Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 13 (2014) 339 – 344
www.elsevier.com/locate/procedia

2nd CIRP Conference on Surface Integrity (CSI)

Results of Surface Integrity and Fatigue Study of Wire-EDM compared to Broaching and Grinding for demanding Jet Engine Components made of Inconel 718

D. Welling

Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University,
Steinbachstraße 19, 52074 Aachen, Germany

Corresponding author. Tel.: +49 (0) 241 28039; fax: +49 (0) 241 22293 .*E-mail address*: d.welling@wzl.rwth-aachen.de

Abstract

According to the jet engines fir tree slot production requirements, HCF bending test samples were produced by broaching and wire-EDM in Inconel 718. As an additional reference, a ground series has been produced. Initially, the surface integrities of the samples were checked by surface roughness measurements, SEM and rim zone views. All specimens meet the requirements of fir tree slot production. Following, the correlation between the surface integrity and HCF behavior was analyzed on a bending fatigue test bed. The reference series (grinding) possess the highest fatigue strength. The fatigue strength of the wire-EDMed and broached specimen are in the same magnitude. Therefore, from technological point of view wire-EDM provides an alternative to the established broaching process for the production of fir tree slots.

Selection and peer-review under responsibility of The International Scientific Committee of the “2nd Conference on Surface Integrity” in the person of the Conference Chair Prof Dragos Axinte dragos.axinte@nottingham.ac.uk

Keywords: Wire-EDM, Inconel 718, Surface Integrity, High Cycle Fatigue

1. Introduction

The manufacturing technology wire-EDM enters industry sectors which have been unachievable for the technology in the past. The main reasons for this fact are developments concerning generators, wire electrodes and controlling strategies over the last decade. Here, increasing surface integrity qualities and productivities are the key improvements. One of the mentioned industry segments is the manufacturing of safety critical jet engine components for the aeronautic industry. For this application demanding requirements on the surface integrity have to be met. This is traced back to a combination of extreme mechanical, thermal and chemical loads in compliance with the regulations concerning the critical safety issues. Additionally, the aerospace sector assigns the task of a high power to weight ratio going along with a high economic efficiency where the requirement on reliability and service life is essential.

Features of the above mentioned safety critical jet engine components where wire-EDM as manufacturing technology reached the focus of manufacturing engineers are the fir tree slots. These slots provide the form fit for the force transmission between disc and blades. At present, these slots are produced through the technology broaching. The fir tree slot manufacturing process through broaching is characterized as tool wear intensive due to the difficult to cut materials like nickel-alloys which have to be machined. This fact is one reason why alternatives are investigated.

The biggest challenge for wire-EDM to become a substitution process for the slot production is – besides achieving a high productivity - to meet the demanding requirements on surface integrity. Several publications show the feasibility to achieve high-grade surface integrities in aerospace alloys. Aspinwall et al. [1] published a near zero recast layer on Inconel 718 and Ti-

Selection and peer-review under responsibility of The International Scientific Committee of the “2nd Conference on Surface Integrity” in the person of the Conference Chair Prof Dragos Axinte dragos.axinte@nottingham.ac.uk
doi:10.1016/j.procir.2014.04.057

Nomenclature

EDM	Electro Discharge Machining
f_b	Bending Frequency / f_b
FLFS	Finite Life Fatigue Strength
h	Depth of Cut / µm
HCF	High Cycle Fatigue
HCFB	High Cycle Fatigue Bending
HRC	Hardness – Rockwell Scale
HSS	High Speed Steel
ILFS	Infinite Life Fatigue Strength
M_b	Bending Moment / Nm
M_{b0}	Initial Bending Moment / Nm
N	Number of Cycles
N_l	Limit Cycle Number
R	Radius / mm
Ra	Arithmetic Average Surface Roughness / µm
SEM	Scanning Electron Microscope
t	Thickness / mm
v_c	Cutting Speed / (m/min)
w	Cutting Width / mm
γ	Cutting Angle / °
σ_A	Stress amplitude

6Al-4V after wire-EDM. A micro hardness inspection of the rim zones results in the conclusion, that the surfaces were minimally thermally affected. The tests were conducted on a machine tool equipped with a minimum damage generator technology. Based on these results further research on wire-EDM of Udimet 720 and Ti-6Al-2Sn-4Zr-6Mo was carried out by Antar et al. [2]. In this publication a deeper analysis of surface integrity quality improvements through the usage of trim passes was presented. The thickness of the thermal affected layer was analyzed by micro hardness and residual stress measurements. For Udimet 720 a 30 – 50 µm thick layer was identified. A decrease of the maximum stress was achieved through the trim passes. Klocke et al. [3] investigated a wire-EDM process for the fir tree slot production in Inconel 718. One rough and two trim cuts were required to achieve the demanded surface. Precision and surface integrity inspections show that the process meets the requirements of fir tree slot production.

