## COMPARISON OF FRACTURE TOUGHNESS VALUES DETERMINED BY STANDARDIZED METHOD AND SMALL PUNCH TEST

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## ABSTRACT

Large forgings and castings (e.g. steam turbine rotors) reveal significant differences in local mechanical properties as a result of differences in local chemical composition and thermomechanical treatment. In cases, where the critical crack length is to be assessed and/or the remaining lifetime of the component evaluated, local mechanical properties must be taken into consideration, what can be impossible to realize by means of classic mechanical destructive testing, which need relatively large volumes of representative material.

Small Punch Test (SPT) [1] is a relatively new and promising test method making it possible to determine basic mechanical properties and also fracture toughness values of metallic structural materials. The most important advantage of the method is the nearly non-destructive withdrawal of test material of the respective component and the small size of test specimen what is interesting in cases of remaining lifetime assessment, when a sufficient volume of the representative material cannot be withdrawn of the components.

In opposite, the most important disadvantage of the method stems from the necessity to correlate SPT results with the results of classic test procedures and to build up a database of material data in service. The database should comprise not only original (virgin) basic materials and weld metals data but also material properties degraded by service conditions. The correlations between the SPT results and the results of tensile tests, fracture toughness values and time to rupture characteristics at creep temperatures etc. are necessary for the remainig lifetime assessment of structure in long-time service.

The paper describes the comparison of ultimate strength and fracture toughness values determined by standardized methods [2], [3] and the small punch test of several low-alloyed steels and Al-alloys.

### **KEYWORDS**

Mechanical Properties. Fracture Toughness. Standardized Tedst Methods. Small Punch Test. Al-Alloy. Low-Alloy Steels.

#### INTRODUCTION

In many industrial applications, materials are subjected to degradation of mechanical properties as a result of service conditions, temperature, cyclic loading, humidity or other corrosive media, irradiation, their combination etc.

The assessment of the remaining lifetime of components and structures is commonly based on correlated procedures including numerous destructive, non-destructive and mathematical techniques that should guarantee reasonably precise assessment of the damage extent of materials in question and the remaining lifetime evaluation of the respective components.

The answers to customers' demands to extend the lifetime of existing components beyond their original design life must be based on detailed assessment of the degradation extent,

what can be rarely realised by means of traditional mechanical (standardised) tests that need relatively large volumes of representative material for the test specimen manufacturing. This fact accelerated the research of miniaturized test specimens that can be sampled from components non-invasively.

The miniaturized test specimens include e.g. miniature Charpy bars or compression test samples, interesting results can be obtained also by means of instrumented hardness testing ("Ball Indentation Test"). Among these, a technique called the Small Punch Test (SPT) has emerged as a promising candidate. It represents an efficient and cost-effective technique, which has the potential to enable measurement of realistic material properties.

The Code of Practice [1] gives guidance on the procedure to be followed when carrying out the Small Punch Creep tests. The objectives of such tests are to evaluate the creep behaviour of materials exposed in operating plant components in order to provide data needed for plant life and integrity assessment. The Code of Practice primarily addresses metallic materials tested under creep loading but can also be used for other materials and loading conditions. Determination of tensile test data can also be realised using this methodology.

A major benefit of the SPT is that it often enables mechanical characterisation of material from in-service components in a minimally invasive, virtually nondestructive manner; i.e., component material is removed for testing without necessary repair.

The SPT provides a direct means of mechanically testing material from a localised region of a component or structure, such as the heat-affected zones of weldments, coatings, etc. The test potentially provides a more reliable means of characterisation than indirect methods based on laboratory simulations of the localised region or analytical predictions based on general models, [1].



Figure 1. Geometry of small punch test specimen deformation, [1]

The small punch tests are used for:

- assessment of yield point and ultimate strength of steels with strength within 500 1700 MPa,
- estimation of transition temperature,
- creep characteristics determination at elevated temperatures,
- estimate of fracture toughness.

## TENSILE TEST AND SMALL PUNCH TEST COMPARISON

The tensile test were performed for several steels, see Table 1. The correlation was based on the following expression:

$$\frac{F}{\sigma} = 3.33k_{sp}R^{-0.2}r^{1.2}h_0$$

where

- *F* maximum force during the small punch test,
- *R* diammeter of the test fixture,
- *r* diammeter of the loading ball,

 $h_0$  original test specimen thickness (0,500 mm ± 0,005 mm),

 $k_{sp}$  proposed coefficient (1,385),

 $\sigma$  maximum stress at SP test.



