CIMAC

INTERNATIONAL COUNCIL
ON COMBUSTION ENGINES

Working Group 4 – Crankshaft Rules

Multiaxial Fatigue Algorithm Challenge

MFAC

MULTIAXIAL FATIGUE ALGORITHM CHALLENGE

1. Introduction

1.1. CIMAC Working Group 4 (WG4) is preparing a recommendation to the International Association of Class Societies (IACS) to modernize the rules for engine crankshaft design assessment.

1.2. The current rules for the design assessment of crankshafts are given in Reference [1].

1.3. A fundamental goal of the design assessment is to determine if the crankshaft design has adequate margin to high-cycle fatigue failure modes.

1.4. During normal engine operation, crankshafts are exposed to dynamic multiaxial loads that are cyclic and complex. Modern computer-aided-engineering simulation software allows the prediction of the dynamic loads and stresses within the crankshaft during the engine combustion cycle. (CIMAC WG4 is also developing recommendations and guidelines for the accurate prediction of the dynamic loads and stresses in engine crankshafts.)

1.5. There are numerous multiaxial fatigue stress / strength algorithms in the literature, and in software tools, that allow the assessment of fatigue design margin. However, it is not generally known or recognized or agreed which algorithms are best suited for engine crankshaft analysis.

1.6. The purpose of this “Algorithm Challenge” is to help CIMAC WG4 identify the multiaxial fatigue algorithms most suitable for the design assessment of engine crankshafts.

2. Overview of the “Algorithm Challenge” methodology

2.1. Under the auspices of CIMAC WG4, a series of constant-load high-cycle fatigue tests have been conducted on a particular crankshaft design. These tests determined the mean high-cycle fatigue strength of a crank throw under four different load regimes, including synchronous proportional and non-proportional multiaxial loading. The details of the material properties, geometry, load regimes, and test protocols are provided in this document.

2.2. Given the information provided in this document, stakeholders in the practice of developing or using multiaxial fatigue algorithms are challenged to predict the results of the crank throw fatigue tests without knowing the results beforehand.

2.3. CIMAC WG4 will compile the predictions received from the respondents and revert with a summary comparison of all predictions to the actual test results. The summary of the predictive data will be anonymous and sent only to stakeholders who respond to the challenge.

3. Description of the Crank Throw Fatigue Testing

3.1. Overview

3.1.1. A total of 64 single crank throw specimens were machined from a representative crankshaft material and tested on resonant fatigue test rigs. All the specimens were made to the same geometry, material and heat treatment. Unhardened fillets were used in this phase of the testing. The test specimen is suitable for induction hardening and cold rolling of the fillets, for possible future test phases.

3.1.2. The standard staircase test method of ISO 12107:2003 (see Reference [2] below) was used to determine the 50% survival probability for 5E6 runout cycles under four different combinations of bending and torsion loading. All fatigue testing was done with sinusoidal waveforms, at room temperature, in air.

3.2. Crank Throw Specimen Geometry

3.2.1. Appendix 1 is a sketch of the crank throw specimen, machined from Ø165 mm round bar. Figure 1 illustrates a 3-D solid model of the crank throw specimen that is available for download from the webpage shown below as Reference [4].

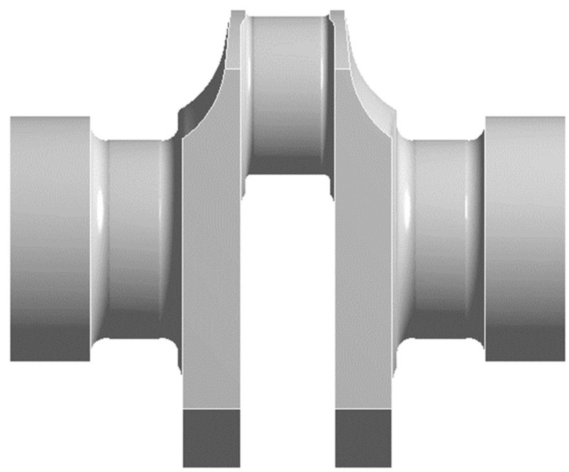


Fig. 1 – 3D model of the crank throw specimen.

3.3. Material Properties and Processing Information

3.3.1. The material used in the fatigue testing was 34CrNiMo6 hot-forged round bar with the characteristics shown in Table 1. All bar material was made from the same heat. Note that the forged round bar does not have grain flow lines typical of a forged crank throw.

3.3.2. The crank throw specimens were machined to within ~5 mm of the finished dimensions. They were then heat treated, quenched and tempered, to achieve the specified mechanical properties shown in Table 2, prior to final machining.

3.3.3. Two lengths of the Ø165 mm round bar stock were quartered lengthwise and put through the same quench and temper heat treatment as the rough-machined crank throw specimens.

3.3.4. A total of 52 small-size specimens were extracted from the quartered round bar material to allow determination of tensile and fatigue strength properties using

ISO standards. Appendix 2 shows the geometry of the tensile, axial and torsional fatigue test specimens.

