TALAT Lecture 2404

Quality Considerations

51 pages, 29 figures

Advanced Level

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Objectives:
- To provide understanding of underlying concepts and tools for handling experimental data and its comparison to existing design recommendations
- To provide understanding of classification parameters for structural details and quantitative links between design principles and quality criteria
- Enable sophisticated design for further structural details not included in current recommendations
- To teach methods of enhancing fatigue strength, especially as post-weld treatments

Prerequisites:
- Background knowledge in engineering, materials and fatigue required

Date of Issue: 1994

2404 Quality Considerations

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2404.01 Fatigue Design Data Management

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The Aluminium Data Bank is a joint project of the Technical University of Munich, Germany, and the Iowa State University, Ames, Iowa, USA. It serves the harmonised documentation, analysis, evaluation and presentation of material data, especially in the area of fatigue, from earlier small specimen tests and more recent comprehensive data generated from larger welded components and full-size elements. Data from other aluminium joint types as well as substantial fracture mechanics and crack propagation data is being added.

The further development is visualised under the ALFABET Project. The Aluminium Data Bank shall be coupled through an application oriented interface to other information sources like literature, handbooks, expert knowledge and instruments such as design concepts and procedures, codes, recommendations. Of great importance is here the management of a large body of information in conjunction with the options offered, from a retrospective search of characteristic values from the original sources to the evaluating and design procedures.

While the above statements outline the two main goals from the user's point of view it has been necessary to deal with additional questions of why, what for, advantages and disadvantages, how, whom to address, what data to document and process in dealing with a distinct package of information as is the case in drafting the design concepts for aluminium structures. Some of these ideas are mentioned briefly as introductory remarks to the specific task of ALFABET since they help provide guidelines along which the project itself will have to move. But these also provide elements for further work and harmonisation of procedures in testing and evaluating material and structural component behaviour, i.e. tasks to be addressed within the intended work of RILEM.

The development of a data bank has the purpose to use computers to provide a better access to data, but also help scrutinise this data. Material data should be computerised to the same level as other computerised engineering tools, such as design procedures and recommendations. These steps help broaden the range of materials choices and share materials experiences more effectively. The developed materials data system, and in our specific task the structural design system itself, should exhibit easy access, accuracy, availability for further computerised use, timelessness, completeness and uniformity, data comparison and user-friendly presentation.

Looking into the types of databases that may be developed it was recognised that these may be built some times merely as published data. The user of a database wishes to have a reliable distributor of the database, most times he will need multiple (compatible ?)

databases, he will have his own computer and he will not want to learn many systems, he needs user-oriented on-line help.

Developing a public available database will be associated with some disadvantages though. There may be a weak or diffuse objective, the product itself not user-friendly. Also inconsistency in the materials (fatigue in our case) parameters, stale data, and data acquisition will depend on volunteer effort. End user does not control activities of database manager. Further, there will generally not be enough experts to validate data and funding of the database activities will be variable and insufficient.

Being aware or even having experienced some of the above disadvantages it was tried to avoid them as far as possible in the development of ALFABET by: (a) emphasising the collecting and reporting of new materials and components behaviour information, (b) focusing on high priority industry fatigue data requirements (the fact should be stressed here that the AlDaBa and ALFABET projects are design-oriented and not so much material selection tools), (c) standardising and automating fatigue data collection and storage formats, (d) periodically purging the active system of stale data, (e) supplementing the expertise of validation experts with knowledge base systems, and (f) adequate and consistent funding of activities. The last point is, admittedly, a point of major concern.

Thus the general materials data flow in a data bank development could be as follows:

- data generation by testing or in-service measurement
- data analysis by modelling and statistical procedures
- data dissemination by publication and databases themselves
- data combination and comparison, re-analysis and "standardisation" of values
- distribution of handbooks, publication of databases

Finally, types of fatigue data required and suggestions on the data format are summarised in **Figure 2404.01.01** and **Figure 2404.01.02**.

Standard Material Coupon Tests
* Material Data
* Stress-Life
* Strain Life
* Failure Location
* Crack-Growth Rate

Material/Structural Coupon Design Verification Tests
* Duplicate local geometrical details
* Duplicate fabrication and service preparation details
* Simulate expected service history

Component and Full-Scale Design Verification Tests
* Duplicate complete fabrication history
* Duplicate joining and set-up conditions
* Simulate expected service history
* Compare to or perform in-service measurements

TALAT alu Training in Aluminium Application Technologies	Required Fatigue Data	2404.01.01

Fatigue Test Data Format

Material Identification
reference source,
data base or other

Test identification
type, standard or other, date

Description of specimens
identification
preparation
joining procedure
inspection and results
specimen layout reference
specimen orientation
specimen geometry

Test Parameters and Procedures
date
test facility and engineer
test environment
testing machine and fixture
loading parameters
loading rate
strain instrumentation
data collection method
sample rate

Test Results and Analysis
no. of specimens
rate of loading
loading parameters
loading statistical data
mechanical parameters
physical parameters
strength or/and strain
nominal, average
standard deviation, coefficient
failure location
failure mode
test validation, data quality
raw test data source
remarks, if any, such as
significant deviation
from standard

Source: D. Kosteas, TUM

TALAT Training in Aluminium Application Technologies	Fatigue Test Data Format	2404.01.02

As will be seen in the following, several of these suggestions have already been taken into account and have been incorporated in the format of the Aluminium Data Bank.

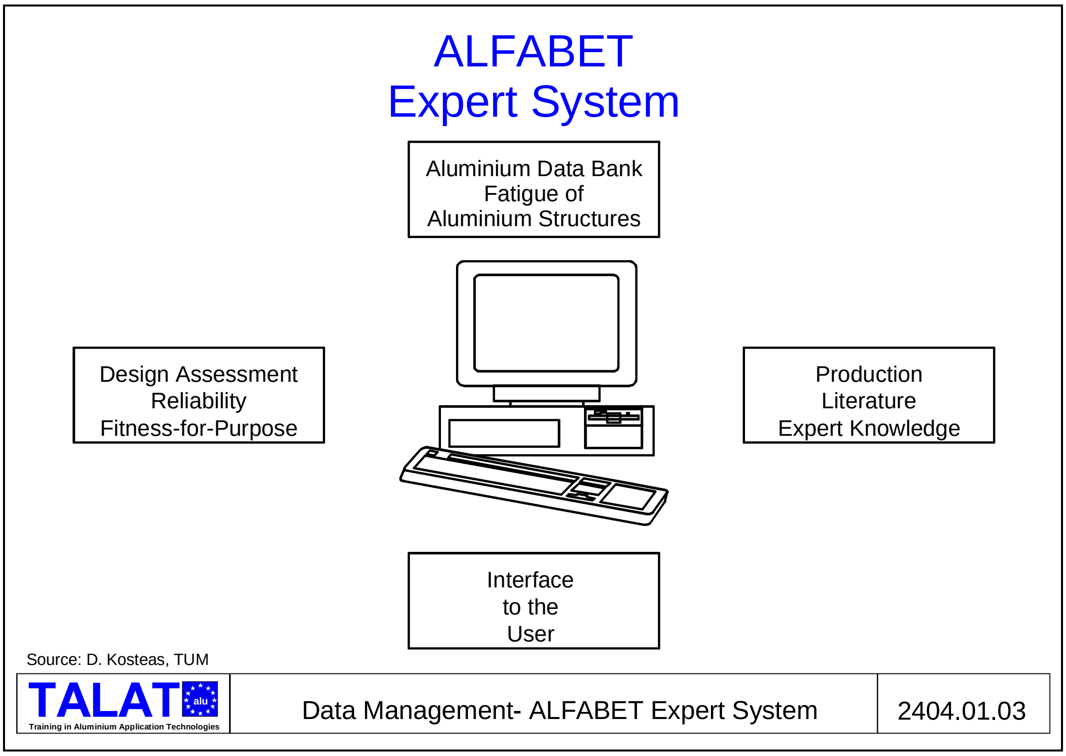
Early Developments

First decisive steps in the computerisation of fatigue test results in the form of a data bank for aluminium can be traced back to initial work by Munse followed by efforts by Sanders around 1970 who started the Welding Research Council Aluminium Data Bank at Iowa State University [1]. Data were initially stored on punched cards.

Regressional analysis software was developed in the late sixties by Kosteas at the University of Karlsruhe [2] and applied thereafter on consecutive comprehensive evaluations on aluminium fatigue test data. A cooperation was initiated in the early eighties under the Committee on Aluminum Fatigue Data Exchange and Evaluation (CAFDEE) [3] resulting since 1985 in a simultaneous installation and operation of the Aluminium Data Bank at the Iowa State University and the Technical University of Munich.

One of the primary tasks of the last years has been the user-oriented adaptation of available aluminium test data and software for its evaluation, whereby the former main frame computer operation has been abandoned in favour of the now broadly available personal computers.

The logical extension and applicability in engineering design led to the concept of a management system for such material, technological, manufacturing, quality control and reliability information and processes as needed during the design procedure of aluminium constructions, **Figure 2404.01.03**.



The first task is complete by now and consists of what is understood as the Aluminium Data Bank (ALDABA). The bank is itself a part of the second more comprehensive task, the Aluminium Fatigue Behaviour Evaluation Task (ALFABET) Project. These two are described in more detail in the following chapters.

The Aluminium Data Bank

The Original PC Version

In the first stage of the data bank, from 1987 to 1989, the use of commercially available software was favoured since development and employment had to be performed in parallel. Extensive analyses, significant to drafting the ECCS European Recommendations for fatigue design in aluminium, were carried out [4]. This work was invaluable in testing procedures and providing decisions for future applications.

The data bank management was based on the dBase III+ software package. A positive fact was the rather powerful structured query language (SQL) for data retrieval and selection. However concerning the user menu, graphics, colours or hardware programming we were confronted by serious handicaps. In order to circumvent licence problems with directly applicable programmes, i.e. *.EXE or *.COM files, dBase programme runversions were constructed by means of the compiler system "Clipper". Available data was stored in three parts:

(a) the literature data bank,
(b) the detail and data description data bank, and
(c) the fatigue test data points themselves and their mathematical processing.

Parts (a) and (b) were written in dBase III+, whereby the rather complex statistical formulas of part (c) were executed in Pascal - all parts integrated to one programme by means of "Clipper". Part (b) is essential to the user since it allows data set selection and detail classification. A comprehensive parameter field has been covered by the format of the detail description data bank, see **Figure 2404.01.04**.