Through the impact of the resulting surface integrity of manufacturing technologies on the part endurance, the study of failure characteristics caused by the manufacturing process itself is fundamental. Due to the fact, that most highly stressed parts are loaded with alternating forces the comparison of the cycle fatigue strength of different machined parts is essential. In the past several publications were released which deal with the comparison of wire-EDM and conventional manufacturing technologies in terms of their influence on the fatigue strength on aerospace alloys. In 1988 Jeelani et al. [4] studied the influence of wire-EDM cutting speed on the fatigue life of Inconel 718 specimen. No significant influence was detected. Compared to polished samples the fatigue life of the wire-EDMed samples decreased slightly. Klocke et al. [5] compared wire-EDM and grinding of Ti-6Al-4V components. Both series were produced with standard process parameters. Surface roughness measurements indicated a minor surface roughness value for the ground specimen. In contrast the fatigue tests showed a higher fatigue life for the wire-EDMed series. Antar et al. [6] and Soo et al [7] compared wire-EDM and flank milling in terms of their influence on the fatigue life of Udimet 720 and Ti-6Al-2Sn-4Zr-6Mo parts. Both state a minimal higher fatigue life of the milled specimen, which is constituted to the different residual stress states of the wire-EDMed and milled specimen.

The literature survey outlines the fact that no comparison study in terms of high cycle fatigue analysis of the manufacturing technologies wire-EDM and broaching has been done in the past. Due to the fact that this becomes very important in the substitution process of wire-EDM for broaching of fir tree slots, the aim of this paper is to analyze and compare the surface integrity and fatigue strength of the both named manufacturing processes. A corresponding grinding process is used as an additional reference. As test material the nickel-based alloy Inconel 718 is chosen which is the standard material for rotating components in the turbine section of jet engines.

2. **Experimental work**

2.1. Test material specification and equipment

For the tests the aerospace alloy Inconel 718 was selected. Several publications show the difficult-to-cut material properties and their effects on the machinability via cutting [8-10]. Table 1 shows a typical chemical composition of the nickel-based alloy [11]. The used solution treated and aged Inconel 718 is characterized by a coarse grain size which varies from 10 µm – 80 µm and possesses a hardness of 45 HRC.

Table 1: Inconel 718 composition

Element	Ni	Fe	Mo	Ti	Cr	C	Nb	Al
Weight %	Bal.	18.5	3	0.9	19	0.04	5.1	0.5

For the production of the wire-EDMed samples a GF AgieCharmilles 440 ccS machine tool was used. It is equipped with an anti-electrolysis ‘clean cut’ generator, which achieves best surfaces due to high-frequency energy-rich pulses. The broached specimens were machined on a FORST vertical broaching machine tool.

A CNC-Grinding machine tool was taken for the manufacturing of the ground series. Surface roughness measurements of the test pieces were conducted with a Mahr MFW-250 measuring head. The measuring procedure was done in accordance to the specifications of the DIN EN ISO 4288. Further analysis of the surface integrities were done by SEM and cross-section polishing inspected with optical microscopy. The high cycle fatigue bending (HCFB) tests were conducted on a Cracktronic 160 machine build by the company Rumul. It is a dynamic testing machine which works at full resonance.

2.2. HCFB sample geometry and production

In Figure 1a, the dimensions of the HCFB-samples are shown. They have an overall dimension of 55 mm x 10 mm x 3 mm and a minimum cross section of 3 x 5 mm². The side faces are polished and the edges are chamfered to assure that the origin of crack initiations are at the machined surface. The samples were produced in four manufacturing steps:

- Production of raw material block by wire-EDM,
- polishing of radius
- separation of specimen by wire-EDM and
- finishing of surfaces with the specific manufacturing technology.

