Machining and Fracture Toughness Testing of Miniature Compact Tension Specimens in Hot-Cell.

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1. Introduction

Obtaining the fracture toughness properties of irradiated material is sometimes of crucial importance to guarantee safe operation of reactors or to select adequate materials for new reactor concept such as in fusion or ADS. However, irradiated material is generally available in very small quantities. Therefore, the possible use of miniature compact tension specimens is investigated in this study.

2. Specimens

A large amount of broken irradiated charpy specimens are present in storage coming from the surveillance program of the Belgian nuclear reactors. Due to the limited amount of fracture toughness specimens available in surveillance capsules and the need for direct fracture toughness measurements to perform better safety analysis, several techniques exist to re-use these broken specimens.
One of these techniques is the reconstitution which consists to make a new specimen (see Figure 1) after welding and machining of two new studs on an insert of the original material to obtain a charpy size specimen 10x10x55 mm. This technique requires reconstitution equipment and is time consuming in milling work (± 8 h per specimen in hot-cell).

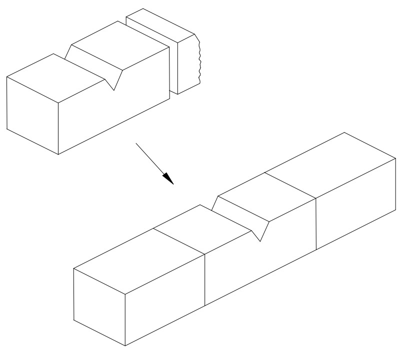

Figure 1: Fabrication of a precracked charpy (PCCV) obtained by reconstitution

The second approach is to machine subsize specimens from the original halves.
At SCK•CEN, a research program was started some years ago to investigate the miniaturization of specimens. The first design was the mini charpy 3x4x27 mm. Four samples can be extracted from a half broken charpy (see figure 2). Mini charpy test results were found in good agreement when compared with standard ones. Recently, this specimen design has been precracked and used in fracture mechanics with good results [1].
The miniaturization of the tensile specimen was successfully applied (internal round-robin on 22NiMoCr37 material), and is extensively used for research on irradiated

material. Here also four mini-tensile samples can be machined from a half broken CV (see figure 2).
Another type of miniaturized specimen extracted from the broken CV is the CRB (Crack Round Bar) which is an attractive specimen for modeling due to his simple profile, but requires constraints corrections and precracking equipment (see figure 2).
The last but not least miniature specimen to be investigated is the mini C(T) (compact tension specimen). Likewise, four mini C(T) can be machined from a half broken CV.

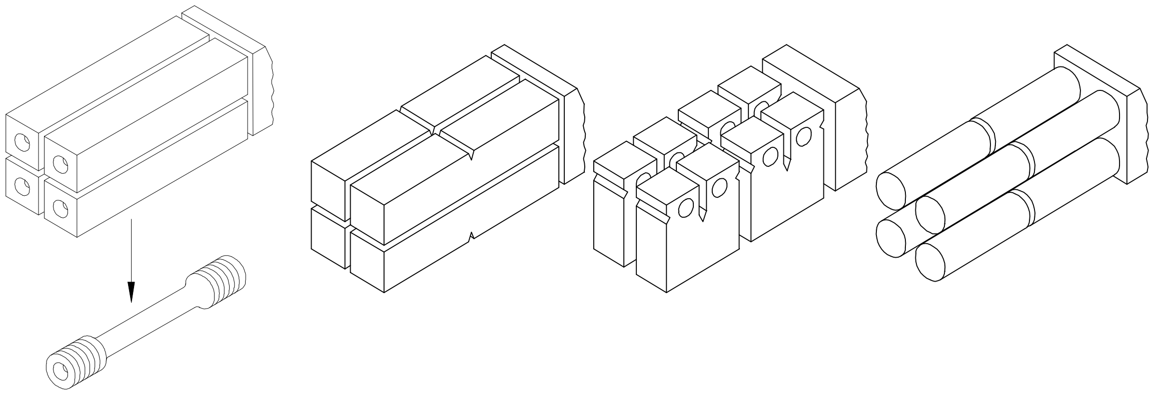

Figure 2: Different available geometries machined from a half charpy specimen.

3. Machining procedure

The qualification procedure was performed on 24 non irradiated specimens machined and tested outside the hot-cell.
The same technique is applied to irradiated material. 32 mini-C(T) specimens were machined directly from half broken irradiated charpy's on a conventional milling machine located in a hot-cell. A saw cut width of 1.6 mm is reached and allowing to obtain four miniature samples per half charpy.
The nominal specimen dimensions are 4.15 mm for the thickness and 8.3 mm for the nominal width. External grooves are machined to allows displacement measurement on the load line using a modified clip on gauge developed at SCK•CEN.