3.3.5. Table 2 provides the tensile test results from 8 specimens extracted from the quartered round bars. The **mean** values should be used as the tensile properties of the crank throw test specimens. Table 2 also provides the material composition and cleanliness results.

3.3.6. Table 3 provides the results of axial and torsional fatigue tests of small specimens using the staircase method. The 50% survival probability fatigue strength was calculated using the Mood-Dixon estimation described in reference [2]. These data should be considered as representative of the material fatigue strength of the crank throw test specimens.

3.4. Crank Throw Fatigue Test Rigs

3.4.1. Crank throw fatigue testing was performed using three resonant fatigue test rigs at Maschinenfabrik Alfing Kessler GmbH in Aalen, DE. Two rigs are uniaxial, either in bending or in torsion, and the third is a multiaxial rig capable of synchronous proportional and non-proportional loading in combined bending and torsion.

3.4.2. In all three rigs, weights were attached by press-fit to the Ø80 mm diameters at either end of the crank throw (see Fig. 1 and Appendix 1). Controlled excitation forces were applied near a resonant frequency to impart the desired moments on the crank throw. All loads were verified by strain gauges applied to the crank throw specimen.

3.5. Load Regimes

3.5.1. Testing of the crank throws was performed with the four load regimes shown schematically in Fig. 2. Bending moments were applied in the plane of the crank throw (see Fig. 3a).

3.5.2. The multiaxial combined bending and torsion testing was done with a constant ratio of 3:1 between the torsional moment and the bending moment, shown schematically in Fig. 2.

3.5.3. The multiaxial test rig operated with a constant axial load of 3160 N acting in compression on the crank throw (see the arrow in Fig. 3c). This implies that the multiaxial rig operated with an R-ratio less than -1. Also, please note that this constant axial load was <u>not</u> applied on the <u>uniaxial</u> bending and torsion tests.