Figure 2. Record of the punch force vs. punch displacement during small punch test

Material	F <sub>max</sub> [N] SP test	R <sub>m</sub> [MPa] from tensile test	R <sub>msp</sub> [MPa] SP after correlation
CSN 16537	2331	902.8	905.5
X12Cr13	1919	733.4	745.4
X14CrMoVNbN10-2	1928	824.0	748.9
22CrMoNiWV8-8	2085	820.2	809.9
Steel "7"	1729	688.2	671.6
Steel "8"	1801	700.9	699.6
Steel "6"	1804	719.3	700.8

Table 1. Steels used for tensile test and small punch test correlation



punch displacement [mm] Figure 3. Small punch test records of low-pressure rotor steel CSN 16 537

### FRACTURE TOUGHNESS DETERMINATION

The J-integral in the elastic-plastic region can be correlated with the fracture deformation  $\epsilon_f$  by means of the following equation:

$$J_{IC} = K.\epsilon_{\rm f}$$
 -  $J_{\rm o}$ 

In the case of low-alloyed steels, the constants K and  $J_o$  were proved to be material independent, i.e. K = 280 N/mm a  $J_o$  = 50 N/mm.

The determination of the effective fracture deformation  $\epsilon_f$  can be measured on metallographic samples, or determined from the displacement at rupture d<sup>\*</sup> by means of the following empiric expression:

$$\varepsilon_{\rm f} = \ln \left( h_{\rm o}/h_{\rm f} \right) = \beta \left( \frac{d^*}{h_{\rm o}} \right)^3$$



Figure 4. Small punch test specimen after test

## AL-ALLOY AICu4SiMg FOR ROTOR WEDGES

AI	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	Zr
90,50	0,10	3,90	0,70	0,20	0,40	0,50	0,15	0,25	0,05
95,00		5,00		0,80	1,20	1,20			

The chemical composition of the alloy is summarized in Table....

#### Table 2. Chemical composition of AlCu4SiMg Alloy

The tensile to rupture test results acc. to EN ISO 10002-1 are summarised in Table .....

Designation	$R_{p0,2}$	$R_{m}$	А	Z
Deelghauerr	(MPa)	(MPa)	(%)	(%)
7-4	431	470	9,0	20
7-8	469	518	11,0	28

 Table 3. Tensile to rupture test results

#### FRACTURE TOUGHNESS DETERMINATION – PRECRACKED CHARPY SPECIMENS



Figure 5. Example of fracture toughness test record, Specimen No.7-13



Figure 6. Fracture surface of Specimen No.7-13

	T (°C)	F	Max F	Aend	Fend	а	f(a/W)	K <sub>IC</sub>
Designation		Ν	kN	J	kN	mm	-	MPa m <sup>1/2</sup>
7-12	23	1409	1,41	0,28	1,41	5,47	3,11	17,52
7-13	-35	1648	1,65	0,45	1,65	5,31	2,95	19,44
7-14	100	1762	1,76	0,39	1,76	5,17	2,82	19,84
7-15	100	2326	2,33	0,50	2,33	5,23	2,87	26,72
7-17	-50	2326	2,33	0,50	2,33	5,00	2,66	24,77
7-26	40	1708	1,71	0,32	1,71	5,12	2,77	18,93

# Table 4. Fracture toughness test results.Critical Stress Intensity Factor Values

Fracture toughness - AlCu4SiMg Alloy



Figure 7. Fracture toughness of AICu4SiMg alloy

## SPT RESULTS FOR FRACTURE TOUGHNESS DETERMINATION

The Figures 8 and 9 show SPT records and comparison of fracture toughness values from classic and SPT.



Figure 8. Quasi-static small punch test curves at room temperature,

## Al-alloy AlCu4SiMg



Figure 9. Fracture toughness values comparison for Al-Alloy EN AW-2017A T4

## EN AW-2017A T4 ALLOY FOR FAN BLADES

The chemical composition of the alloy is summarized in Table....

AI	Cu	Fe + Ni	Mg	Mn	Ni	Si	Zn
91,80	3,80	0,70	0,40	0,80	0,10	0,70	0,30
	4,80		0,80	0,80			

### Table 5 Chemical composition of EN AW-2017A T4 alloy

The tensile to rupture test results acc. to EN ISO 10002-1 of the EN AW-2017A T4 alloy are summarised in Table .....