Figure 3 shows the different steps of the machining procedure, which are (for one half charpy):

- Step 1: cutting the block to length;
- Step 2: cutting the block in two equal pieces and deburring;
- Step 3: drilling the two holes Ø 2mm into the block and deburring;
- Step 4: milling the two side-grooving (2 x 0.5 mm) for clip-on gauge;
- Step 5: milling of the notch with a normal mill;
- Step 6: milling of the notch with a special mill to gives the maximal acuity at the tip of the notch
- Step 7: cutting the blocks in two pieces and deburring;

Figure 4 and 5 show such a 0.16T-CT specimen and the eight mini C(T) recovered from the two halves of a broken charpy specimen.
Machining time is one of most important economical factor which influence the final decision on the specimen type selection. The costs to machine one mini C(T) in hot-cell is three times less than a precracked reconstituted charpy.

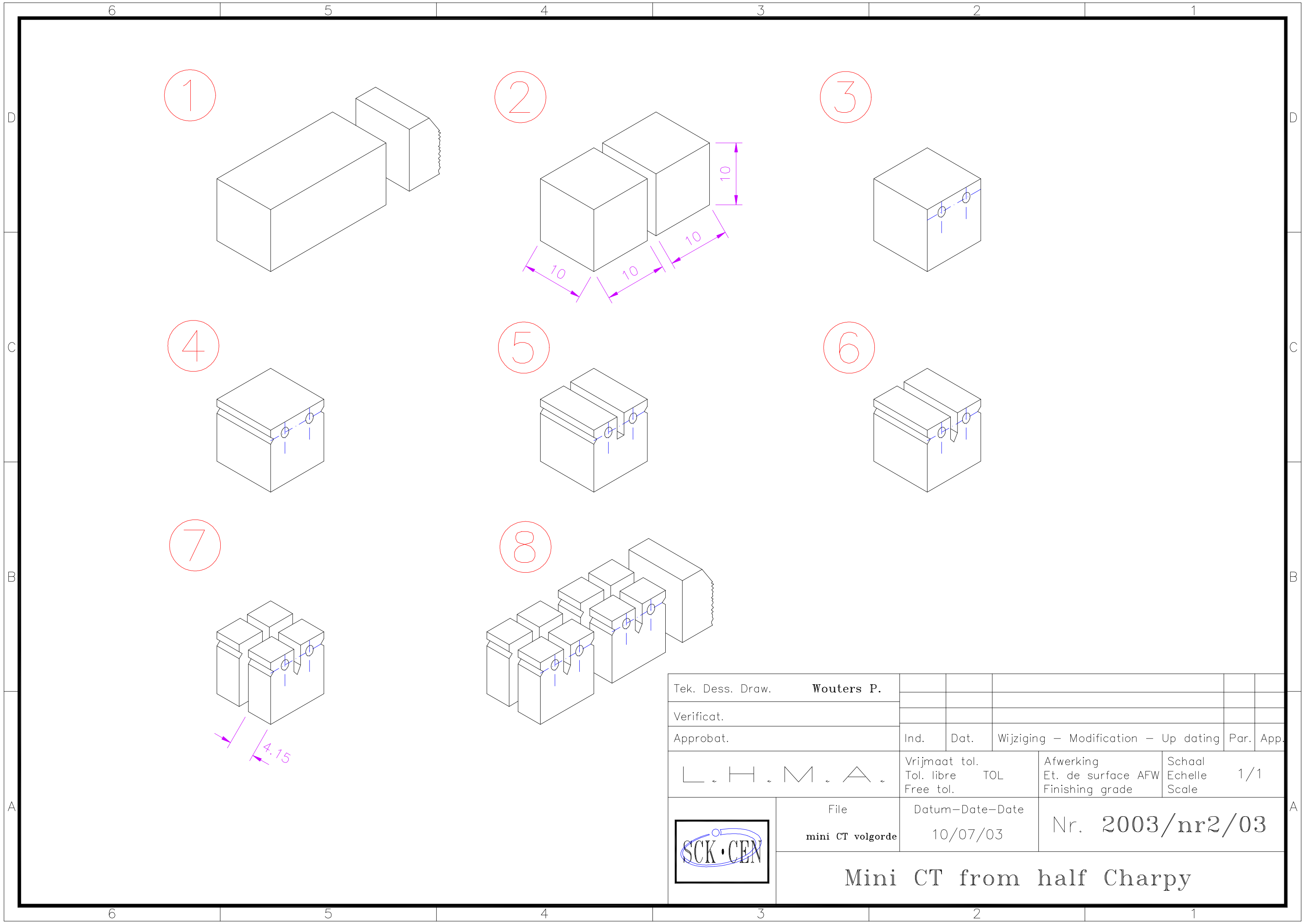

Figure 3: The different machining steps to obtain four MC(T) from one half charpy specimen