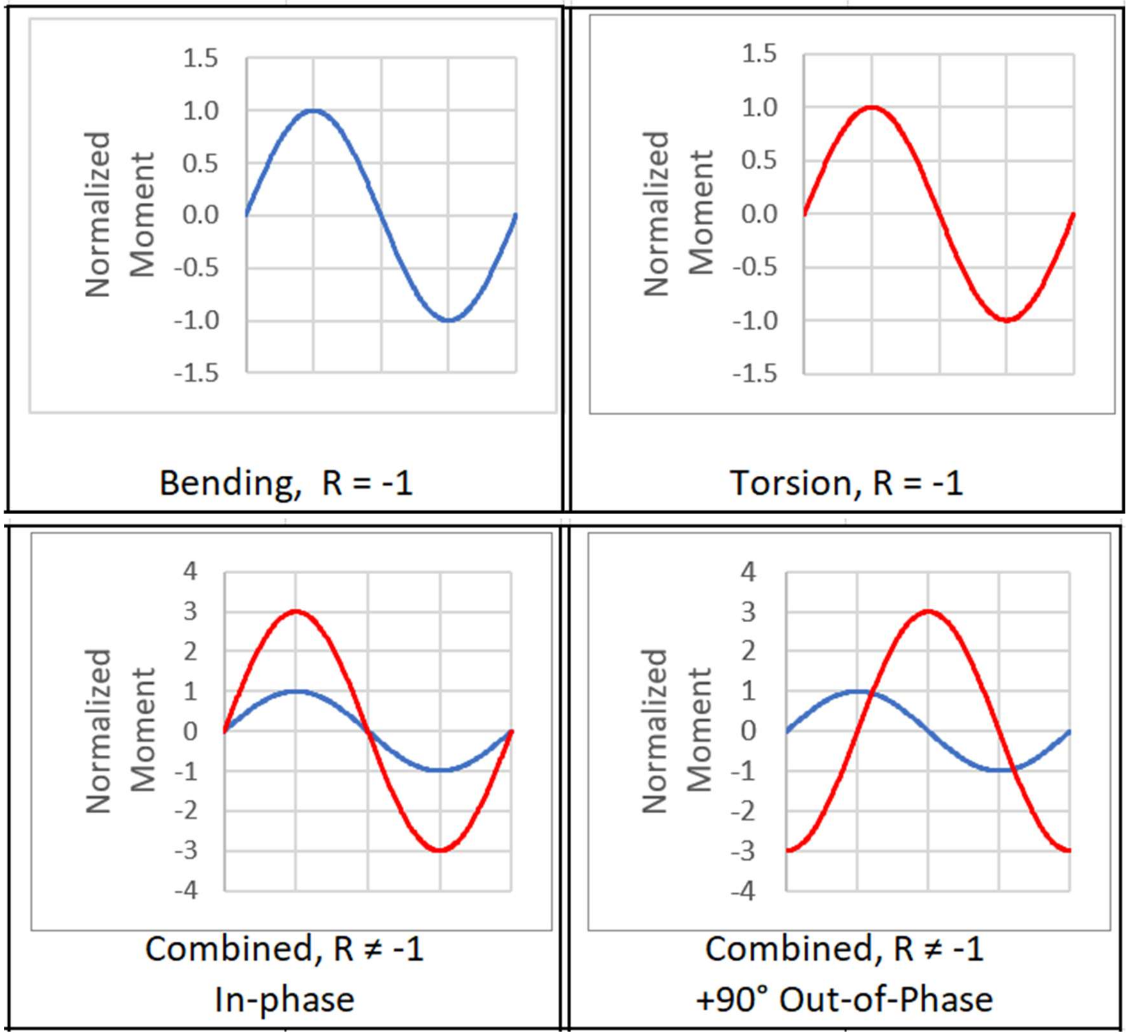


Fig. 2 –Four load regimes for the crank throw fatigue testing.

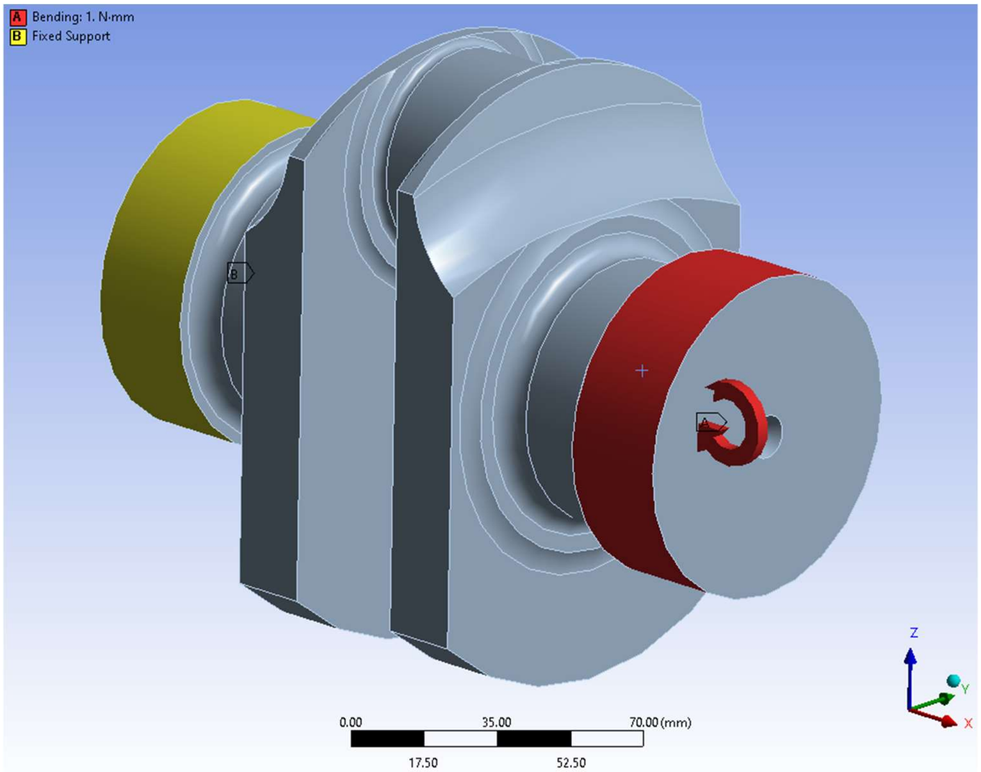


Fig. 3a – Alternating bending moment.