In Figure 1b, the raw material block with the polished radius is shown. This has been cut out of a forged material block. In Figure 1c, a separated HCFB specimen is pictured. Within the next manufacturing step the specimen are finished.

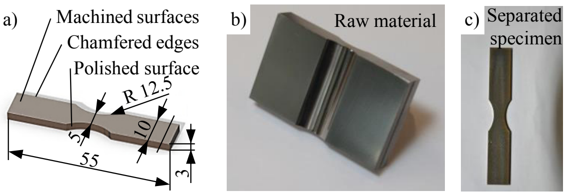

Figure 1: HCFB specimen geometry (a), raw material (b) and separated specimen (c)

The wire-EDMed specimens were manufactured using the wire-EDM technology table published by Klocke et al. [3]. This table works with a 3 cut-strategy for brass wire electrodes and is specially developed for cutting Inconel 718. The achieved surface roughness meets the requirements for the aerospace industries in terms of Ra < 0.8 µm. For the broaching operation separated specimen with the thickness t = 3.2 mm were produced. In Figure 2, the broaching set up to finish the specimen is shown. The finishing of the specimen was conducted in two steps. After the broaching tool (material: HSS) passed vertically the clamped sample two times to achieve the final surface finish, the sample was turned around to machine the second surface in the same way as the first side. The applied cutting speed was $v_c = 2$ (m/min). The machined area with a width w = 20 mm is highlighted.

Table 2: Cutting parameters

Depth of cut h / µm	15	Cutting width w / mm	20
Cutting angle γ / °	10	Cutting speed v_c / (m/min)	2

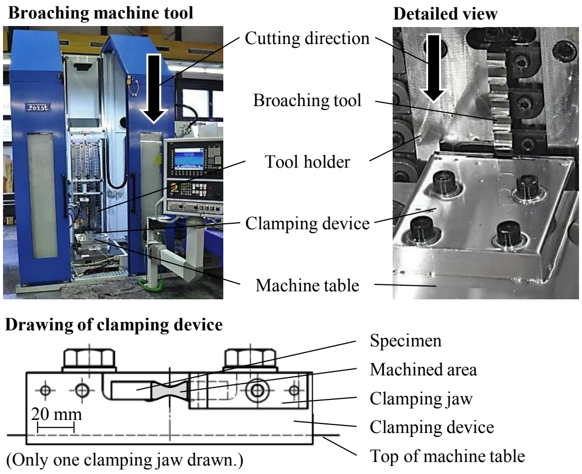

Figure 2: Broaching set up

Table 2 summarizes the applied machining parameters. These parameters were chosen according to a finishing broaching segment to produce fir tree slots. The ground specimens were machined with common aerospace grinding parameters to machine parts out of Inconel 718. For each series 30 specimens were produced. In Figure 3, the three machining operations are summarized and the numbering of the series is declared.

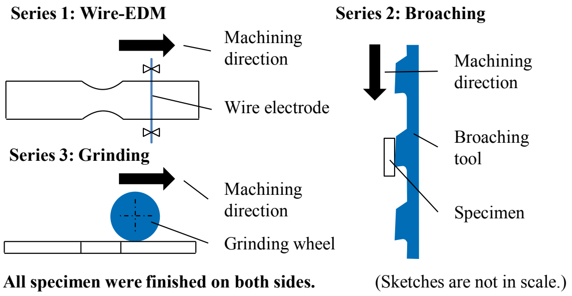

Figure 3: Declaration of series and schematic diagrams of production

3. Surface integrity study

The surface integrities of all series were examined and compared. The optical appearance can be seen in Figure 4a. The wire-EDMed specimen appears rather mat; the broached and ground surfaces have a shiny characteristic. In Figure 4b, the surface roughness measurements are shown. Each of the finished surfaces was examined in correlation to the mapped measuring direction. All series meet the turbine industries requirement on surface roughness for fir trees of Ra < 0.8 µm. The wire-EDMed specimen feature the highest value with a mean surface roughness Ra $= 0.7$ µm. The mean value of the broached specimen is Ra $= 0.28$ µm and the ground specimen feature the lowest surface roughness value Ra < 0.2 µm. The position of the measuring direction referred to the machining direction has to be considered in the analysis of the data. Due to minimal wire vibrations in the trim cuts the surface roughness value of wire-EDMed surfaces in machining direction is empirically higher than in wire unwinding direction. In terms of broaching and grinding the Ra values in machining direction is lower due to the mechanics of the manufacturing processes. The broached specimen were measured orthogonal to the machining direction and the ground specimen were measured in line with the machining direction.