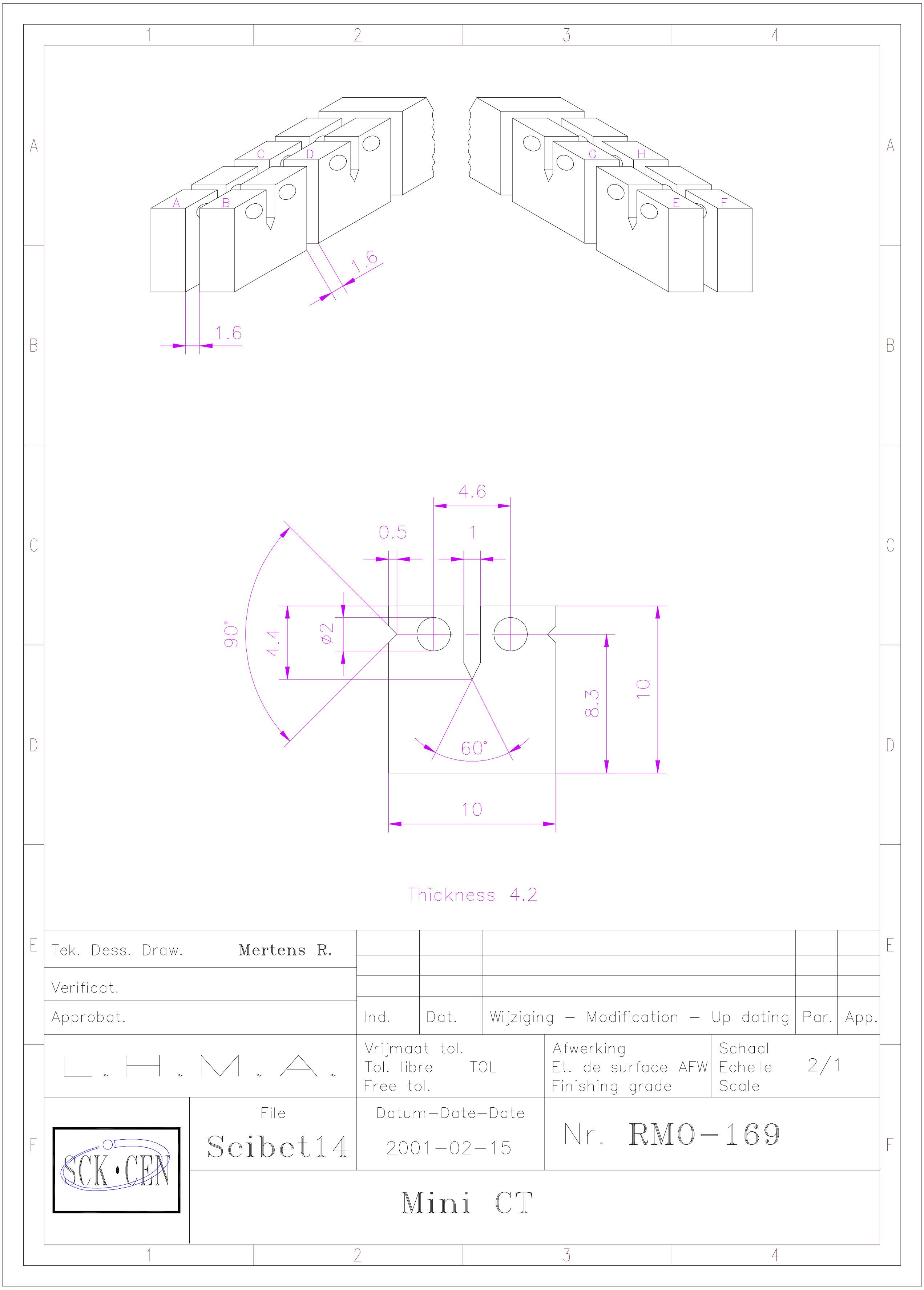

Figure 4: Detail of the 0.16T-C(T) and the eight specimens recovered from one broken charpy