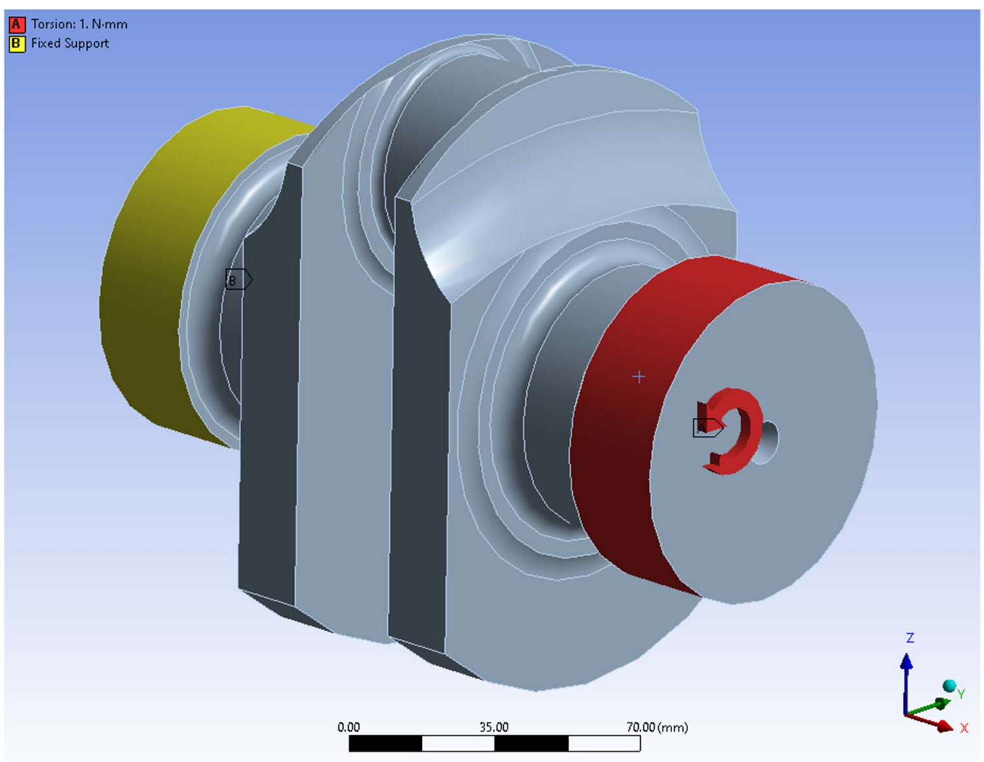


Fig. 3b – Alternating torsion moment.

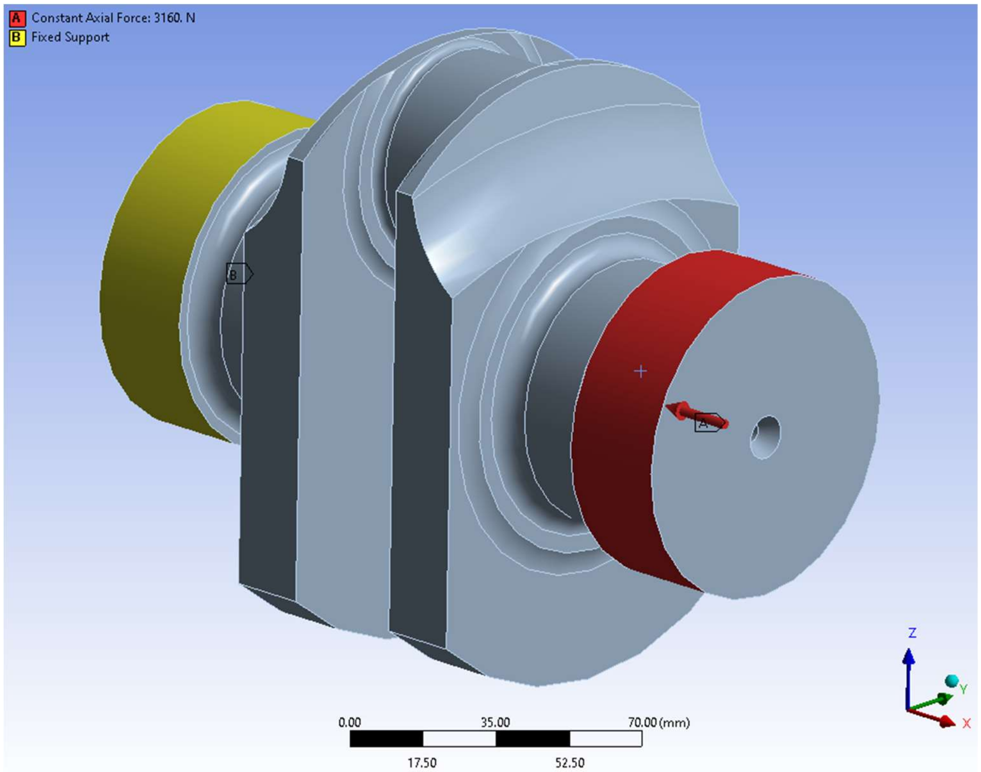


Fig. 3c – Constant axial compressive load case (applies only to the combined bending and torsion multiaxial load regimes).