A. General
1. Data Set No.
1. Literature No.
3. Page No., Table No., etc.
4. Test Year (19__)
5. Confidential (Y/N)
6. Last Check (dd/mm/yy)
7. Remarks

B. Joint Description
1. Basic Weld Type
2. Edge Preparation
3. Weld Geometry

Joint Dimensions
4. R (mm)
5. F (mm)
6. p (degrees)
7. H (mm)
8. D (mm)

C. Specimen Description
1. Specimen Description
2. Thickness (mm)
3. Width (mm)
4. Tested Yield Strength (MPa)
5. Yield Point Off-Set (%)
6. Tested Ultimate Strength (MPa)
7. Ultimate Strain (%)
8. Gage Length (mm)

D. Welding Process and Procedure
1. Welding Process
2. Welding Procedure
3. Welding Position
4. Filler Material (4 Letter AA)
5. Filler Material (Product Name)
6. Welding Wire Diameter (mm)
7. Shielding Gas
8. Shielding Gas Flow Rate (l/min)
9. No. of Passes
10. Welding Speed (cm/min)
11. Welding Current (Ampere)
12. Welding Voltage (Volts)
13. Non-destructive Examination Technique
14. Discontinuities
15. Pre-Weld Treatment
16. Post-weld Treatment I (Notch Shape Modification Methods)
17. Post-weld Treatment II (Mechanical Treatments)
18. Post-weld Treatment III (Thermal Methods)

E. Base Material
1. Alloy Designation (4 Letter AA Designation)
2. Temper or Heat Treatment
3. Product Name or National Designation
4. Fabricator
5. Product Form
6. Chemical Composition
7. Tested Yield Strength (MPa)
8. Yield Point Off-Set (%)
9. Tested Ultimate Strength (MPa)
10. Ultimate Strain (%)

F. Test Conditions
1. Test Machine
2. Mode of Loading
3. Orientation of Weld and Load
4. Environmental Conditions
5. Type of Loading
6. Temperature (°C)
7. Frequency (Hz)
8. Failure Criteria
9. Basis of Recorded Stress or Strain
10. R-Ratio
11. Number of Stress Levels
12. Number of Data Points

Source: D. Kosteas, TUM

TALAT Training in Aluminium Application Technologies | Test Data Description Parameters | 2404.01.04

The data bank primarily covered fatigue test data of various alloys in structural engineering applications (alloy groups 5xxx, 6xxx and 7xxx), base material and numerous welded joint types. The original CAFDEE data bank included approx. 15000 data points on small specimens, which have now been to a large extend re-checked and validated. Though interesting in many ways these older data on small specimens presented problems regarding the capability to lead to reliable conclusions [5]. There were serious gaps in the documentation, even of geometrical or welding and, at times, testing parameters. Beyond this, small specimen data will not reflect actual component behaviour in service. These facts have been widely acknowledged and led to decisions about 10 years ago in the area of aluminium constructions for experimental research in fatigue and eventually for evaluating carefully performed observations mainly on large components.

In the course of these comprehensive fatigue test series at the Technical University of Munich between 1982 and 1990 a nucleus of approx. 1,000 extensively documented and published data points on large structural components, beams, have been generated. Further fatigue tests performed by industry on components and made available during the recent recommendations drafting process [6] will hopefully become publicly available in the near future. These, together with recent work performed by Fisher and Menzemer, will increase the contingent to more than 2,500 data points. It should also be mentioned that in the course of the last years' evaluation almost another 20,000 data points on small specimens provided by industry [6] served in drafting the European Recommendations [7, 8].

The New Version

A user-friendly data bank, allowing ready access to information and compatibility to all other steps in the structural design procedures, should enable a simple, logical and reliable dialogue with the user. This led to a menu-driven programme with controls against unintended input errors.

Consequently the decision was made in 1989 to choose the latest Turbo-Pascal version 5.5 as the new programming language (this being at that time the only language allowing object-oriented-programming). Another advantage for the user was reached by using the much more rapid and reliable BIOS system to control input/output functions and thus avoiding any harmonisation problems with other programmes.

A basic feature in this new version is the main menu, guiding the user through the whole programme. An object-oriented window and menu management system had to be developed with simple mouse- or key-driven selection of programme functions. In a dialogue with the user, further information may have to be supplied and its plausibility checked immediately. Common compilers on the market did not offer such language capacities, so that all tools were written in assembler language, guaranteeing maximum control of the hardware combined with maximum of operation speed.

In the last two years the statistical/regression data part of the bank, as well as the data information and data set description parts of the system was finished for mouse-supported operation. The main menu appears on the screen, when typing "ALF.EXE", which outlines the capacities of the programme. The division into three main parts is established through the menu points 'Literature Data', 'Data Description' and 'Fatigue Test Data' (see **Figure 2404.01.05**).

Programming languages are planned to be flexible and open for each area, so normally these languages provide no special features for screen or file handling. Pascal, as such a programming code, offers no special routines for generating menus or other features. All had to be developed and tested in first place. The aim was to give the whole system a unique and simple outlook and operating capacity. Turbo-Pascal allows only a very simple file handling, so further new tools had to be developed for writing and reading so-called 'streams' into and from a file. A further comprehensive parameter field had to be developed for covering the format of the literature description data bank (see **Figure 2404.01.06**). To computerise this format another editor had to be written, which allows the user a interactive input of all information (see **Figure 2404.01.07**).

Outline of ALFABET Test Data Description

Material Identification
reference source, data base or other

Test Identification
type, standard or other, date

Description of specimens
identification
preparation
joining procedure
inspection and results
specimen layout reference
specimen orientation
specimen geometry

Test Parameters and Procedure
date
test facility and engineer
test environment
testing machine and fixture
loading parameters
loading rate
strain instrumentation
data collection method
sample rate

Source: D. Kosteas, TUM

TALAT Training in Aluminium Application Technologies	Outline of ALFABET Test Data Description	2404.01.05

Literature Data Record

1. Literature Number
2. Reference Literature Number
3. Author 1 to Author 5
4. Title
5. Source
6. Date of Publication
7. Tested Material 1
8. Tested Material 2
9. First Keyword
10. Second Keyword
11. Third Keyword
12. Confidential
13. Library Source

Source: D. Kosteas, TUM

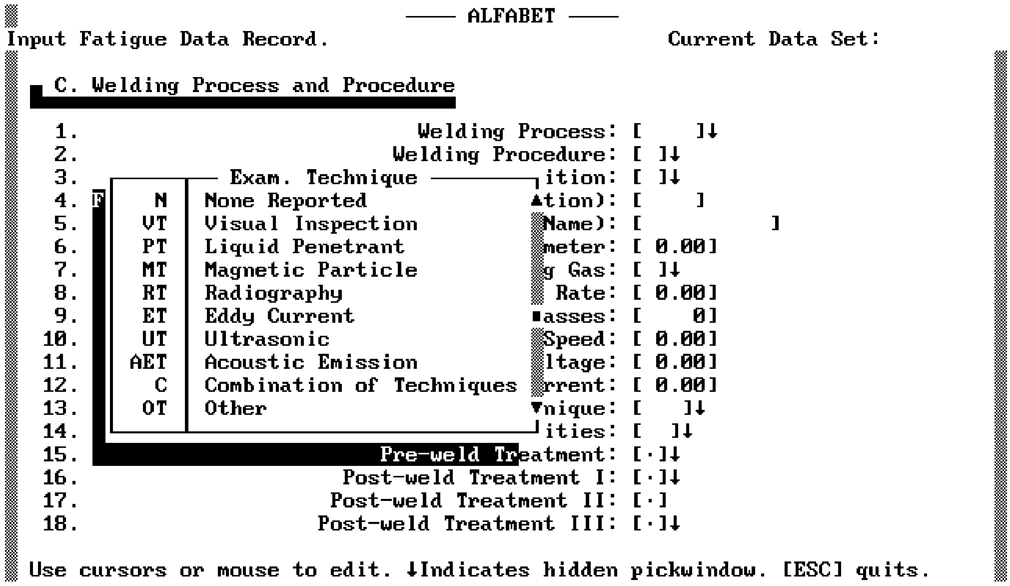
TALAT Training in Aluminium Application Technologies	Literature Data Description Parameters	2404.01.06

```
                         —— ALFABET ——
 Edit Literature Data Record.                   Current Data Set: FW1700.0↓

                                                  Literal Data Records
  Lit. Reference Nº: [FW1700.0]
   Sander's Lit. Nº: [··············]
            Author1: [Kosteas, D.··················]
            Author2: [Poalas, K.···················]
            Author3: [·····························]
            Author4: [·····························]
            Author5: [·····························]
              Title: [Voraussage des Ermüdungsverhaltens geschweisster········]
                     [Aluminiumbauteile.·····································]
        Publication: [Lehrstuhl für Stahlbau, Technical University of Munich.·]
                     [Munich, West Germany.··································]
               Date: [30.06.1986]
  Prim. Mat. Tested: [7020······]
   Sec. Mat. Tested: [5083··································]
   Primary Key Word: [Beams·································]
      Sec. Key Word: [Components····························]
    Other Key Words: [Residual Stresses·····················]
       Confidential: [·]
     Library Call Nº: [·····························]

  Use cursors or mouse to edit. ↓Indicates hidden pickwindow. [ESC] quits.
```

Source: D. Kosteas, TUM

TALAT – Training in Aluminium Application Technologies	Literature Editor	2404.01.07

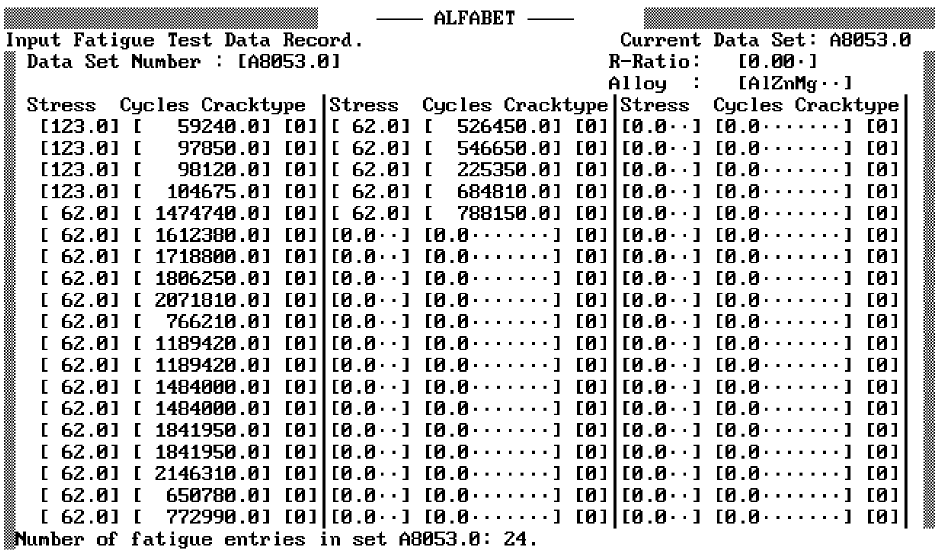
The data description parameter field, as shown in **Figure 2404.01.08**, was computerised according to this new editor system. To give the user as much help as possible and to avoid complex manuals, it was decided to use „pickwindows" for all the abbreviations of the classification of the specimens, the types of weldments, the weld procedures and pre- and post-weld treatments where needed. Now all information necessary for later reclassification and combination of data sets can be stored in that way.



Source: D. Kosteas, TUM

TALAT	Detail Description Pickwindow	2404.01.08

A further editor had to be developed to add and edit the actual fatigue data points, see **Figure 2404.01.09**. Within this record, a data-set-number, the R-ratio, the tested alloy and the data point given in stress range, cycles to failure and a toggle to characterise run-outs are given.