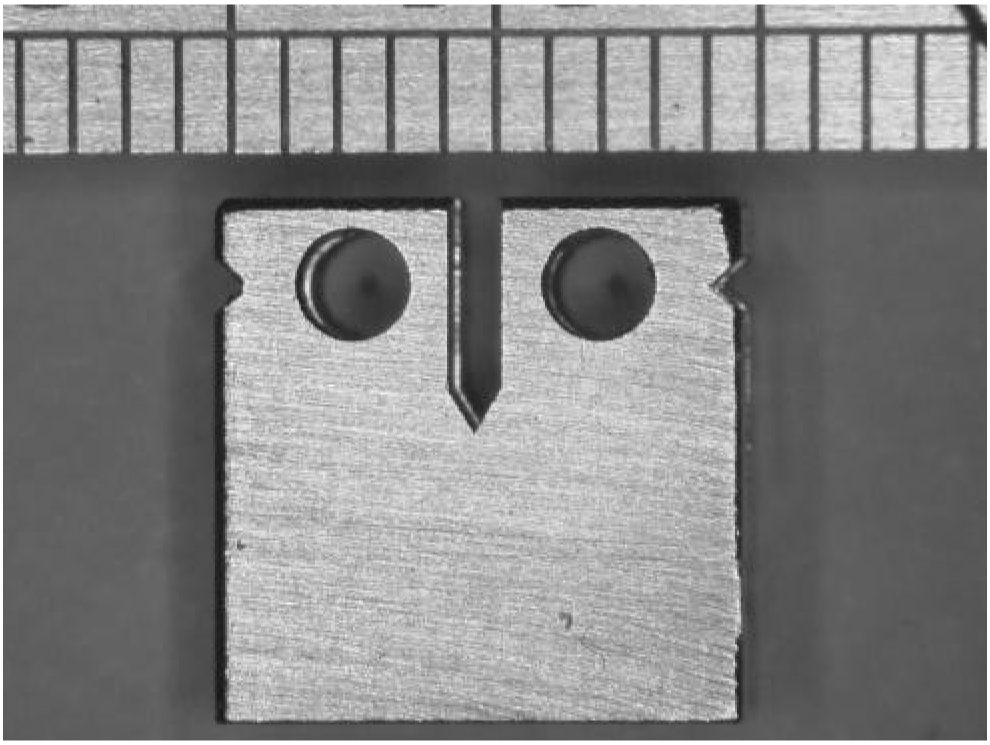

Figure 5: 0.16T-C(T) as machined with side grooving for clip-on gauge

4. Material

The materials used in this study are the 22NiMoCr37 in the non irradiated condition and an European forging equivalent to a A508 Cl3 for the irradiated condition.
The DIN 22NiMoCr37 is a forged ring investigated within an European round robin in which more than 750 CT were tested [2]. The material used in the irradiated condition is a pressure vessel steel of a belgian reactor. Chemical composition and mechanical properties are summarized in Table 1 and Table 2.

Material	C	S	P	Si	Mn	Ni	Cr	Mo	Cu
22NiMoCr37	0.22	0.004	0.006	0.23	0.88	0.84	0.39	0.51	0.08
A508 Gr2 Cl1	0.16	0.011	0.011	0.28	1.07	0.73	0.28	0.42	0.07

Table 1: Chemical composition (weight %).

Material	$ó_{YS}$ (Mpa)	$ó_{TS}$ (Mpa)	T_{41J} (°C)	USE (J)	T_0 (°C)
22NiMoCr37	456	608	-50	194	-90
A508 Gr2 Cl1	452	587	-34	184	-12

Table 2: Mechanical properties of the selected materials at ambient temperature in the non irradiated condition. $ó_{YS}$ is the yield strength, $ó_{TS}$ is the ultimate tensile strength, T_{41J} the charpy transition temperature indexed at 41J, USE the charpy upper shelf energy and T_0 the reference temperature.

5. Dimensional control

Machining was done following standard requirements for determination of fracture toughness (ASTM E399, E1820 and E1921). Table 3 gives the dimensional control of the specimens. Average values of the series are compared with the required ones issued from the standards.

Standard	Nominal Values	Outside hot-cell	Inside hot-cell
W ± 0.005W	8.3 ± 0.042	8.356 ± 0.016	8.38 ± 0.056
B = W/2 ± 0.01W	4.15 ± 0.083	4.050 ± 0.050	4.141 ± 0.066

Table 3: Average values obtained outside and inside the hot-cell.

The comparison with the standard nominal values shows some discrepancies when machined in hot-cell, that is why in stead of using nominal values, specific measured values of each specimen are taken into account in the calculations.

6. Precracking

Precracking is done remotely on a servo hydraulic testing machine. The clip-on gauge is mounted on the specimen (see figure 6) before mounting on the machine load line (see figure 7). Clip-on gauge with short arms is used in order to avoid problems during precracking (vibrations).