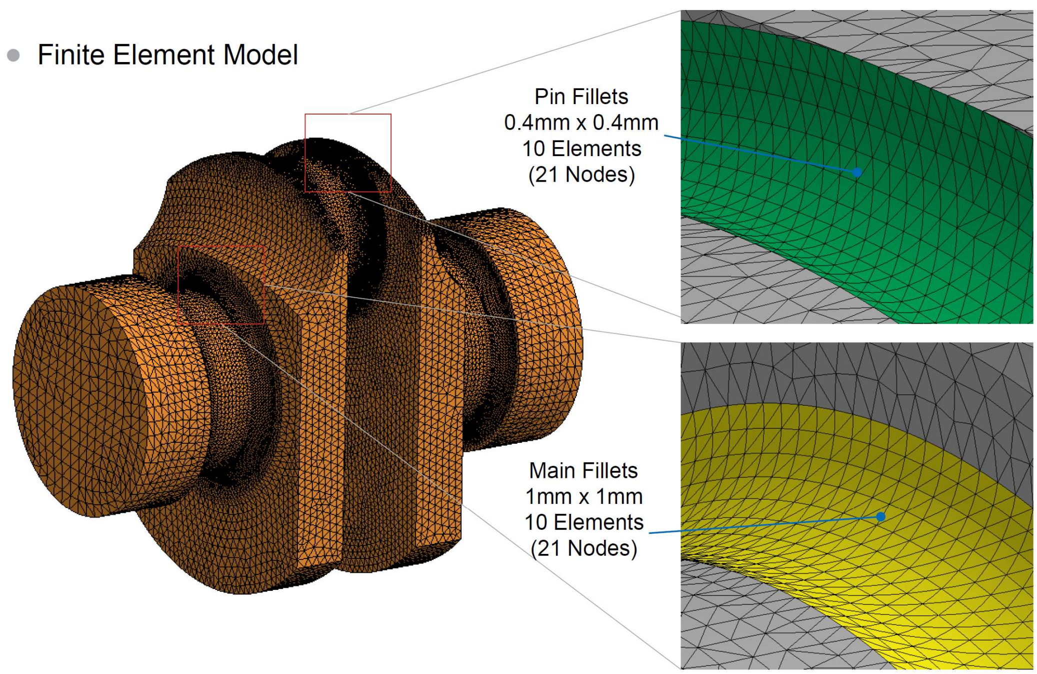


Fig. 4 – Finite element model of the crank throw test specimen.

Table 1 – Forged bar material requirements.

Property	Specification (minima)
Microscopic cleanliness according to DIN 50602	Max 20 K4(O+S)
Reduction Ratio	>4:1
Diameter, mm	165-175
Cut Length, mm	190-200 or multiples thereof
Composition	34CrNiMo6
Heat Treatment	Normalized round bar followed by quenching and tempering of the rough-machined part.

Table 2 – Measured mechanical properties and composition of the test material at room temperature.

Property	Spec.	# of samples	**Mean**	Min	Max
Tensile Strength, Rm, MPa	900 min	8	**1053**	1030	1084
Yield Strength, $Rp_{0.2\%}$, MPa	690 min	8	**935**	914	960
Reduction in Area, %A	40% min	8	**54**	51.3	56.7
Elongation, %L	13% min	8	**16**	14.8	17
Surface Hardness, HB,	283 min	20	**322**	317	328
Composition (34CrNiMo6 +QT):					
C %	0.30-0.38	1	**0.37**		
Si %	0.40 max	1	**0.24**		
Mn %	0.5-0.8	1	**0.63**		
P %	0.025 max	1	**0.013**		
S %	0.035 max	1	**0.005**		
Cr %	1.3-1.7	1	**1.56**		
Mo %	0.15-0.30	1	**0.27**		
Ni %	1.3-1.7	1	**1.63**		
Cleanliness per DIN 50602, K4(O+S)	20 max	2	**13 K1**		

Table 3 – Small specimen fatigue test results.

Loading (Sinusoidal, R=-1, Room Temp., Air)	Staircase samples	Runout Cycles	**50% Survival Probability Strength Amplitude**
Axial	16	5E6	**470 MPa – Axial Stress**
Torsional	15	5E6	**363 MPa – Torsional Stress**

4. Responding to the Challenge

4.1. Meshed models with appropriate mesh density (see Fig. 4) are available for download from the webpage shown below in Reference [4]. Note that there are two models in each zip folder: one with four fillets finely meshed, and the other with only two of the fillets finely meshed. Either model may be used. Meshed models are available for Abaqus and Ansys solvers.

4.2. It is recommended that respondents use the provided meshed models to create a finite element model of the crank throw specimen. If that is not an option, then respondents can create their own FEA models using the 3D solid model, also available for download from the webpage Reference [4].

4.3. For consistency, it is recommended that a Young's Modulus of 205 GPa and a Poisson's Ratio of 0.3 should be used as the linear elastic material properties in the finite element model.

4.4. The material properties and processing information in Section 3.3 of this document should be used in the fatigue assessment. Any material properties that are necessary for the application of the chosen fatigue assessment algorithm, but are not provided in this document, should be estimated or assumed by the respondent, and stated in their response.

4.5. Respondents should perform the necessary simulation and analysis to apply the multiaxial fatigue assessment algorithm(s) of their choice. The result of the analysis must be a prediction of the moment amplitudes (bending or torsion) necessary to fail the crank throw with 50% survival probability at 5E6 load cycles under the four load regimes described in Section 3.5 above.

4.6. Respondents are requested to fill-in the form provided as "MFAC_Response.xlsx" at Ref. [4] and email the file to WG4@cimac.com (Ref. [3]). Participants may submit more than one response to the challenge using different algorithms, and each one will be compiled separately in the final summary.

5. References

[1] UR M53 Calculation of crankshafts for i.c. engines - Rev.3 June 2017 Clean – (search "UR M53" at www.iacs.org.uk for a download).

[2] ISO 12107:2003 – Metallic materials – Fatigue testing – Statistical planning and analysis of data.