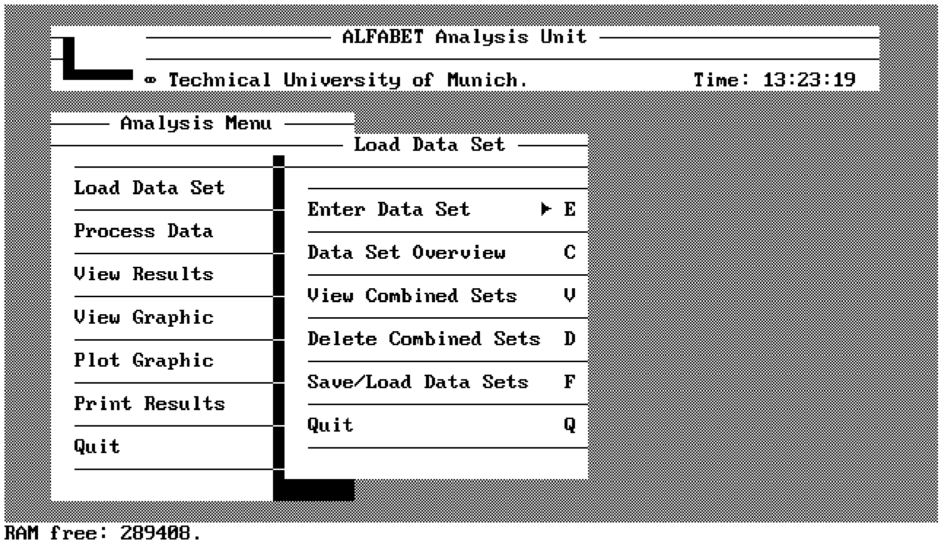


Stress	Cycles	Cracktype	Stress	Cycles	Cracktype	Stress	Cycles	Cracktype
[123.0]	[59240.0]	[0]	[62.0]	[526450.0]	[0]	[0.0··]	[0.0·······]	[0]
[123.0]	[97850.0]	[0]	[62.0]	[546650.0]	[0]	[0.0··]	[0.0·······]	[0]
[123.0]	[98120.0]	[0]	[62.0]	[225350.0]	[0]	[0.0··]	[0.0·······]	[0]
[123.0]	[104675.0]	[0]	[62.0]	[684810.0]	[0]	[0.0··]	[0.0·······]	[0]
[62.0]	[1474740.0]	[0]	[62.0]	[788150.0]	[0]	[0.0··]	[0.0·······]	[0]
[62.0]	[1612380.0]	[0]	[0.0··]	[0.0·······]	[0]	[0.0··]	[0.0·······]	[0]
[62.0]	[1718800.0]	[0]	[0.0··]	[0.0·······]	[0]	[0.0··]	[0.0·······]	[0]
[62.0]	[1806250.0]	[0]	[0.0··]	[0.0·······]	[0]	[0.0··]	[0.0·······]	[0]
[62.0]	[2071810.0]	[0]	[0.0··]	[0.0·······]	[0]	[0.0··]	[0.0·······]	[0]
[62.0]	[766210.0]	[0]	[0.0··]	[0.0·······]	[0]	[0.0··]	[0.0·······]	[0]
[62.0]	[1189420.0]	[0]	[0.0··]	[0.0·······]	[0]	[0.0··]	[0.0·······]	[0]
[62.0]	[1189420.0]	[0]	[0.0··]	[0.0·······]	[0]	[0.0··]	[0.0·······]	[0]
[62.0]	[1484000.0]	[0]	[0.0··]	[0.0·······]	[0]	[0.0··]	[0.0·······]	[0]
[62.0]	[1484000.0]	[0]	[0.0··]	[0.0·······]	[0]	[0.0··]	[0.0·······]	[0]
[62.0]	[1841950.0]	[0]	[0.0··]	[0.0·······]	[0]	[0.0··]	[0.0·······]	[0]
[62.0]	[1841950.0]	[0]	[0.0··]	[0.0·······]	[0]	[0.0··]	[0.0·······]	[0]
[62.0]	[2146310.0]	[0]	[0.0··]	[0.0·······]	[0]	[0.0··]	[0.0·······]	[0]
[62.0]	[650780.0]	[0]	[0.0··]	[0.0·······]	[0]	[0.0··]	[0.0·······]	[0]
[62.0]	[772990.0]	[0]	[0.0··]	[0.0·······]	[0]	[0.0··]	[0.0·······]	[0]

Source: D. Kosteas, TUM

TALAT	Fatigue Data Editor	2404.01.09

So when using the actual programme, the first step to store data is to choose the literature part and type in the data source. In a second step, for each data set being created, a description file is necessary for a detailed classification of the actual data points. Then the actual data points can be added, see **Figure 2404.01.10**.

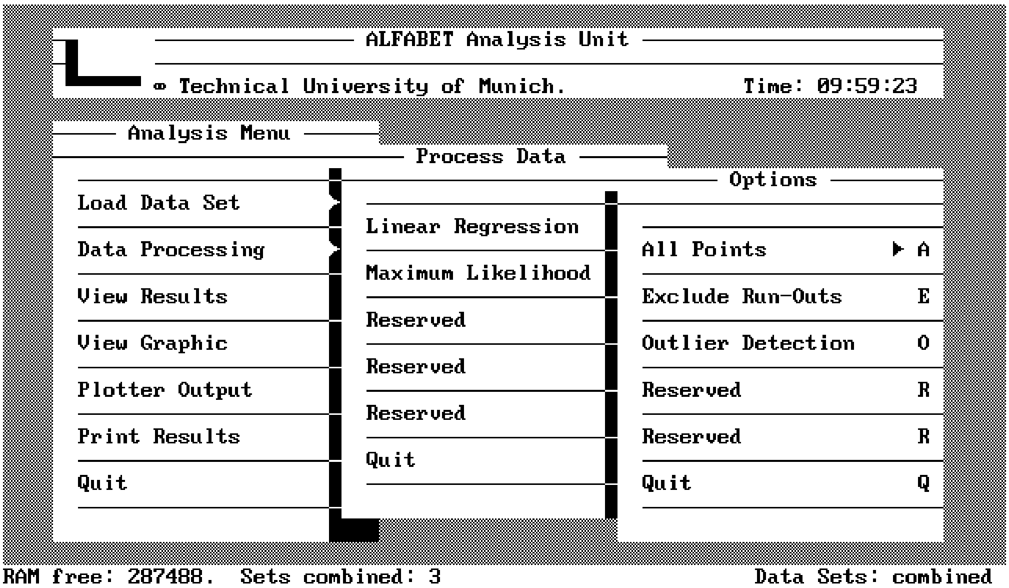


Source: D. Kosteas, TUM

TALAT Training in Aluminium Application Technologies	Data Analysis Menu	2404.01.10

The third and primarily used part of the programme is the analysis part. It provides for the free combination of several data sets with various possibilities of regression analysis, like linear regression or maximum likelihood. In the first step under the menu point 'Load Data Sets' one or several sets can be selected by a picklist or by just typing in the data set reference numbers (see **Figure 2404.01.10**).

This list of selected data sets can be re-edited in a overview. The second step will be the analysis of these single or combined sets by linear regression or by maximum likelihood analysis (see **Figure 2404.01.11**). Options are provided, within the linear regression analysis, such as treating run-outs as broken points or excluding them from the whole procedure. Another feature is the decision to delete so-called outliers or include them in further analysis - a tool useful to the user in the comparative evaluation of fatigue data.



Source: D. Kosteas, TUM

TALAT Training in Aluminium Application Technologies | Regressional Analysis Options | 2404.01.11

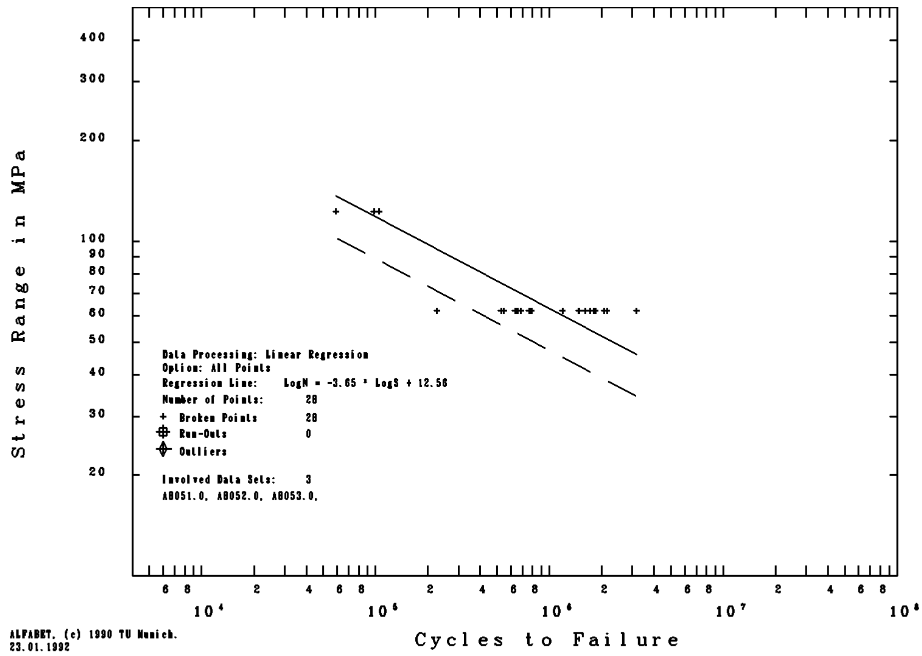
When the data analysis is performed, the results can be displayed on the screen by the menu point 'View Results' (see **Figure 2404.01.12**). Within the menu point 'View Graphic' a spreadsheet (see **Figure 2404.01.13**) with logarithmic axes, the calculated data points with the mean regression line and a 97,5% survival line is shown as a diagram on the screen. Of course all results, as well as the S-N-diagram, can be printed or plotted out or even stored in a file.

Only few parts of the whole programme are missing at this time. One of the missing options is the selection of data sets in terms of the stored data set descriptions. This part will be made operational within the next months and the databank programme will be finished and ready to be released with all the data, including newly collected data.

```
Data processing:  Linear Regression   Options:  All points  Outliers:  none

Average Values:          Mean LogS:  2.039         Mean LogN:  5.168

Regression Line Equation:    LogN =  -2.56  *   LogS   +  10.39

Variance and Standard Deviations:
SSR:             0.992      Standard Deviation (LogN)         :  0.195
Variance of LogN: 0.038     Standard Deviation (LogS)         :  0.076
                            Standard Deviation of the Slope   :  0.220
                            Standard Deviation ot the Intercept:  0.449

95% Confidence Intervals for slope and Intercept Parameters:
  -2.920    < Slope <  -2.205            9.662     < Intercept <   11.126

Estimated Mean Stress # 2·10^6  Cycles to Failure:   39.552  MPa
Estimated Mean Stress #   10^5  Cycles to Failure:  127.309  MPa
Estimated LogN Stress Range  30 MPa: Log N =  6.609  ; Cycles =      4061362
Estimated LogN Stress Range  50 MPa: Log N =  6.040  ; Cycles =      1096859
Estimated LogN Stress Range 100 MPa: Log N =  5.269  ; Cycles =       185659

97,5% Probability of Survival #  2·10^6 Cycles    :   29.72    MPa
97,5% Probability of Survival #    10^5 Cycles    :   95.67    MPa
```

Source: D. Kosteas, TUM

TALAT	Regressional Analysis Results	2404.01.12



TALAT	S-N Diagram of Calculated Data	2404.01.13

The ALFABET Project

Linking the Aluminium Data Bank as one information source to further such sources and decision-forming tools (literature, handbooks, manuals, expert knowledge, the latter being naturally limited in its availability by time or age) and then to design recommendations, together with appropriate reliability and fitness-for-purpose estimates offers a complete system for the design of aluminium structures. Of prime interest will be the development of an interface between these information sources and the user, which will provide guidance to the user allowing for design levels of varying sophistication degree according to the desired application. Since respective efforts on the development of design recommendations have demonstrated the need for further clarification of manufacturing and quality control parameters to allow for reliable classification of structural details, a close cooperation with the industrial side providing "manufacturing and welding technology" to supplement the above efforts on the "design technology" is strongly recommended and desired.

Work associated with the development of the data bank as stated above is understood as Phase I of this project. Phase II deals with the link between data description and data analysis. As already pointed out this is of essential importance to the detail classification and evaluation in the design procedure and reliability analysis. Extensive structural detail description and fatigue data, see **Figure 2404.01.01**, supported by graphics and cross-reference to detail design parameters, manufacturing options, quality criteria and strength behaviour must be provided. In this step occurs also the input of corresponding welding technology information to an extent appropriate and necessary to the corresponding design and reliability level.

Several add-on packages occupy a position between Phases II and III, such as finite element modelling and analysis, reliability analysis, fracture mechanics analysis and life estimations. These are to be linked to respective material and component values as given through the data bank. Work has already commenced in independent projects recording such data.