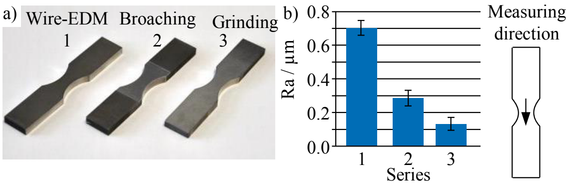

Figure 4: Specimen of each series (a), surface roughness values (b)

In addition to the surface roughness measurements, SEM pictures of the surfaces were prepared (see Figure 5). The wire-EDMed surface features a homogenous topography. The fine view exposes a spattered characteristic, which is typical for a wire-EDMed surface due to the deposition of melted material. The broached specimens feature a very flat surface. In the fine view slight tool marks and small raptures can be detected. These raptures might occur due to pull outs of small carbide particles during cutting, which afterwards fracture the surface when they were dragged by the cutting edge over the surface (compare with [12]). Compared to the broached specimen the ground specimen exhibits more distinct tool marks.

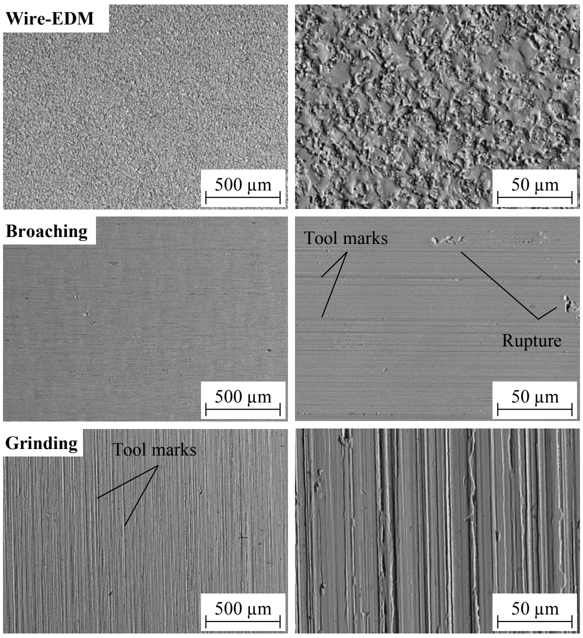

Figure 5: SEM pictures of surfaces; coarse view (left column), fine view (right column)

In Figure 6, the microscopy inspections of the machined rim zones are shown. On the wire-EDMed specimen a thin white layer is visible. The mean thickness is minor 2 µm. No micro cracks or other surface defects have been detected. Two different analyses according to the cutting direction have been prepared for the broaching specimen. The view in cutting direction (upper view) shows a slight rough surface. A small thermo-mechanical layer is visible. The other view shows a flat surface topography. Also here a small thermo-mechanical affected zone can be seen. Due to the deformation of the grains a mechanical detraction of the manufacturing process is obvious. Approximately 5 – 8 µm under the surface the parent and non-affected material can be seen. These surface conditions are typical for a broached fir tree slot. For the ground specimen nearly the same aspects as in the broached series can be seen. A zone which was affected by a thermo-mechanical and a zone which was affected by mechanical forces are obvious. Concerning the direction of the grain deformation the ground and broached specimen feature an arbitrary property due to the machining direction according to the specimen (compare Figure 3 and Figure 5). The topography of the wire-EDMed rim zone and the broached rim zone in cutting direction feature the same characteristics.