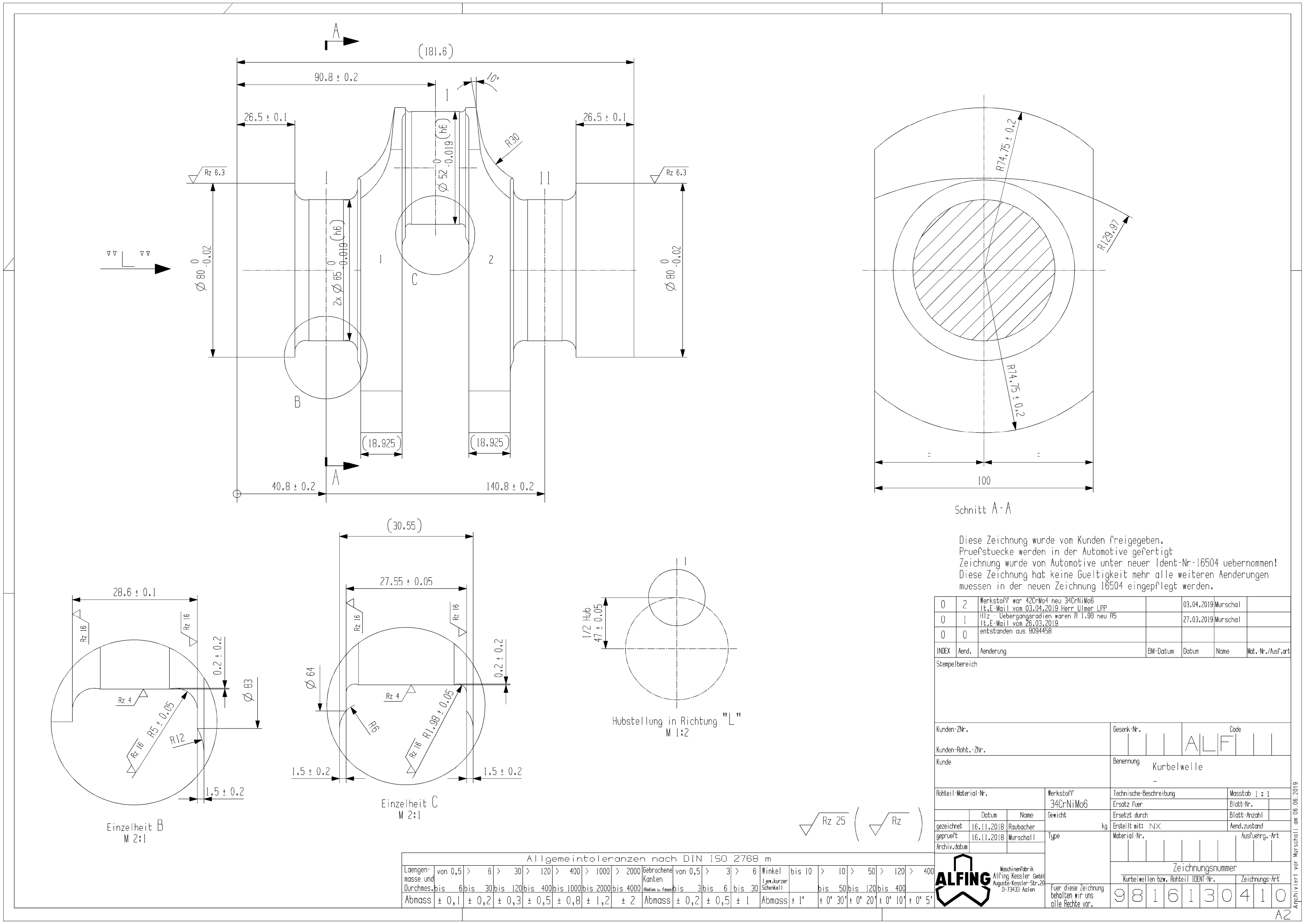
[3] CIMAC WG4 – Crankshaft Rules – WG4@cimac.com .

[4] MFAC webpage: https://www.cimac.com/working-groups/wg4-crankshaft-rules/algorithm-challenge/index.html