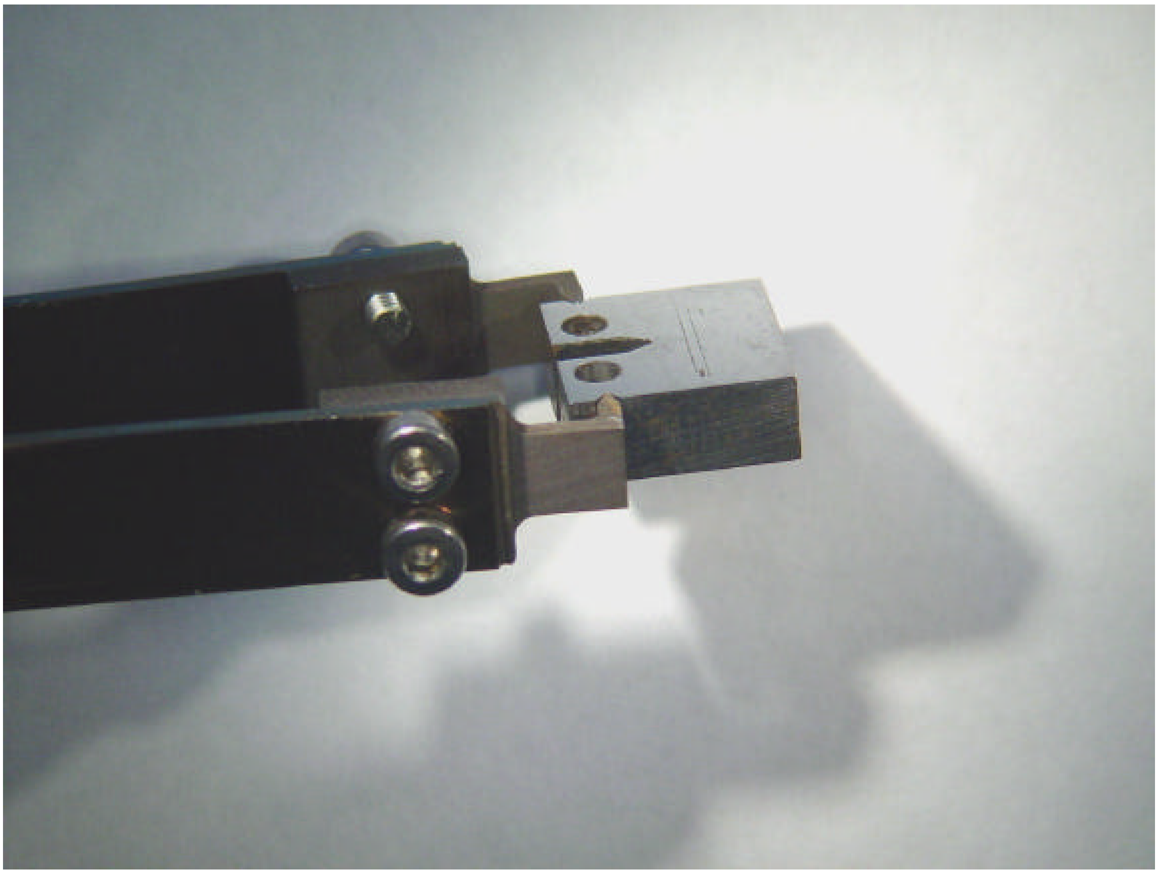

Figure 6: Positioning of the clip-on gauge on the 0.16T-C(T) specimen.

Figure 7: mounting the specimen on the machine to be precracked and tested.

Specimens are precracked according to the ASTM E1921; crack propagation is monitored using the compliance measurement. This measurement occurs automatically each 1000 cycles. The fatigue cyclic loading has a frequency of 30 Hz and the amplitude is constantly adapted to avoid plastic deformation. The crack front is relatively straight; therefore specimens are not lateral side grooved after precracking.
The specimens are normally precracked up to a crack extension of $a_0/W = 0.5 \pm 0.05$
the results of the precracking can be found in the Table 4:

	Outside hot-cell	Inside hot-cell
	24 C(T)	32 C(T)
Failed (broken)	0	2
$a_0/W > 0.55$	2	3
$a_0/W < 0.45$	0	7
Average a_0/W	0.532 ± 0.031	0.475 ± 0.051
Out of specification	8.3 %	37.5 %

Table 4: results of the precracking of the mini C(T)

The breaking of the two specimens in hot-cell is not inherent in the technique but is coming from a abnormal reset of the testing machine during the precracking. The crack measurement in hot-cell tends to overestimate the crack length.

7. Testing

The testing and analysis procedure followed, is essentially based on the ASTM E1921-97 standard to determine the reference temperature T_0 for ferritic steels in the transition range. Specimens are tested in an split furnace allowing a large temperature range.
Test results on non irradiated 22NiMoCr37 specimens can be found in Table 5 and are compared to the ones obtained on larger samples. As shown in Figure 8 and taking the size effect into account, results are found to be in good agreement.