In Phase III the actual integration of the above steps to the whole system has to be undertaken, **Figure 2404.01.14**. It will provide the interface and feedback system for the user. An essential part of this work is the verification, operability and close adaptation to application needs of the system. It is self-evident that such an ambitious task can only be carried out as a joint venture.

Continuing efforts to enhance the volume of the data bank are independent of the above phases and will have to be performed parallel to other efforts and on a continuous basis as new information from research or from further sources in literature keeps coming in. Besides the large contingent of data as mentioned previously the following data input tasks are being considered for the immediate future:

- further component test data in currently performed fatigue tests in Europe and USA,
- data as given in Japanese literature,
- validation of component test data as outlined in [9],
- comprehensive fracture mechanics properties data for aluminium alloys currently being recorded at the TUM, and
- extensive crack propagation test data generated by Jaccard [10] or Graf and Kosteas [11,12] at the TUM in the early eighties for base material, weld metal and HAZ material of different aluminium alloys and weldments under variation of stress ratio and plate thickness.

A. Rough goal definition	Expert System for static and fatigue design formulation of application
B. Initial Information Accumulation (largely unstructured in this place)	1. Literature survey and compilation 2. Information from practice 3. Definitions 4. Documentation of standard recommendations etc. cross section references to other documents design and manufacturing rules 5. quality criteria Fitness for Purpose, NDT, Detail Classification 6. Available software Drafting Software
C. Knowledge Presentation	Accumulated documentation material to be structured, ordered and presented in an abstract and universal format
D. Main Information Accumulation	Application oriented, enhanced documentation
E. Pilot or Prototype study	Performed for a number of case-studies Check ES format, alter, amend, re-check (Iteration)
F. Detailed Study	ES integration in actual working format
G. System Development	ES adaptation after D
H. Check and Validation Phase	Actual design cases compared to ES solution
I. Installation and Acceptance Phase	Efficiency in industrial application
J. Maintenance and Updating	

Source: D. Kosteas, TUM

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Design Tools

A first item has been produced by the Technical University of Munich, the "Classification and Design of Fatigue Loaded Aluminium Constructions" as a computerised version of the "ERAAS Fatigue Design" rules. It comprises of a complete manual of the recommendations, quick cross-references, a structural detail unit with full descriptions, a survey menu for the selection of details and a complete design menu featuring all significant spectrum input and performing the final fatigue assessment.

A demonstration of its application is given with the fatigue assessment calculation example in **Lecture 2402**.

Literature/References

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[12] Graf U.: Bruchmechanische Verfahren bei Aluminiumbauteilen“. Dissertation an der TU München in Berichten aus dem Konstruktiven Ingenieurbau, München 1992

2404.02 Quality Criteria and Classification of Structural Details

- Objectives
- Scope of specifications
- Quality levels
- Extent and methods of inspection
- Acceptance criteria
- Remarks on quality assurance and quality requirements
- Structural detail configurations
- Literature/References

A quantitative link between design principles and quality criteria is essential, especially in fatigue. Only with sufficient knowledge of the possible defects or the unavoidable imperfections in structural details can an acceptable level of safety and reliability be reached for the structure.

Pertinent data has been scattered traditionally among diverse documents like material quality specifications, procedure approvals, personnel qualifications, inspection rules, quality control and final product acceptance, maintenance and repair recommendations. They have their justification there and we would like to refer to respective TALAT Lecturess for further information. It remains a fact though that until recently quality specifications (as for instance weld quality classifications by non-destructive methods in DIN 8563 T30, to name just one example) are not fully compatible to respective fatigue design recommendations. Recent efforts in documentation and evaluation of defects or imperfections in welded aluminium structures, their correlation to actual service behaviour under cyclic loading, and the integration of the information in the design procedure linked to the other material-manufacturing-service data will undoubtedly offer a positive development in this area.

In this chapter specifications for aluminium structures on inspection, quality and acceptance are outlined as an inherent part of the design procedure and as a background for the structural detail classification. Some of these rules are general rules to be followed in every good fatigue design. The rules are specific to aluminium as they are drawn from recommendations for the fatigue design of aluminium structures.

The Data Sheets of the European Recommendations for Aluminium Alloy Structures give information on the joint details, their manufacturing, the joining procedure and any post-treatments affecting the fatigue behaviour and consequently the detail classification, i.e. the allowable design stress level. They have been dealt with in chapter 11 dealing with design rules, especially those defined in the European Recommendations. The BS 8118 deal in a rather detailed way in the 2nd part with "Weld Quality, Inspection and Acceptance Specification". Here are given acceptance criteria for weld discontinuities in terms of dimensional limits and are based primarily on fitness-for-purpose principles. These specifications are linked quantitatively to the design rules of the 1st part requiring the designer to select one of 7 quality levels. Information presented in this chapter follows closely the outline of BS 8118 which at the moment offer the most complete set of rules available. They cover explicitly welded joints. These present normally the most critical part in structural components, economically the most challenging, and they cover the bulk of structural applications. So it is justifiable to concentrate on welded joints at first. See also information on "Weld Imperfections" in **Lecture 2401.06**.

Objectives

It is very important to the economy of aluminium that quality levels appropriate to the performance requirements of the various parts of the structure within the environmental conditions of the application are specified and agreed upon.

The competitiveness of structural aluminium details has been demonstrated in the comparisons of **Lecture 2402**, the prerequisite being the fulfilment of certain manufacturing standards. The cost of manufacture can be very much affected by the required weld quality. If it is ill-defined, contracts can be lost through overcautious estimating or - alternatively - financial losses to the fabricator can result. In addition the true quality of the product can be downgraded as a result of excessive repair so that both supplier and purchaser may lose out in the end.

Extra cost can result from excessive and unnecessary inspection with high rejection rates, repairs, and delays in the manufacturing. Reference back to the design stage, recalculations and new fitness for purpose assessments are further unpleasant results. Stringent criteria suitable for welder specification and procedure approval surely have their justification in a number of sophisticated applications where specific advantages of aluminium come into play, but for a good number of welding applications, away from high cycle loading, higher standards of material preparation, cleaning, jigging, welding control, and increased inspection and repair costs can unnecessarily increase the manufacturing costs.

Shortcomings in weld quality specifications for structural welds and the problems arising are summarised in the following **Figure 2404.02.01** and **Figure 2404.02.02**.

The objectives can be summarised as follows:

> To provide assurance that the quality of every welded joint is adequate to enable all design limit states to be achieved:
>
> 1. With maximum economy of inspection resources, taking into account current NDT practice and its limitation
> 2. With minimum cost and delay arising from repairs

3. With minimum need for consultation between design office and fabrication shop during manufacture
4. With maximum definition of costs at the tender stage

Shortcomings of Weld Quality Specifications for Structures

Aspect	Shortcomings
Inspection	1. No guidance methods 2. No guidance on extent
Acceptance Criteria	1. None given 2. Too onerous 3. Some not assessable 4. Arbitrary - not related to performance requirement

Source: D. Kosteas, TUM

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Problem	Consequential Implications for Safety	Consequential Implications for Cost
1. Difficulty in estimating		yes
2. Inadequate inspection	yes	yes
3. Unnecessary inspection		yes
4. Unnecessary repair	yes	yes
5. Delay to contract		yes
6. Claims		yes

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Scope of the Specifications

Actually any provisions made here in quality, inspection and acceptance criteria must comply with the respective provisions of design. In this case of reference to the BS 8118, Part 2 document reference to BS 8118 Part 1 on Design or to other specifications covering for instance material properties or welding processes is assumed. Such specifications may still differ from country to country at the moment but homogeneity will eventually be achieved in the future. Bearing in mind the close cooperation during the data evaluation stage in drafting the BS 8118 and the ERAAS Fatigue Design documents the statements made in this chapter hold true to good extent in the case of the

ERAAS as well. This is especially true for the general format of the quality specifications. The specific limiting values and the ensuing classifications, in some cases the respective fatigue strength values, will have to be scrutinised in order to achieve full homogeneity.

All joint and arc weld types included in the design rules are covered - fillet and butt welds, and butt, T, cruciform lap and corner joints, made by MIG or TIG welding. Consequently most actual applications in framed, latticed or stiffened plate construction made from plate or extrusions are thus covered. Castings are not covered. Neither are pressure vessels or piping covered, nor welds where special aesthetic considerations may apply are considered.

The inspection scope and the acceptance criteria specified may also be part of a contract document if wished. The requirements should be treated as a minimum mandatory specification. Relaxation of the requirements could lead to a loss of safety margin.

The inspection scope and the acceptance criteria are mentioned in this chapter only as far as they assist in understanding the outline and background information for the structural detail classification.

Quality Levels

Seven quality levels are defined depending on the performance requirements for the welds concerned, **Figure 2404.02.03**, together with an estimate of the frequency with which each level is likely to be applied in normal structural work.

Quality Levels

Quality Level	Number of Levels	Stressing Conditions	Estimated Scope of Application
MINIMUM	1	<1/3 static and fatigue limits (i.e. stiffness control design)	< 5%
NORMAL	1	full static, low fatigue	> 95%
FATIGUE	5	full static, increasing fatigue	< 5%

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A new feature is that the scope of application is to be indicated on the drawings. Unless noted on the drawings Normal quality will be assumed. If certain joints in the structure require a fatigue strength in excess of Class 20 (in the BS 8118, i.e. fatigue strength design value at $2*10^6$ cycles) the required class (above Class 20) will be marked on the drawings.

This ensures maximum economy by directing quality control resources to those areas which particularly need them.

Extent and Methods of Inspection

This part is not directly involved in the design procedure, it is rather the product of its application, the acceptance criteria, that interest the design engineer and influence the classification of structural details. Nevertheless, since it inherently affects the acceptance criteria themselves and since, as mentioned, it has to be integrated in the reliability and economic considerations it has been decided to include this information.

The four main methods of assuring weld quality are of equal importance:

- ensuring that a viable welding procedure is implemented
- ensuring that operatives are competent
- ensuring that quality is controlled during production
- ensuring that the f i n a l product meets the required quality standard

The first two items are ensured by requiring procedures and welders to be tested in accordance with respective specifications. The third item, quality control during production, is considered to be primarily the responsibility of the fabricator, so that there are no mandatory requirements at this stage apart from the inspection of joints prior to welding.

Methods and scope of final inspection of the product are summarised in the tables below. The inspection procedure is divided in four stages:

(a) immediately prior to welding - visual and dimensional inspection -,

(b) after completion of welding - visual and dimensional inspection -,

(c) after visual inspection - non destructive testing -, and

(d) after non destructive testing - inspection through destructive testing.

Efficient deployment of inspection resources is essential and inspection should be increased according to the following rules:

(1) Visual inspection is still considered to be the most important method

(2) The scope of inspection is increased where high quality level is necessary for performance. In this transversely stressed welds are given more inspection than longitudinally stressed welds

(3) The scope of inspection is increased where joint and weld types require more welding skill and may be more prone to defects, i.e. single sided butt welds.

(4) The term 'defect' is used correctly to mean a discontinuity which is unacceptable according to the specification in terms when used in a contractual context.

(5) Non-destructive testing methods are selected according to their economy and efficiency in detecting defects. In this respect radiography is only stipulated where absolutely necessary, mainly on thin material where no other method exists and where fatigue requirements are high.

(6) Where NDT is incapable of giving adequate assurance of quality on its own it is supplemented by destructive tests on coupon plates

(7) Fatigue quality classes are omitted where they exceed the maximum class permitted by BS 8118 Part 1 for the particular weld, joint type and orientation.

Details to Methods and Scope of Inspection

Stage 1:

It is recommended that, for Normal and Fatigue Qualities all joints are visually inspected by a competent person for cleanliness, fit-up and safety immediately prior to welding. This may be by the welder himself, if he is properly trained. In which case he would sign off the appropriate QA form.