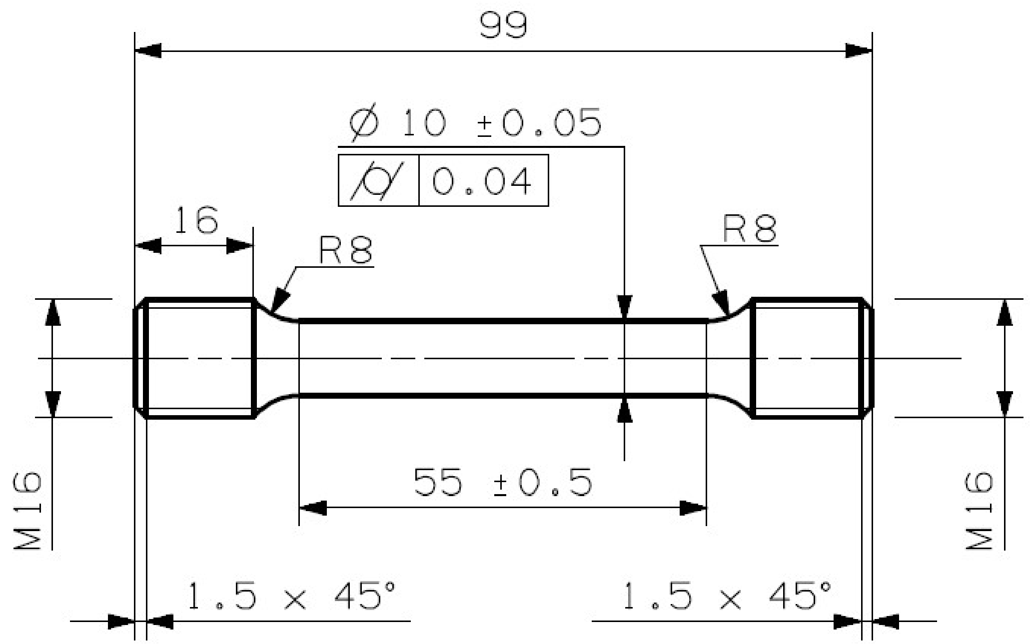
6. Revision History

Rev #	Date	Revision Author(s)	Description
0	2020-05-06	MAF Subgroup	Initial release.
1	2020-06-17	MAF Subgroup	Clarification of stress values in Table 3.
2	2021-03-16	MAF Subgroup	Update to include axial force preload.
3	2021-04-22	MAF Subgroup	Minor corrections and clarifications.

Appendix 1 – Sketch of CIMAC WG4 Crank Specimen 9816130410



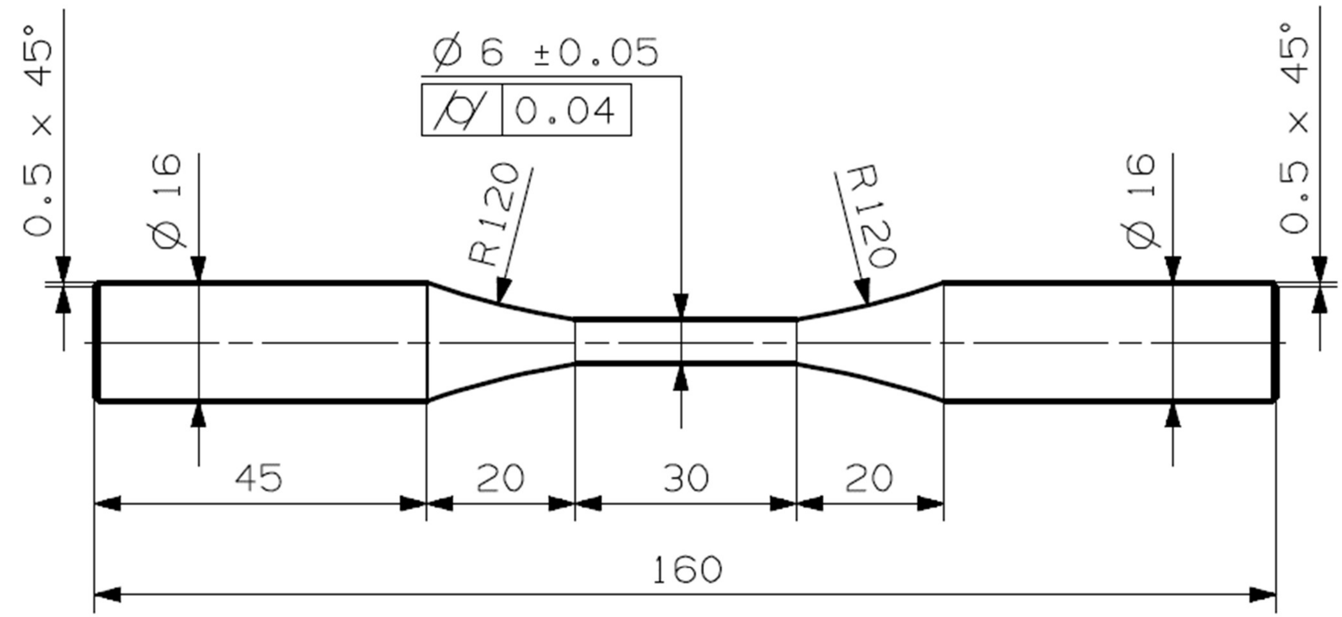
Appendix 2a – Tensile test specimen geometry used by MAN.



If the total length differs by ± 1.5mm
then compensate for the thread length
and make them equal in length.

Ra1.6 | 164 | All over, except where otherwise stated.

Appendix 2b – Axial fatigue test specimen geometry used by MAN.



If the total length differs by ± 1.5mm
then compensate at the 45mm in the ends
and make them equal in length.

Ra1.6 | 164 | All over, except where otherwise stated.

Appendix 2c – Torsional fatigue test specimen geometry used by Kobelco.