Specimen code	T (° C)	a_0 (mm)	W (mm)	B (mm)	a (mm)	K_{JC} (MPa m)	DATA VALID
X5D4G	-130	4.37	8.36	3.94	0	60	YES
X5D2G	-130	4.49	8.36	4.09	0	70	YES
X5D2F	-130	4.44	8.35	4.08	0	71	YES
X5D4D	-130	4.50	8.34	4.02	0	73	YES
X5D4H	-130	4.56	8.34	4.06	0	81	YES
X5D4F	-130	4.40	8.36	3.95	0	85	YES
X5D2E	-130	4.47	8.35	4.08	0	93	YES
X5D4E	-130	4.08	8.34	4.03	0	108	YES
X5D2H	-130	4.33	8.36	4.05	0	116	YES
X5D3A	-120	4.19	8.35	4.05	0	79	YES
X5D3H	-120	4.54	8.36	4.06	0	83	YES
X5D3D	-120	4.46	8.35	4.06	0	87	YES
X5D3B	-120	4.13	8.38	4.07	0	91	YES
X5D2A	-120	4.87	8.35	4.08	0	60	YES
X5D2B	-120	4.54	8.41	4.08	0	95	YES
X5D3C	-120	4.20	8.35	4.07	0	96	YES
X5D2D	-120	5.33	8.36	4.07	0	104	YES
X5D4B	-120	4.41	8.36	3.91	0	112	YES
X5D2C	-120	4.54	8.34	4.08	0	129	YES
X5D3G	-120	4.41	8.37	4.08	0	134	NO
X5D4A	-120	4.40	8.38	4.07	0	139	NO
X5D3F	-120	4.12	8.35	4.10	0.04	157	NO
X5D4C	-120	4.51	8.33	4.05	0.08	180	NO
X5D3E	-120	4.30	8.35	4.08	0.09	196	NO

Table 5: Test Results on the 0.16T-C(T) of the 22NiMoCr37 material.

An example of test curve (specimen X5D2A) is given in Figure 9 and Figure 10 shows the fracture surface after testing.

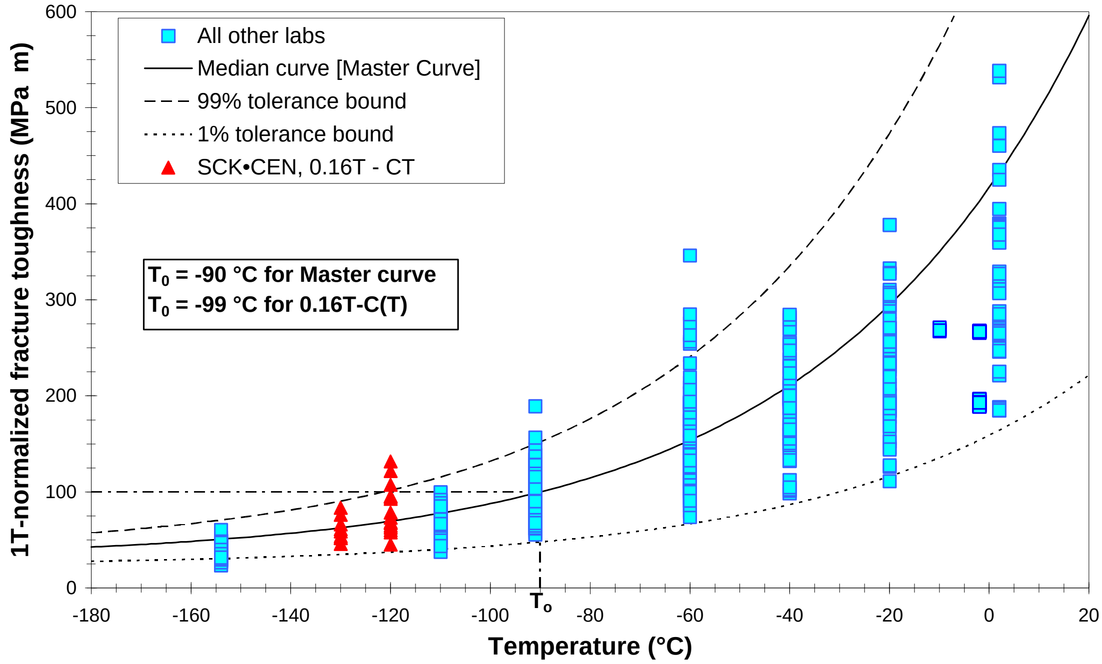

Figure 8: Comparison of the non irradiated 0.16T-C(T) tests with the "Euro Mater Curve" (Round Robin on 22 NiMoCr37 material).