It also goes without saying that an important aspect of in-house quality control inspection is to ensure that welders are working strictly to the approved procedures at all times.

<table>
<tr><td colspan="4">Stage 1: Immediately prior to Welding</td></tr>
<tr><td><u>Visual and dimensional Inspection</u>
To ensure that the following comply with the approved welding procedures</td><td>Joint Type</td><td>Required Quality Class</td><td>Number of Joints of each Type (Note 1)</td></tr>
<tr><td rowspan="2">(I) Surface condition
(II) Preparation and fit-up dimensions
(III) Jigging and tacking requirements</td><td rowspan="2">All</td><td>Minimum</td><td>20</td></tr>
<tr><td>Normal and Above</td><td>100</td></tr>
</table>

Note 1: see summary of notes below

Stage 2:

The same comments apply to post weld inspection, with the exception that for Minimum quality the extent of visual inspection is 5% instead of 20% in Stage 1. An important part of this inspection is to ensure that the right welds are in the right locations. It is not enough to check only the welds that are there.

Stage 2: After Completion of Welding				
<u>Visual and Dimensional Inspection</u>	Features Requiring Inspection	Joint Type	Required Quality Class	Number of Joints of each Type % (Note 2)
To ensure that the following comply with the requirements of Table 5 (I) Overall weld geometry (II) Profile discontinuities (III) Surface discontinuities	Overall weld geometry	All	All	100
	Weld discontinuities	All	Minimum	5
			Normal & Fat 24 to 50	100

Note 1: see summary of notes below

Stage 3:

This covers the non-destructive testing (NDT) for Normal and Fatigue Qualities only. The NDT always follows visual inspection as the latter can frequently identify areas of doubtful qualities, so that where NDT is less than 100% such areas can be included.

Transverse in-line double sided butt welds only have partial NDT for Normal quality. Start stop positions are penetrant dye checked (for crater cracking mainly). Spot ultrasonic checks are recommended (1 in 20 between 8 and 25 mm thickness). Above 25 mm the frequency of checking is increased to 1 in 5 as the risk of lack of fusion and cracking is likely to increase with thickness. Below 8 mm thickness ultrasonic testing is not practicable and the only requirement is for 1 in 20 joints to be radiographed if the reinforcement is dressed flush. Otherwise, it is assumed that there are no surface breaking cracks of lack of fusion the risks of failure from serious internal defects will be minimal.

For higher fatigue qualities the scope of inspection increases as the criticality to ever smaller discontinuities increases drastically. Fatigue quality 42, which only applies to dressed flush butt welds, requires 100% inspection by dye, ultrasonic and radiographic methods.

Single sided transverse butts are treated in the same way as double sided butts except that 100% ultrasonic testing is required above 8 mm thickness to ensure that adequate penetration (and hence throat size) has been achieved. There are no Fatigue qualities because the fatigue strength of this detail is limited by Part 5 to class 17 (if full penetration) or class 15 (if partial penetration).

Transverse Tee and cruciform butts are treated in a similar manner to in-line butts except that Part 1 limits the fatigue class to 29. Also, the extra reinforcement normally associated with these joints gives them a greater tolerance to root discontinuities than with in-line butts. For this reason ultrasonic testing is only recommended for thickness' equal to 25 mm or more. At thickness' of about 25 mm the risk of lack of fusion increases if preheat is not applied. Radiography is not practicable for these joints.

Transverse Tee and cruciform fillet welded joints only require dye penetrants to check for surface breaking cracks or lack of fusion. Fatigue classes 24 and 29 can only be achieved if very large fillets are used as failure through the throat from the root is class 14.

Transverse lap joint welds are recommended to receive 100% dye penetrant testing, as lack of fusion or toe cracks at the ends of gussets and coverplate type details are more serious than in short fillet welded attachments.

Longitudinal welds require no distinction to be made on the basis of weld or joint type. The most likely cause of failure is from crater cracks or lack of fusion at weld ends or, on the higher class details, stop-starts. For this reason progressively increasing use of dye penetrants is recommended as fatigue quality increases. It should be noted, that this will not detect buried discontinuities, particularly in multi-pass welds, unless done pass by pass.

Stage 3: After Visual Inspection (Note 2)								
Non-Destructive Testing (does not apply to minimum class) To ensure that the following comply with the requirements of Table 5 (I) Surface discontinuities (II) Sub-surface discontinuities								
				Number of joints of each type % (Note 1, 3)				
Joint Type	Orientation	Weld Type	Required Quality Class	Penetrant Dye	Ultrasonic		Radiographic	
					$8<t<25$ mm	$t>25$ mm	$t<8$ mm	$t>8$ mm
Butt	Transverse	Double Sided Butt	Normal	100 S&S	5 (Note 5)	20	5 DF	---
			Fat 24	100	100	100	5 DF	---
			Fat 29	100	100	100	20	---
			Fat 35	100	100	100	100	---
			Fat 42	100	100	100	100	100
		Single sided butt, backed & unbacked	Normal	100 S&S	100 (Note 5)	100	5 DF	---
Tee,	Transverse	Butt	Normal	100 S&S	---	20	---	---
Cruciform			Fat 24	100	---	100	---	---
			Fat 29	100	---	100	---	---
Tee,	Transverse	Fillet	Normal	100 S&S	---	---	---	---
Cruciform			Fat 24	20	---	---	---	---
			Fat 29	100	---	---	---	---
Lap	Transverse	Fillet	Normal	100	---	---	---	---
All	Longitud.	all	Normal	100 WE	---	---	---	---
			Fat 24	100 WE	---	---	---	---
			Fat 29	100 S&S	---	---	---	---
			Fat 35	100 S&S	---	---	---	---
			Fat 42	100	---	---	---	---
			Fat 50	100	---	---	5	20

Notes 1, 2, 3 and 5: see summary of notes below

Stage 4:

The critical discontinuity sizes for the higher fatigue class details are so small for Fatigue qualities 35 and above that it is recommended that run on/run off coupon plates are sectioned and tested to provide more definite evidence of quality. The maximum frequency recommended is 1 in 20 joints. In the case of small components with high volume production it may be economical to test the component itself.

Stage 4: After non-destructive testing (Note 6)						
Destructive Tests	Joint Type	Orientation (Note 4)	Weld Type	Required Class	Number of Joints of each type % (Note 1)	Test type
To confirm results of	Butt	Trans	Butt	Fat 35 Fat 42	2 5	3 macro-sections
non-destructive		Long	Butt	Fat 50	2	followed by
testing on higher	Tee,	Long	Butt	Fat 42	2	2 nick breach tests
class joints	Cruciform		Fillet	Fat 42	2	geometry permits

Summary of Notes pertaining to the preceding tables:

Note 1:
Where less than 100% of the joints are to be inspected the sample shall include at least one weld from each joint where a different welding procedure is required. In the case of destructive tests at least 2 welds from each joint shall be included. In any case at the start of production the first 5 joints of each type shall be inspected. In the event of a non compliance with Table 5 being found a further 5 joints shall be tested before reverting to the recommended partial inspection.
Where there is no specific recommendation for non-destructive testing this is indicated by hyphen.

Note 2:
Where access for inspection of a joint may be eliminated by subsequent work prior to completion of all welding, that joint shall be inspected before that work is carried out.

Note 3:
WE = within 20 mm of weld end
S & S = within 20 mm of a stop and start
DF = applies only where weld caps have to be dressed flush.

Note 4:

'Transverse' applies to all welds whose axes are orientated at an angle greater than 45° to the longitudinal axis of the member. Welds whose angles are less than 45° shall be treated as 'longitudinal. All welds within 100 mm of the connection between load-carrying members or main loading points shall be treated as 'transverse'. Note 5: Radiography may be used in place of ultrasonic inspection for detection purposes. However ultrasonic inspection may be required for assessment of the compliance of discontinuities with Table B2. Note 6: Where run-off test plates are used for destructive testing they shall be located so that they comply with Note 1. Where production components are to be sampled for destructive tests the appropriate additional number of components shall be made at the time of production.

Frequency of Partial Inspection

The percentages of joints to be inspected are clearly subjective recommendations based on engineering experience. They may need to be increased in some critical applications. On the other hand where high product repetition occurs, using automated processes and good quality control, there may be justification for reducing the frequency.

Note 1 draws attention to the need to increase final inspection frequency if non-compliance is detected. Consideration should be given to some increases in frequency even if the discontinuity is acceptable but close to the permitted limit, for example if it failed the requirements for the next higher quality.

Acceptance Criteria

With regards to acceptance criteria reference is made to Table B2 in Appendix B of BS 8118 Part 2, which summarises the recommended acceptance criteria. It lists permitted dimensional limits on all those weld discontinuity types that may have an effect on the design limit states. It forms the background information for the classification of structural details, it gives full quantitative information on discontinuities in welds and also a quantitative correlation between weld parameters and performance, i.e. fatigue strength.

The following main features are mentioned:

(a) it covers all seven quality levels. The higher the performance requirement, the higher will be the required level. In most cases the higher the quality the smaller is the allowable discontinuity size

(b) the minimum and fatigue quality levels are intended to be applied to specific joints, as required, rather then complete structures.

(c) the dimensional measurements are defined by reference to diagrams of typical structural joints.

(d) the discontinuities are grouped into four categories, each relating to particular inspection techniques. Overall geometry and profile measurements will be visual with the aid of measuring tapes and weld gauges. Surface breaking discontinuities will be visually inspected with the aid of weld gauges and penetrant dyes. Subsurface discontinuities will be determined by ultrasonic and radiographic techniques.

(e) The permitted dimensional limits are determined primarily on a fitness for purpose basis (FFP), assuming maximum stresses permitted by Part 1. However, FFP would for one reason or another allow gross discontinuities which are indicative of serious lapses of quality control, either in material or workmanship, their sizes are limited for practical reasons.

(f) The permitted discontinuity sizes for longitudinally stresses welds are often significantly relaxed over those for transverse welds according to FFP criteria. This can have important economic benefits, particularly in structures such as rail vehicles where the welds are predominantly stresses in the longitudinal direction. In framed or lattice structures the definition of 'longitudinal' and 'transverse' in Note 4 should be clear. In more complex structures, e.g. stiffened shells, the 'longitudinal' welds should be labelled as such on the drawings to obtain the necessary benefits.

(g) Characterisation of subsurface discontinuities is kept to a minimum to avoid unnecessary inspection problems.

(h) The symbols and terminology are consistent with those in ISO/DIS 10 042.2 where applicable.

(i) The tabled information on acceptance criteria of BS 8118 (Table B2 in Appendix B, Part 2) is intended to be suitable for use by inspectors and welding engineers in the fabrication shop without recourse to the designer. For this reason permitted methods of rectification of non-confirming welds are given in the final column of the table.

    Only in the cases where major dismantling of the joint would be required has the designer to be consulted.

In cases where the stressing conditions are known to be very low and when delay for repair might be very expensive to the contract, the designer may be asked to do an engineering critical assessment (ECA). This course of action should not be encouraged as a general practice.

The prime technical objective of the table is to ensure that the risk of failure from a weld discontinuity is not greater than that from any other cause considered by Part 1. At the same time discontinuity limits must not be so restrictive that the cost of welding and risk of repair is unacceptable.

The prime contractual objective of the table is to ensure that it is both comprehensive in its coverage and comprehensible to welding engineers and inspectors. Technical correctness is of no avail if the requirements are incorrectly interpreted.

These objectives presented a formidable task when the number of influencing factors was taken into account. **Figure 2404.02.04** lists the main ones. Even if only three values were ascribed to each variable the number of possible permutations would exceed 10 million!