ねじり試験片形状（軸力ねじり疲労試験機用）_R1
Torsional test piece shape (for axial force torsion fatigue tester) _R1

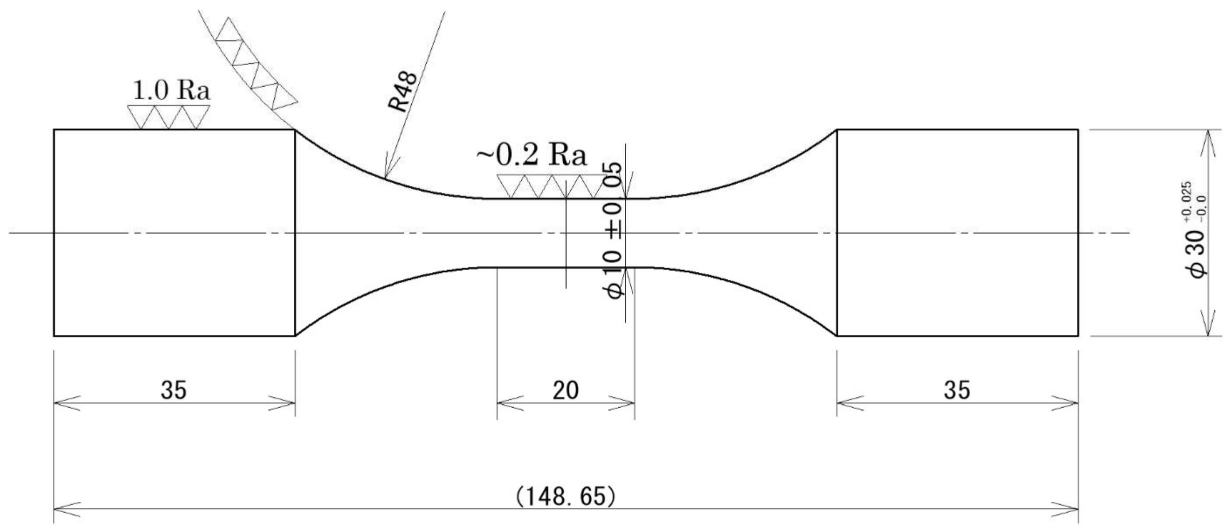


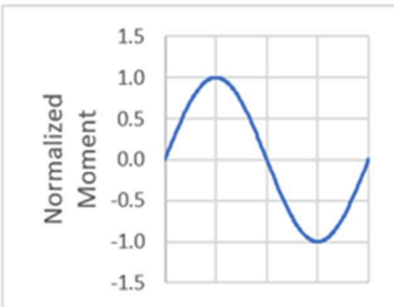
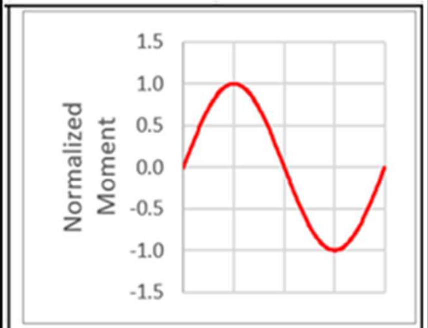
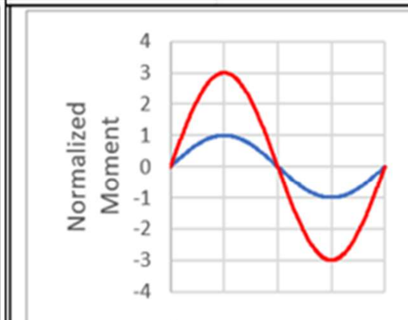
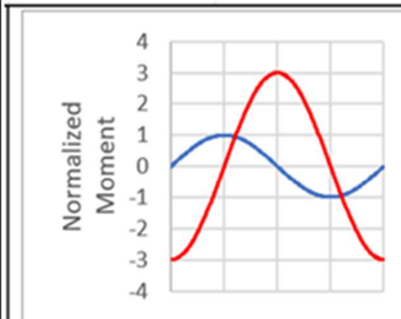
図 1. 確定図
Figure 1. Definite drawing

Appendix 3 – Response Form (Available as “MFAC_Response.xlsx” at Ref. [4]).

Name of Respondent: ______ Company or Institution: ______

Results:

Fill-in the predicted moment amplitudes (bending or torsion) necessary to fail the crank throw
with 50% survival probability at 5E6 load cycles under the four load regimes shown below, and email to WG4@cimac.com:

Bending moment: ± ___ Nm	Torsion moment: ± ___ Nm	Bending moment: ± ___ Nm (Torsion moment = 3xBending Nm) (Axial force = 3160 N constant)	Bending moment: ± ___ Nm (Torsion moment = 3xBending Nm) (Axial force = 3160 N constant)
 Bending, R = -1	 Torsion, R = -1	 Combined, R ≠ -1 In-phase	 Combined, R ≠ -1 +90° Out-of-Phase
Failure Location:	Failure Location:	Failure Location:	Failure Location:

Multiaxial Algorithm Used: (Please provide a brief description and references or web-link to the algorithm / software tool used.)

Assumptions: (Please provide a description of the assumptions, e.g., material, that were necessary to perform the analysis.)

Comments / Caveats: (Please provide as much additional information as desired.)