Designation	R <sub>p0,2</sub>	Rm	A	Z
Doolghaton	(MPa)	(MPa)	(%)	(%)
P-4	325	477	17.0	19
T-4	264	426	16.5	11
L-4	251	401	19.0	28
2	259	420	18.0	20
3	262	419	21.0	28

Table 6 Tensile to rupture test results



Original pendulum angle	e (°):	10,5
Test Temperature (℃):		23
Final Force F <sub>stop</sub> (kN):		1,53
Energy to F <sub>stop</sub> (J):		2,08
Crack Length a (mm):		5,75
Stable crack extension	a (mm):	0,62



Figure 11. Fracture surface after the dynamic fracture toughness test, Spec. No. 3-14

		Stable crack extension values									
Specimen	a0	21	22	23	24	25	26	а7	28	∆a aver	
3-12	0.35	0.35	0.52	0.57	0.43	0.57	0.32	0.43	0.47	0.45	
3-13	0,16	0,16	0,21	0,24	0,21	0,31	0,38	0,30	0,16	0,25	
3-14	0,63	0,60	0,44	0,54	0,62	0,68	0,78	0,65	0,73	0,62	
3-15	0,20	0,19	0,19	0,17	0,27	0,35	0,44	0,25	0,25	0,26	
3-16	0,28	0,25	0,25	0,22	0,26	0,29	0,16	0,30	0,33	0,25	
3-17	1,65	1,58	1,20	1,21	1,26	1,39	1,51	1,89	1,57	1,46	
3-11	0,74	0,81	0,90	0,89	1,02	1,02	1,14	1,16	1,07	0,98	

Table 4 Stable crack extension values for the J-R Curve, EN AW-2017A T4 alloy

	Temper. Dea C	Max F	Fstop	а	f(a/W)	K	J <sub>el</sub>	J <sub>pl</sub>	J	K
Designation		kN	kN	mm	-	m <sup>1/2</sup>	kJ/m <sup>2</sup>	kJ/m <sup>2</sup>	kJ/m <sup>2</sup>	m <sup>1/2</sup>
3-4	23	1,40	1,20	5,77	3,45	16,58	3,97	47,24	51,21	62,80
3-5	-35	1,70	1,51	5,58	3,23	19,46	5,47	80,31	85,78	81,27
3-6	-50	1,57	1,36	5,82	3,53	19,20	5,32	62,98	68,31	72,52
3-11	23	1,47	1,33	6,07	3,88	20,62	6,14	63,33	69,47	73,14
3-12	23	1,53	1,43	5,63	3,29	18,76	5,09	60,07	65,15	70,83
3-13	23	1,55	1,44	5,66	3,32	19,15	5,30	55,01	60,30	68,14
3-14	23	1,53	1,37	5,75	3,44	18,81	5,11	98,18	103,29	89,18
3-15	23	1,16	1,02	5,91	3,65	14,88	3,20	37,98	41,18	56,31
3-16	23	1,56	1,40	5,62	3,28	18,35	4,87	66,75	71,62	74,26
3-17	23	1,32	1,20	6,15	3,99	19,19	5,32	58,65	63,97	70,18
3-18	40	1,68	1,55	5,55	3,20	19,79	5,66	47,91	53,56	64,22

 Table 5 Fracture Toughness Evaluation, EN AW-2017A T4 alloy



It can be seen from the test records of single test bars that ductile initiation ocurred at all test temperatures, so that the fracture toughness of this Al-Alloy should be considered as a constanti within the whole respective temperature range and its value was determine from the J - R curve at room temperature, see Figure 12.

"Low-Blow" method was used to determine the J – R curve in this case. Experimental points reveal a considerable scatter and several points were invalid because of larger stable crack extension than allowed by standards. Critical J – integral value given by an intersection of the J – R curve with the blunting line is  $J_{IC} = 30 \text{ kJ/m}^2$ , technical value at stable crack extension  $\Delta a = 0.2$  is  $J_{0,2} = 73 \text{ kJ/m}^2$ . For the purposes of critical crack dimensions calculation, the  $J_{IC} = 30 \text{ kJ/m}^2$  was used.

### SPT RESULTS FOR FRACTURE TOUGHNESS DETERMINATION

The Figures 13 and 14 show SPT records and comparison of fracture toughness values from classic and SPT.



Figure 13. Quasi-static small punch test curves at room temperature, Al-alloy EN AW-2017A T4



Figure 14. Fracture toughness values comparison for AI-Alloy EN AW-2017A T4

#### SUMMARY:

The small punch test proved to be a useful tool for the mechanical properties determination during service in cases where the possibility of sufficient amount of representative material is limited.

The both tensile and creep to rupture data can be well correlated and also fracture toughness values determined by means of the small punch testing. The reliability of the small punch test data and the correlation coefficients should be based on more experimental data making it possible to use mathematical statistics.

We would also recommend a wide round-robin testing among numerous laboratories all over the world.

#### REFERENCES

- [1] Small Punch Test Method for Metallic Materials. Part B: A Code of Practice for Small Punch Testing for Tensile and Fracture Behaviour
- [2] ASTM E 1820 01.: Standard Test Method for Measurement of Fracture Toughness. American Society for Testing and Materials, PA, 2001.
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