Variables Affecting Acceptability of Discontinuities

Main Factor	Variables
DETAIL GEOMETRY	Member Type Joint Type Weld Type Orientation of weld axis to member axis
PERFORMANCE REQUIREMENT	
Loading Types	Static Cyclic
Stress Pattern	Tension Compression Shear Severity of gradient Orientation of stress to weld axis
WELD DISCONTINUITY	Type Orientation of discontinuity to stress Size Location

Source: D. Kosteas, TUM

TALAT Training in Aluminium Application Technologies | Variables Affecting Acceptability of Discontinuities | 2404.02.04

The problem was one of grouping and simplifying the variables so that the most dominant parameters were retained. For example no distinction is made between welds in tension or compression. Any effect on fatigue is ignored by Part 1. The extra communication problems of labelling tension and compression on the drawings and ensuring correct interpretation in the fabrication shop was not considered to be worth the effort.

´Orientation´ is an all important factor. A further simplifying assumption was that longitudinal welds away from main joints and loading points would be required to transmit primarily shear force.

The assumption is made that all modes of failure are by ductile tearing and that any growth of a discontinuity under cyclic loading must be limited to ensure that failure by plastic collapse does not occur prior to the end of the design life of the joint.

The table does not pretend to solve all quality problems. One of the many difficulties is the limitation of current commercial NDT techniques to detect, characterise and (particularly) measure the dimension of small embedded discontinuities. For the higher classes, where it is considered that measurement is impracticable, if it is large enough to be detected and characterised then it is assumed to be large enough not to be permitted. This may lead to some argument, but hopefully, as the higher class qualities will not be required very often, it should not have a serious effect overall. For this reason it is very important that the designer does not overspecify the required quality level.

Detailed comments on individual acceptance criteria:

Overall geometry involves checking that the right weld is in the right place and of the right length. This may seem an obvious requirement, but it needs stating, as this can be the one of the most serious sources of error of all. The dimension D is the nominal dimension, weld type etc. specified on the drawings.

Throat thickness in butt welds is defined in the symbol drawings as the minimum transverse distance between the two joints surfaces. This takes into account the effect of cap profile and lack of penetration. For fillet welds the same applies, but here the root gap must be taken into account if it is known. There is no negative tolerance on throat size as there is no practical NDT method for measuring true throat on fillets and their butts. In order to avoid unnecessary repair due to local non-compliance on average value over 50 mm may be used for Minimum and Normal class. Local shortfalls in throat can become more significant in fatigue situations and so the averaging is not permitted. For Normal class an upper tolerance of +5 mm is allowed for fillet welds to alert the inspector to instances where the procedure has not been followed. It also may imply excessive heat input which could give rise to weld metal cracking or extensive softening which might not occur in the original procedure.

Leg length of a fillet weld has no negative tolerance. This ensures that risk of failure from the fusion boundary rather than the throat is avoided. As compared with throat thickness, the average facility is not allowed for the highest fatigue classes only (which only applies to longitudinal welds) in order to control variations in profile. There is no limits on asymmetry of the 2 legs as in ISO/DIS 10042, which is considered to be an unnecessary waste of inspection effort on production welds in structure.

Toe angle has a minimum limit of 90° for Normal Class. This is chosen to be an easy method of avoiding unacceptable convex weld profiles which may obscure lack of fusion (cold lap). It avoids the current practise of having to assess weld profile shape on the basis of profile comparison diagrams. The toe angle is considered to be a more important (and more easily measured) parameter than the cap shape and leg asymmetries used by ISO/DIS 10042 to control profiles. It is simply checked with steel rule or a weld gauge with a right angle corner. For fatigue Classes the minimum toe angle is increased to 175° (i.e. ground flush) for transverse fillets to reduce the stress concentration. For longitudinal welds the limits of 90° can be maintained (except for Class 50 which only applies to ground flush butts).

Excess weld metal in butt weld is limited for similar reasons to those given for excess throat size above. However the limit of 0.5 mm applies to ground flush welds. More tolerance is given to longitudinal butts for the same reasons as for the toe angle. Any aesthetic requirements for smoother cap finish would have to be added by the designer.

Incomplete groove or concave groove is not allowed for fatigue classes on transverse butt welds. However, for longitudinal weld where it is much less likely to cause a stress concentration it is allowed up to 10% of the thickness up to class 35, but not permitted on a ground flush weld.

Linear misalignment is generally limited up to 20% and 40% of the wall thickness for Normal Quality for transverse and longitudinal in-line butt welds respectively. This should be reasonably easy to achieve without undue cost. BS and CEN procedure and welder qualification levels limits are about 10% as a rule. Cruciform joints have double the limit for transverse in-line butt welds on account of the greater resistance to bending. They are also more difficult to align accurately. The limits for in-line butts are tightened up significantly for the fatigue classes as this is a simple way of reducing unnecessary stress raisers, whilst being easily checked by the inspector. There is no value above class 24 for cruciform joints as this is the maximum class permitted for design by Part 1.

Undercut limitations for Normal Quality are based primarily on the need to ensure that the net loss of section is controlled. For this reason the undercut on joints which are welded from two sides must be summed. As with misalignment the limits are reduced in line with increase in fatigue class. The length of undercut is unlimited for normal class, restricted for classes 24 and 29 (which include transverse attachments) and disallowed for higher fatigue classes (which only apply to transverse butt welds). The allowable total undercut is 10% of the thickness for longitudinal welds which is double that for transverse welds. The limits for coverplate (lap) ands are higher as this high stress raising detail is class 17. The smallest undercut limit is 0.3 mm (see note 3). Above 20 mm thickness the limit is constant. These Normal Quality undercut requirements can represent a significant relaxation on the European welder and produce limits which only allow 0.2 mm if continuous or 0.5 mm if local. The equivalent UK limits allow 'slight intermittent' undercut up to 0.5 mm or 0.1t whichever is smaller.

Lack of root penetration limits for single sided butt welds are similar to those for undercut. For transverse welds there are no fatigue qualities as Part 1 limits the stress to class 17 even if nominal full penetration, owing to the difficulty of verification of the root by NDT the limits for longitudinal welds are substantially relaxed. The 'D' refers to the specified lack of penetration in the case of partial penetrated joints specified by the designer. Both the UK and the European procedure and welder qualification standards forbid any lack of penetration on 'full penetration' butts.

Porosity is limited to a 2 mm diameter pores if surface breaking. There is also a limit of 10% nominal loss of section on any line parallel to the weld aims for transversely loaded welds (20% if longitudinal). There are no specified limits for embedded porosity as it cannot be accessed properly without radiography which is not specified for Normal Quality. The main practical limitation on porosity is really the degree to which it obscures other more serious discontinuities. In which case an ultrasonic inspector may reject it for that reason, if bad enough. For fatigue classes the limits are tightened up. The specification is very much simpler to apply than the welder and procedure qualification specifications which have separate criteria for many different cavity types.

Lack of fusion is permitted to a limited degree on a fitness-for-purpose basis. It must be remembered that structural designers specify more partially fused joints (fillets and partial penetration butts) that fully fused joints. To extend the procedure and welder qualification requirements of 'no lack of fusion' to all production welds is therefore grossly uneconomical. The danger is that if the inspector cannot characterise the discontinuity properly it is likely to be rejected if it looks like lack of fusion. Also, with MIG welding minor lack of fusion occurrences are difficult to avoid from time to time. Surface breaking lack of fusion is forbidden for Normal Quality and above. This is because it is potentially much more damaging than embedded lack of fusion, particularly at a weld toe. Being planar, lack of fusion is more crack-like. Within 6 mm of the surface the length is strictly limited except for longitudinal welds. If more than 6 mm below the surface it is acceptable up to a nominal initial area loss of 5% for transverse welds and 10% for longitudinal. These are expressed as limits on accumulated length over 100 mm or 1.5t and 3r for transverse and longitudinal welds respectively, which gives the above area losses for a 3 mm high lack of fusion. This is the only height limit, as NDT cannot measure smaller limits adequately. Lack of fusion above 3 mm was considered to amount to unacceptability poor welding and hence was rejected on grounds of loss of quality control.

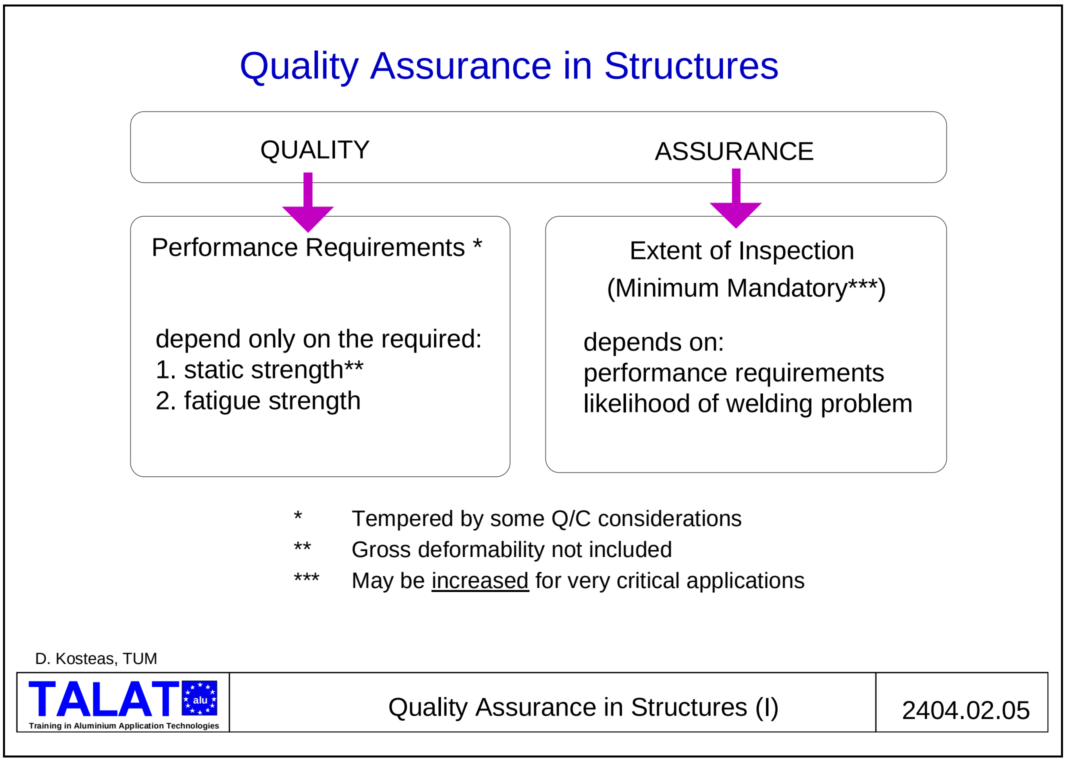
Cracks are not permitted except for crater cracks where Minimum Class is allowed. Small HAZ cracks do occur in 6000 series alloys from time to time. If they are small enough not to be detected or characterised as such by NDT then they would be unlikely to impair the performance of the joint. Otherwise cracks are considered unacceptable on the grounds that they represent a serious departure in control of welding metallurgy.

Acceptable remedial measures are given in the last column of the table, should non-conformities be found. These may be repairs by grinding out only or grinding followed by welding. Only in the case of serious errors where the joint has to be fully taken apart and remade does the engineer (designer) have to be involved.

Remarks on Quality Assurance and Quality Requirements

The basic aim of quality assurance is to provide evidence to the purchaser that the necessary quality of a product has been achieved. For this reason it is necessary to define the required quality and to provide sufficient data that the purchaser can be convinced that the quality has been met.

It is important not to confuse these two issues. **Figure 2404.02.05** illustrates this point. The minimum required quality in the production of welds should normally be higher than that needed to obtain the required performance. It is the designer's responsibility to define the performance requirement.



If the purchaser wants greater assurance that the required quality has been met, and is willing to pay for it, then the scope and methods of testing should be extended. If these need to be increased for particular critical applications the contract documents can impose additional requirements.