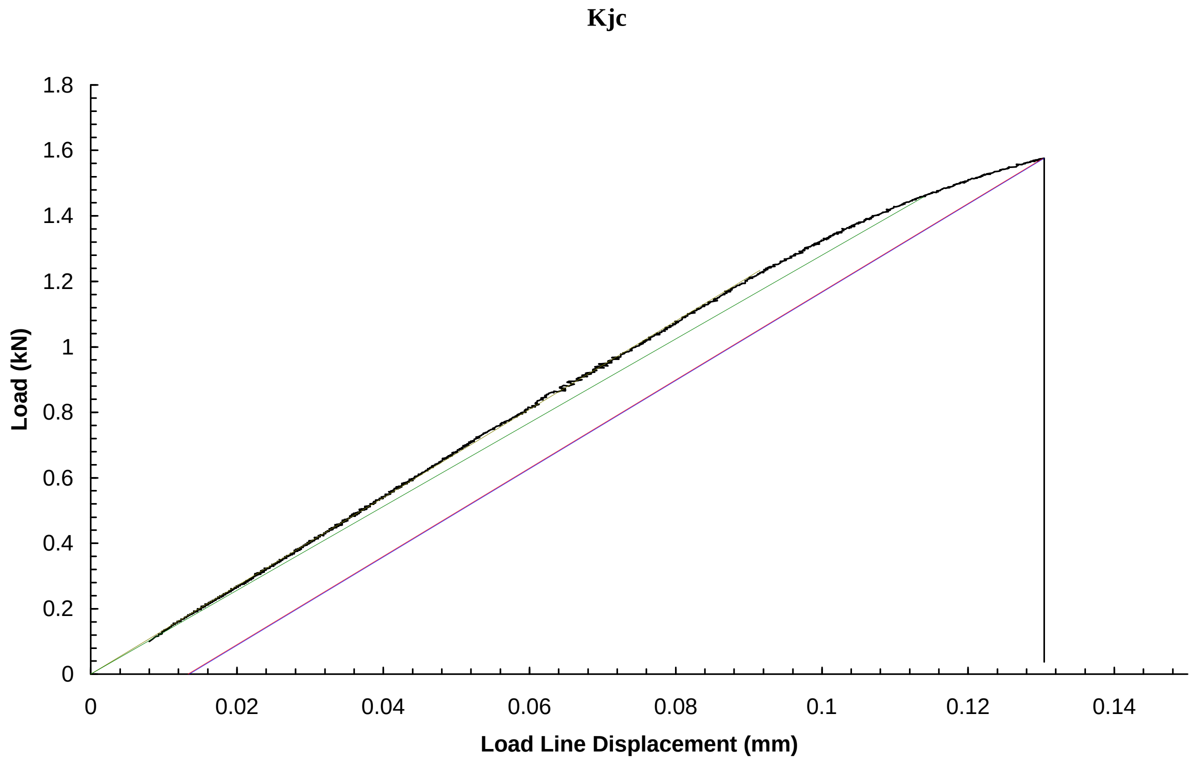

Figure 9: Example of load versus displacement curve of the X5D2A specimen, tested at -120°C

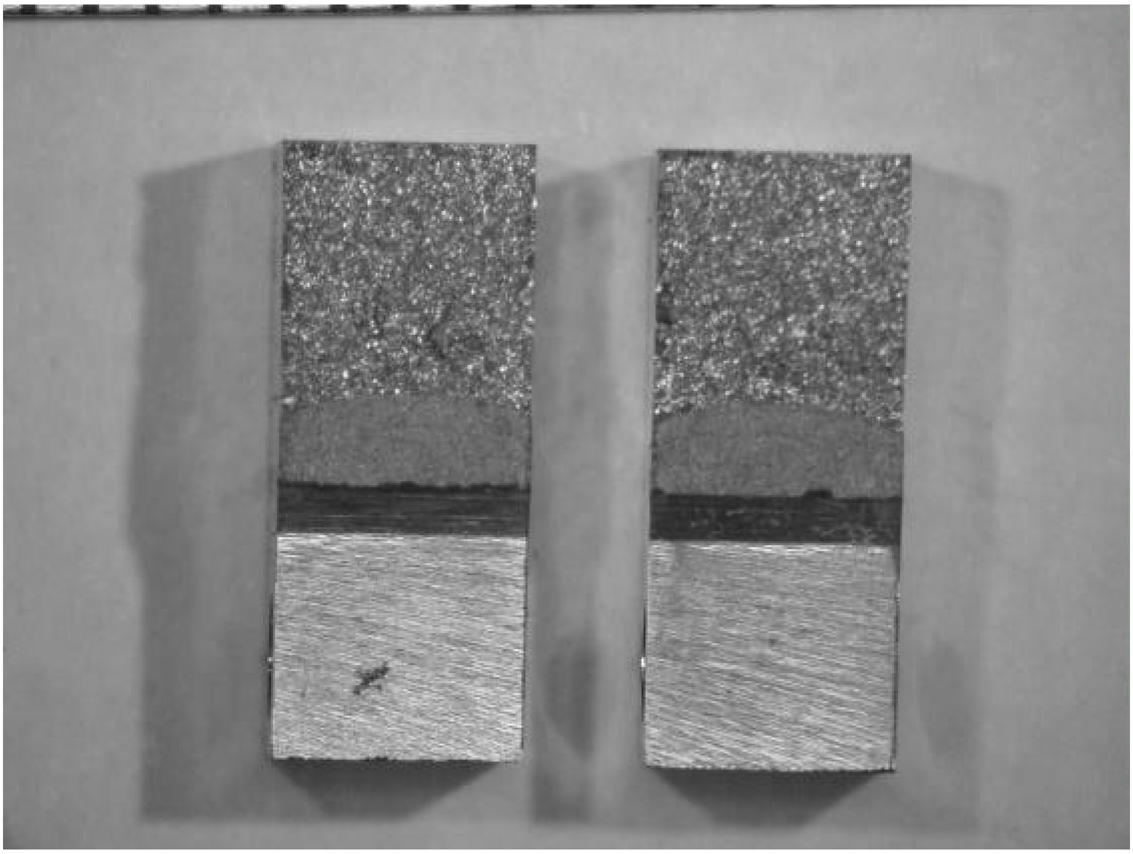

Figure 10: Fracture surface of the specimen X5D2A after testing.