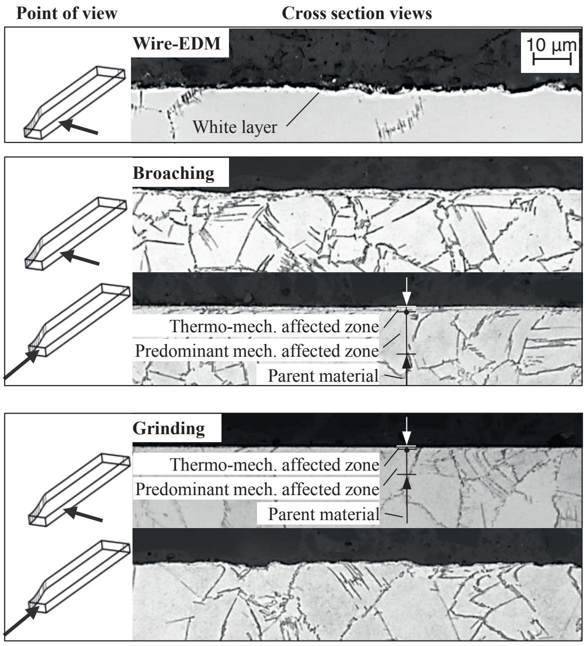

Figure 6: Rim zone views of specimen according to the machining direction

4. HCFB tests

4.1. Test set up and procedure

In Figure 7, the set up for the HCFB tests is shown. The specimen is clamped on the testing machine. One clamping side is fixed and the other side is oscillating and applies a defined oscillating sinusoidal moment with an amplitude of M_b and a mean value of zero.

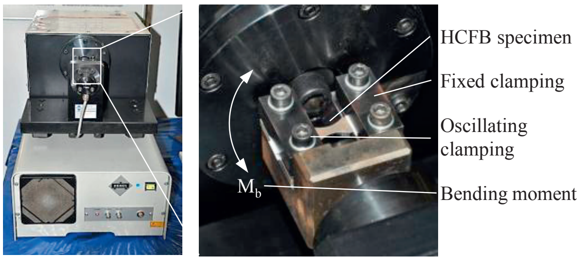

Figure 7: HCFB test set up

As testing procedure the stair case method was chosen. In Figure 8a, an example of the method's process is sketched. The test starts at an initial bending moment M_{b0}. If the specimen exceeded the limit cycle number N_l, the bending load is increased by ΔM_b. If a specimen failed before achieving the limit cycle number N_l, the load is decreased by ΔM_b. This procedure is qualified for high cycle fatigue tests to evaluate (TA) the 50% failure probability in the transition area [13] (see Figure 8b). The test conditions for the present research include a limitation of the cycle numbers to $N_l = 5 \cdot 10^6$ cycles. The bending frequency occurs to f_b = 70 - 75 Hz.

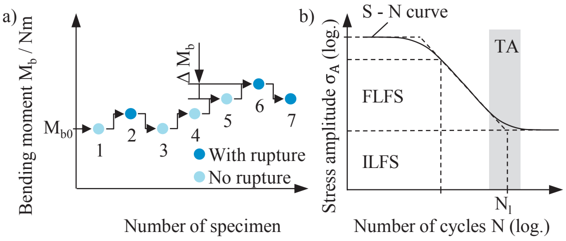

Figure 8: Example of stair case method (a) and S-N curve (b)

4.2. Test results and discussion

In Figure 9a, the result of the HCFB tests is shown. The ground series feature the highest fatigue life. The bending moment at which 50% of the specimens fail is higher than M_b = 3 Nm. The broached and wire-EDMed series possess a bending moment in the same magnitude. The wire-EDMed specimens have a 2% minor value than the broached specimen, which have a value of M_b = 2.2 Nm. The higher mean value of the ground specimen can be described through the fact that the tool marks on the surface continue in line with the introduced tensile stresses (due to the bending tests) on the specimen's surface. The broached specimen feature tool marks rectangular to the introduced tensile stresses. The fractures through carbide break outs on the broached specimen and the EDMed craters might have the same effect on the fatigue life. In Figure 9b, a fracture surface of a wire-EDMed specimen is exemplary shown. The fracture surfaces of all ruptured specimen have the same characteristics. The surface can be divided in a fatigue and a fracture area. The structure of the fatigue area is finer than the structure of the fracture area. The areas are separated through a crack growth frontier. On the top of the surface the crack initiation can be detected. The comparison of the crack initiation regions of the three series did not show any differences.