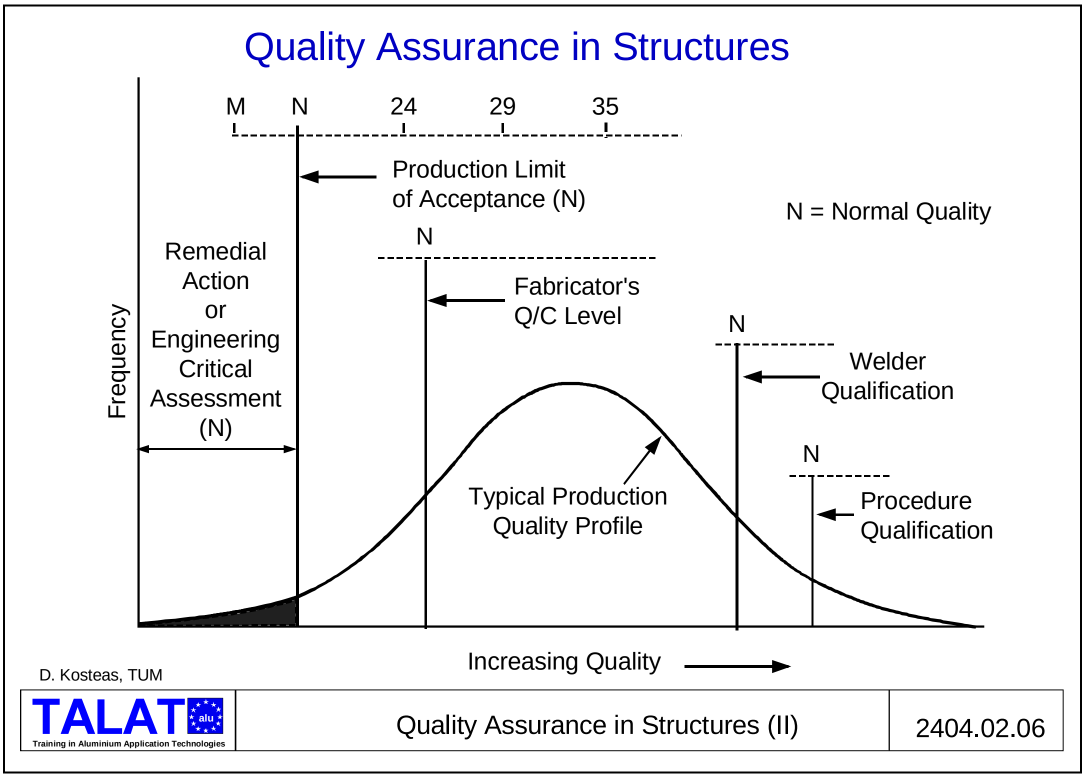
In the author's view, additional assurance of performance should not be obtained by increasing the required quality level above what is needed. The money is better spent on ensuring that the original quality has actually been met. For example partial inspection may be increased to 100% inspection on critical welds.

From the point of view of welder morale it is much better that repairs are done only where really necessary, rather than for some arbitrary reason unrelated to the service requirements of the product.

Selection of Quality Requirements According to Stage of Work

One major problem in structural work has been the imposition of procedure qualification standards for production welds. The requirements of BS 4870 Part 2 acceptance levels are not easy to meet consistently over a period of production. For Normal quality welds the standard is unnecessarily high, and this can result in significant extra cost if welding conditions are difficult.

The fundamental problem is illustrated in **Figure 2404.02.06**, which shows a typical quality profile for a fabrication shop over a period covering different types of work. The variations will be due to uncontrollable factors such as complexity of design detail, accuracy of fit-up, experience of welders, pressure of programme, competitiveness of price etc.



At the outset it is important that the procedure quality obtainable is as high as possible as the tests will be normally done under ideal conditions on simple test pieces without the normal shop pressures, probably using one of the best welders.

Ideally the welder qualification level should be slightly lower than the producer test level for the same reasons, but allowing for the fact that all welders may not reasonably be expected to have the same standard. In BS 4870 and BS 4871 the acceptance standards are in fact the same for procedures and welders respectively. This principle has been reflected in the draft European Standards pr. EN 288 and 287 for procedure and welder acceptance, respectively. In these documents, Level B, the highest of the

three ISO/DIS 10045 quality levels has been adopted for 20 out of 24 discontinuity types, 4 being to Level C (the middle quality).
The procedure and welder levels would be expected to be significantly higher than the average production quality. On the other hand, if the rejection rate is to be kept to an acceptably low level the production acceptance level should be as far as to the left of the quality profile as possible. The importance of keeping the rejection rate to a low level cannot be overemphasised. Not only are repairs costly in terms of extra man hour and delay to the contract, but they also result in further loss of strength (in heat treatable or work hardened alloys), additional distortion and often borderline quality.

For Normal quality therefore, the production quality profile should be such that acceptance level for Normal Quality is as shown in the illustration above. The fatigue quality levels will therefore run a higher risk of rejection as the fatigue quality increases. For the highest fatigue qualities it may be necessary to take particular steps such as conduction special application procedure tests on identical joints to those in question. Also, it is advisable to identify and qualify the most skilled welders to do those particular joints.

The fabricator's in-house quality control level should be selected to have a reasonable margin above the production acceptance level so that the necessary corrective actions to the welding process can be taken before non-compliance arises. For this purpose, ultrasonic measurement of embedded discontinuity dimensions by dB drop methods may be replaced by echo amplitude technique which are quicker to apply.

In summary therefore, it makes economic sense to employ a range of decreasing quality levels according to the four main areas of control listed in (I) to (IV) above

Few other industries tolerate the reject that are typically found in may welding shops. It is time that sensible standards and deployment of inspection are introduced so that this situation can be rectified to the benefit of supplier and purchaser alike.

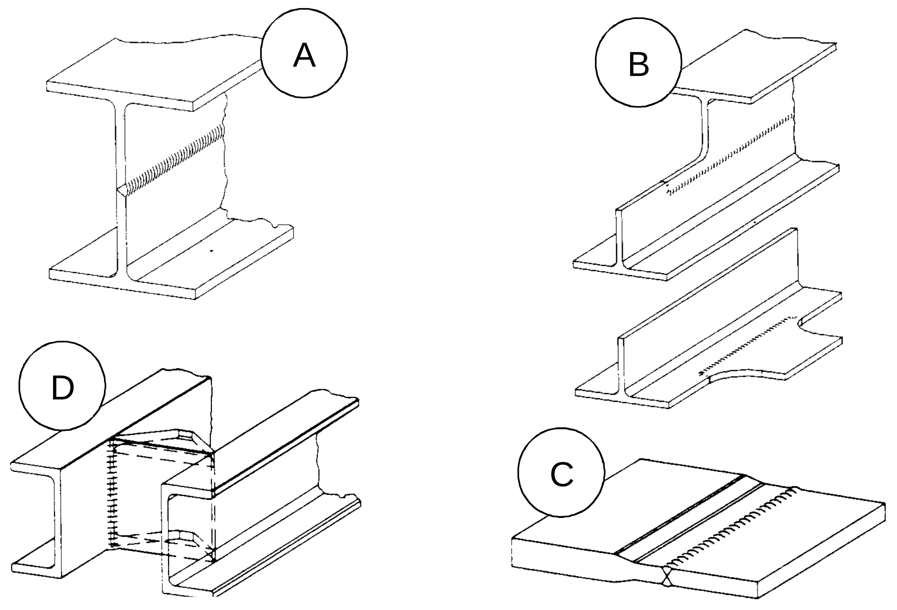
Structural Detail Configurations

The structural details in the design specifications themselves offer already a collection of examples to demonstrate good workmanship in fatigue loaded structures. The following compilation of remarks and further examples summarises experience with weldments in aluminium plates and extrusions.

The basis of a successful welded construction is to be laid at the design stage. A structure in aluminium cannot follow the same design and configuration principles as a structure in steel, since there are basic differences between the two materials. Specially formed extrusions in aluminium allow more degrees of freedom in the design and together with sound workmanship more than compensate any lower strengths of the base material or reductions at the heat affected zone.

The following rules are given for good design of welded details:

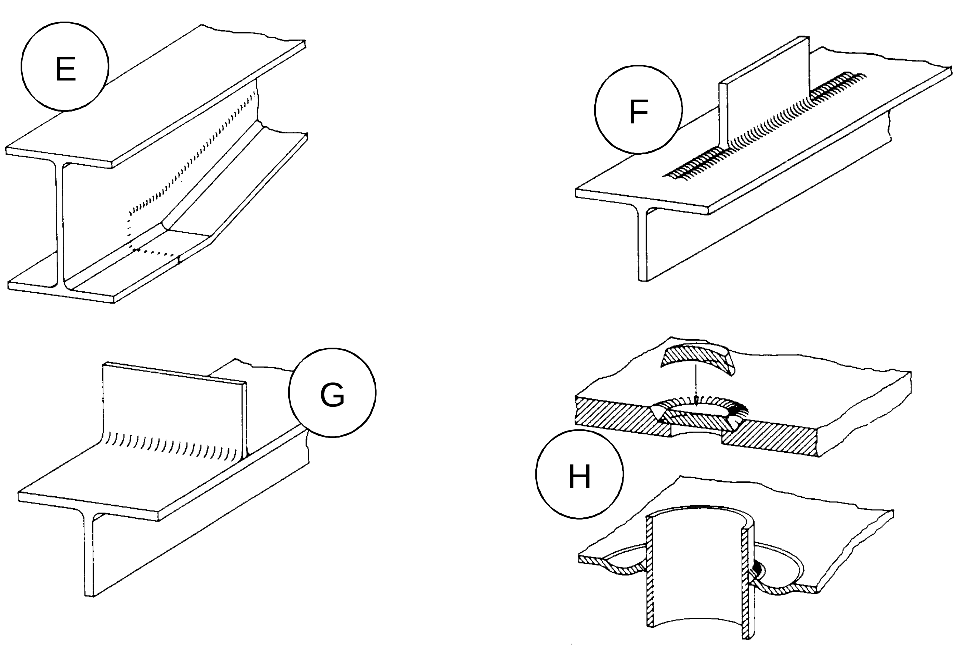
as far as possible in low stress areas, in beams near the neutral axis	**Figure 2404.02.07** (A)
In case of abrupt stiffness changes in the component welds should be placed in greater distance to this location	**Figure 2404.02.07** (B)
Avoid non- or poorly controllable additional stresses on the weld, for instance secondary bending due to eccentricity in the cross section - different plate thickness	**Figure 2404.02.07** (C)
....or due to impediment of deformation through torsional loading	**Figure 2404.02.07** (D)



Source: R. Jaccard, Alusuisse-Lonza Services

TALAT Training in Aluminium Application Technologies	Recommended Weld Detail Configurations (I)	2404.02.07

....or due to abrupt changes in the load path at the location of the weld	**Figure 2404.02.08** (E)
Separate stress concentrations at weld end from geometric notches	**Figure 2404.02.08** (F)
Welds should be positioned so that ensuing residual stresses in the component are kept to a minimum, for example through avoidance of short welds and by using of an edge to edge weld rather (caution should be taken though to ensure good workmanship at the edges)	**Figure 2404.02.08** (G)
....or through respective preparation of the parts to be joined	**Figure 2404.02.08** (H)