Test results on irradiated material are shown in Figure 11 after normalization to 1T-C(T), the scatter of valid data is, as expected, well distributed around the calculated master curve.

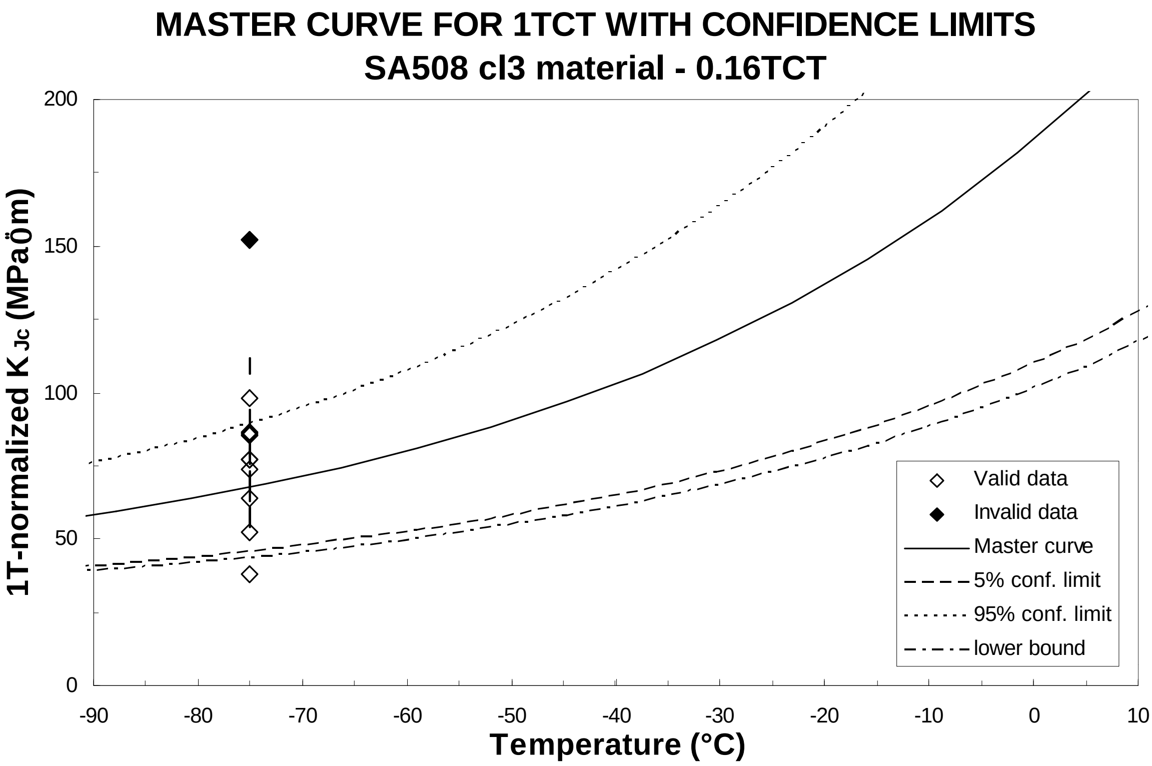

Figure 11: Fracture toughness curve of irradiated SA508 Cl3 material

8. Conclusions

- Cost to machine one mini C(T) in hot-cell is three times less than a precracked reconstituted charpy.
- Actual craks length measured during precracking are shorter than estimated.
- Test results of 22NiMoCr37 unirradiated specimens are in good agreement when compared to the ones obtained on larger samples.
- Test results on SA508 Cl3 irradiated material are well represented by the calculated Master Curve.
- 0.16T-C(T) is a promising geometry that is easy to obtain and uses less a valuable material.

9. References

[1] Lucon E., Scibetta M., Chaouadi R., and van Walle E. (2002). Fracture Toughness Measurements in the Transition Region Using Sub-Size Precracked Charpy and Cylindrical Bar Specimens. Small Specimen Test Techniques: Fourth Volume, ASTM STP 1418, M. A. Sokolov, J. D. Landes, and G. E. Lucas, Eds., American Society for Testing and Materials, West Conshohocken, PA.

[2] Wallin K. (1998), Master Curve Analysis of Ductile to Brittle Transition Region Fracture Toughness Round Robin Data. The "EURO" Fracture Toughness Curve. VTT Publications: 367, Espoo, 1-58.