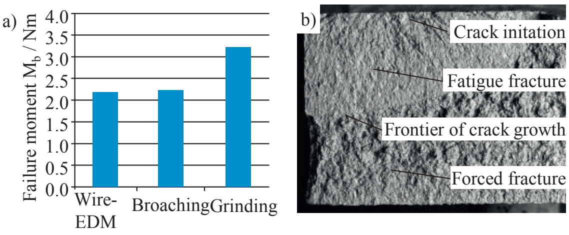

Figure 9: Failure moment for 50% failure probability (a) and fracture surface of EDMed specimen (b)

5. Conclusion

The conclusion of the surface integrity and fatigue analysis of wire-EDM compared to broaching and grinding for demanding jet engine components made of Inconel 718 are:

- The surface integrities of wire-EDMed and conventionally manufactured parts have different characteristics. The mechanical behavior of the conventional manufacturing processes brings directional properties into the surfaces. Grain deformations were detected. The wire-EDMed surfaces are isotropic. All surfaces feature a thermally affected rim zone.
- As testing procedure the stair case method was introduced. This method is qualified for testing the impact of the manufacturing technology on the fatigue life.
- The high cycle fatigue tests show for the broached and wire-EDMed specimen, failure moments in the same magnitude. This result shows that up-to-date wire-EDM machine tool technologies feature surface integrities and accompany fatigue resistant surfaces which are comparable with conventionally manufactured surfaces.
- Especially for the manufacturing of the demanding production of fir tree slots, the presented research exhibits that wire-EDM is an alternative to the broaching process even in terms of the component strength.

6. Acknowledgements

The author’s acknowledge the support of the European Commission in the 7th Framework Programme Transport including Aeronautics call, project number 234325 - ADMAP-GAS.

References

[1] Aspinwall, D.K, Soo, S.L, Berrisford, A.E, Walder, G., 2008. Workpiece surface roughness and integrity after WEDM of Ti–6Al–4V and Inconel 718 using minimum damage generator technology, in: CIRP Annals - Manufacturing Technology 57 (1), pp. 187 – 190.

[2] Antar, M.T., Soo, S.L., Aspinwall, D.K., Cuttell, M., Perez, R., Winn, A.J., 2012. WEDM of Aerospace Alloys Using 'Clean Cut' Generator Technology, Proceedings of the 16th International Symposium on Electromachining, pp. 285 – 290

[3] Klocke, F., Welling, D., Dieckmann, J., Veselovac, D., Perez, R., 2012. Developments in Wire-EDM for the manufacturing of fir tree slots in turbine discs made of Inconel 718, Key Engineering Materials (1665), pp. 1177 – 1182.

[4] Jeelani, S., Collins, M., 1988. Effect of electric discharge machining on the fatigue life of Inconel 718, In: International Journal of Fatigue 10 (2), pp. 121–125

[5] Klocke, F., Welling, D., Dieckmann, J., 2011. Comparison of Grinding and Wire EDM Concerning Fatigue Strength and Surface Integrity of Machined Ti6Al4V Components, In: Procedia Engineering 19, pp. 184–189.

[6] Antar, M.T., Soo, S.L, Aspinwall, D.K, Sage, C., Cuttell, M., Perez, R., Winn, A.J., 2012. Fatigue response of Udimet 720 following minimum damage wire electrical discharge machining, In: Materials and Design 42, pp. 295–300.

[7] Soo, S.L., Antar, M.T., Aspinwall, D.K., Sage, C., Cuttell, M., Perez, R., Winn, A.J., 2013. The Effect of Wire Electrical Discharge Machining on the Fatigue Life of Ti-6Al-2Sn-4Zr-6Mo Aerospace Alloy, In: Procedia CIRP 6, pp. 215–219.

[8] Pejryd L, Beno T, Isaksson M. Machinig aerospace materials with room-temperature and cooled minimal- quantity cutting fluids, Proc. ImechE Vol. 225, Part B: J. Engineering Man. 2011

[9] Rahman M, Seah WKH, Teo TT. The machinability of Inconel 718, Journal of Material Processing Technology 63, pp. 199 - 204. 1997

[10] Ezugwu EO, Wang ZM, Machado AR. The machinability of nickel-based alloys: a review, Journal of Materials Processing Technology 86, pp. 1 – 16. 1999

[11] Reed RC. The superalloys – fundamentals and applications, Cambridge University Press. 2006

[12] Ulutan, D., Ozel, T., 2011. Machining induced surface integrity in titanium and nickel alloys: A review. In: International Journal of Machine Tools and Manufacture 51 (3), pp. 250–280.

[13] Klubberg, F., Hempen, M., Schäfer, H.J. Software SAFD 5.5, IWM der RWTH Aachen, 2006