steels, and their welded joints

The calculated fatigue crack propagation limit curves of base materials locate among the design curves determined by various procedures. Table 5. summarizes our measured average data and measured individual data can be found in the literature [19]. It can be concluded that our average values are in harmony with the individual values.

Table 5. Comparison of measured data with data from the literature

Grade/Mark	R_y	R_m	ΔK_{th}	n	ΔK_{fc}
	N/mm^2	N/mm^2	MPam$^{1/2}$	MPam$^{1/2}$ and mm/cycle	MPam$^{1/2}$
37C	270	405	7,69	3,60	62,70
St38b-2	280	440	5,5	3,7	45
DP-25156	350-380	790-820	–	2,20	261,01
E420C	450	595	5,72	2,55	100,41
H60-3	500	630	5,9	3,8	50
TRIP-28670	≥500	560-720	–	2,06	320,73
X80TM	540	625	–	2,49	136,57
H75-3	600-680	–	4,3-5,2	2,5-2,7	70-75
QStE690TM	780	850	–	2,39	–
N-A-XTRA 70	810	850	2,7	2,7	88
S960QL	1007	1045	–	2,44	125,11
XABO 1100	1125	1339	–	2,00	116,41

5. Conclusions

Based on the results of our experimental tests, evaluated samples and data can be found in the literature the following conclusions can be drawn.

- The proposed method can be generally applied for determination of fatigue crack propagation limit curves for steels and high strength steels, and their welded joints under mode I (tension) and mixed mode I + II (tension and shear) loading conditions. Additional information of applications of the proposed method for metallic materials (e.g. pressure vessel steels, aluminium alloys, austempered ductile iron) and non-metallic materials (e.g. silicon nitride ceramics, polymers, reinforced polymer matrix composites) see in our earlier works in the literature [10, 21-23].
- The limit curves calculated by both methods represent a compromise of rational risk (not the most disadvantageous case is considered) and striving for safety (uncertainty is known).
- Based on the determined fatigue design limit curves integrity assessment calculations can be done for operating structural elements and structures having cracks or crack-like defects:
  - = determination of propagable an critical crack sizes;
  - = calculation of lifetime determined by the propagable crack size;
  - = calculations of remaining lifetime functions, influences on the lifetime values and lifetime function (parameter study);
  - = reliability of remaining lifetime estimation;
  - = calculation of damage parameter and damage function [24].
- The examinations of the welded joints should be continued. The welding technologies, the welding parameters and their influences should be investigated, on the basis of their influences on the properties and the adequacy of the welded joints [25, 26].

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