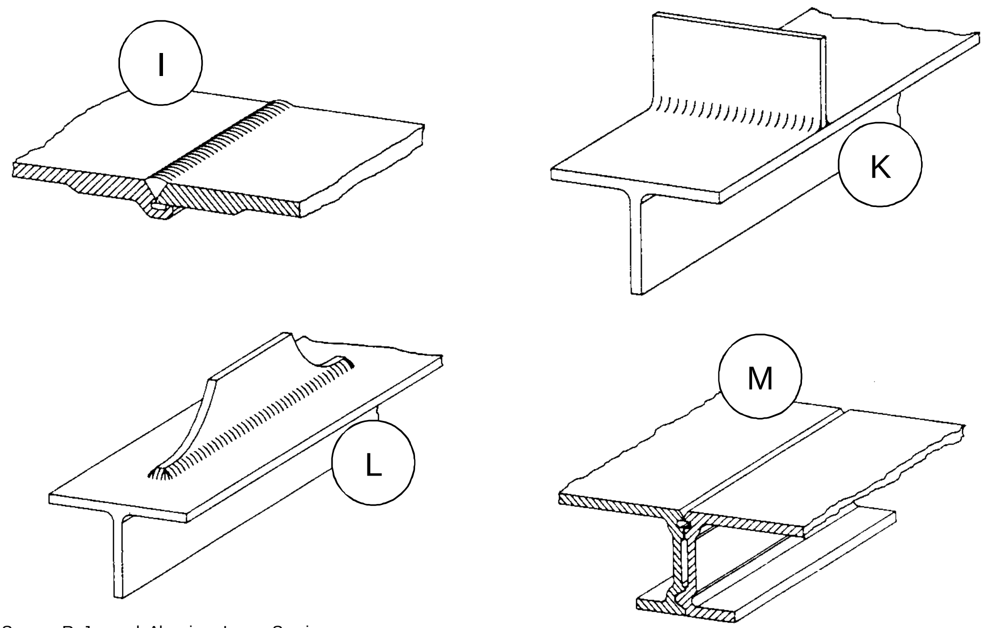


Source: R. Jaccard, Alusuisse-Lonza Services

TALAT Training in Aluminium Application Technologies | Recommended Weld Detail Configurations (II) | 2404.02.08

Welds should be positioned so that industrial manufacturing in the required quality is ensured. This is a rather general requirement for all welds but it may be especially important when the product has to meet higher standards or to undergo increasing fatigue loading.

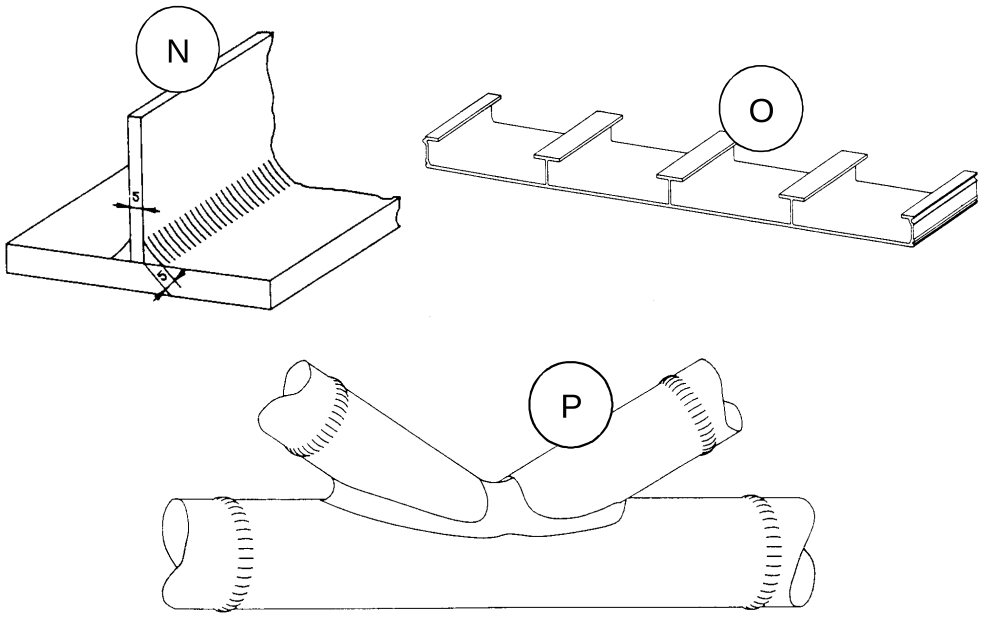
The following requirements are normally mentioned in the case of static loading, but they are also important in the case of fatigue loading as they help reduce stiffness and stress raisers or secondary and residual stresses in the component. – Attachments should be, where possible, welded parallel to the loading direction. – A welding process with low energy input should be used, multiple passes avoided. – A local enhancement of cross section helps compensate for lower strength and if combined with a special extruded part, such as backing bar, where this is required by the welding process selected, enhances further the strength of the joint.	**Figure 2404.02.09** (I)
The notch sensitivity of a weld will be reduced and the fatigue strength of the joint increased, if the shortest possible attachment length is used, prefer transverse attachments over the entire width of the component, if intermittent welds are avoided	**Figure 2404.02.09** (K)
....or if longitudinal attachments or gusset plates are necessary: perform a gradual transition	**Figure 2404.02.09** (L)
if tack welds are avoided by secure fixing of the parts to be joined and by applying longitudinal welds instead of transverse ones, simulta-neously utilising the advantages of specially extruded aluminium shapes	**Figure 2404.02.09** (M)



Source: R. Jaccard, Alusuisse-Lonza Services

TALAT Training in Aluminium Application Technologies	Recommended Weld Detail Configurations (III)	2404.02.09

Weld size should correspond to the plate thickness in butt welds and to the thickness of the thinner part joined in fillet welds.	**Figure 2404.02.10** (N)
Unsymmetrical welds will cause deformations to the component, as in the case of stiffeners. Especially thin-walled parts are very difficult to straighten out after welding. Jigging during the welding or use of large extruded elements with integrated stiffeners can only be recommended.	**Figure 2404.02.10** (O)
Avoid concentrations of welds by using pre-formed or cast parts (we remind that design recommendations do not cover the latter yet and expert advice should be sought), avoid sheet and prefer extruded elements at connections.	**Figure 2404.02.10** (P)



Source: R. Jaccard, Alusuisse-Lonza Services

TALAT Training in Aluminium Application Technologies	Recommended Weld Detail Configurations (IV)	2404.02.10

In selecting the right configuration in welded structures think also of the problems that may arise through exposure to corrosion, especially in connection with the results of weld heat input or post weld heat treatments. Fatigue strength can be reduced significantly in corrosive environment.

Literature/References

NN.: European Recommendations for Aluminium Alloy Structures - Fatigue Design, ECCS Doc. No 68, Brussels, 1992

NN.: British Standards Institutions: Structural Use of Aluminium, BS 8118, Part 1, Code of practice for design, 1992; Part 2, Specifications for materials, workmanship and protection, 1992

2404.03 Improving Fatigue Performance

- Improvement methods
- Geometry or shape changing methods
- Residual stress methods
- Comparison of techniques
- Comparison of cost
- Applicability
- Fatigue improvement - research results
- Literature/References

Problems associated with fatigue as well as stress corrosion cracking of critical components inhibit performance in the various application fields. Effective new ways of combating fatigue and stress corrosion cracking are sought after.

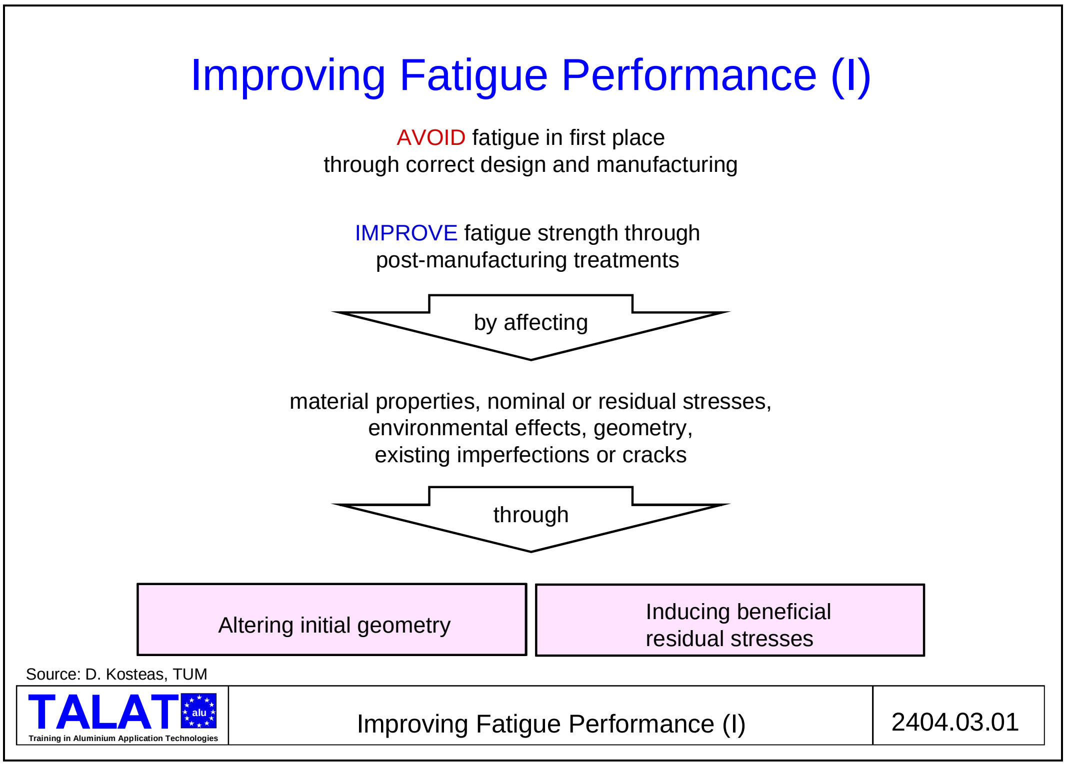
Both fatigue and stress corrosion are mentioned as causes since crack formation is a primary characteristic in both and since they are often interrelated as far as environmental actions are observed. This chapter does not treat though the surface and environment interrelation as far as corrosion phenomena or the decontamination and mechanical treatment of component surfaces (so called surface conditioning procedures that are used to prepare surfaces for resistance spot welding or adhesive bonding) prior to various joining procedures is concerned. Such pre-joining treatments are mentioned in respective chapters of the TALAT course dealing with material surfaces or joints. Here the post-manufacturing treatment methods are handled which improve the fatigue behaviour of an element or joint.

It is pointed out though that the most efficient way to avoid fatigue failure is through careful, correct design and manufacturing in the first place. In this sense a number of workmanship considerations mentioned in Lecture 2402, manufacturing procedures, especially appropriate welding techniques, as given in Lecture 2404.02 on Quality Assurance and Reliability and the structural detail descriptions of current recommendations like "ERAAS Fatigue Design" and "BS 8118, Part 1: Design, Part 2: Workmanship", indicate influences and good design practice. Economical considerations may force the engineer to use a detail of lower fatigue strength. If in such cases the other material properties have to be utilised to their highest extent, fatigue strength enhancing methods may have to be considered and prove beneficial if their application is localised.

Improvement Methods

The following paragraphs outline the most important strength enhancing methods and quantify their effects on structural components.

Fatigue strength or endurance life of a component or, especially, a joint depends on geometry, nominal and residual stresses, material properties, environmental effects and, finally, existing cracks or notches in general. A post-manufacturing treatment (and in most cases this will be a post-weld treatment) will affect one or more of the above in such a way that life to failure is extended. Quantitative statements about such methods, comparing their application, reliability and cost in relation to overall manufacturing and operating costs are of equal importance to the designer as information on the achieved effect, see **Figure 2404.03.01**.



The different methods may be grouped in two main types. Those that (a) alter the initial geometric form and those that (b) induce beneficial residual stresses altering the initial stress pattern (i.e. lower effective stress ranges) at the critical section.

Geometry or Shape Changing Methods

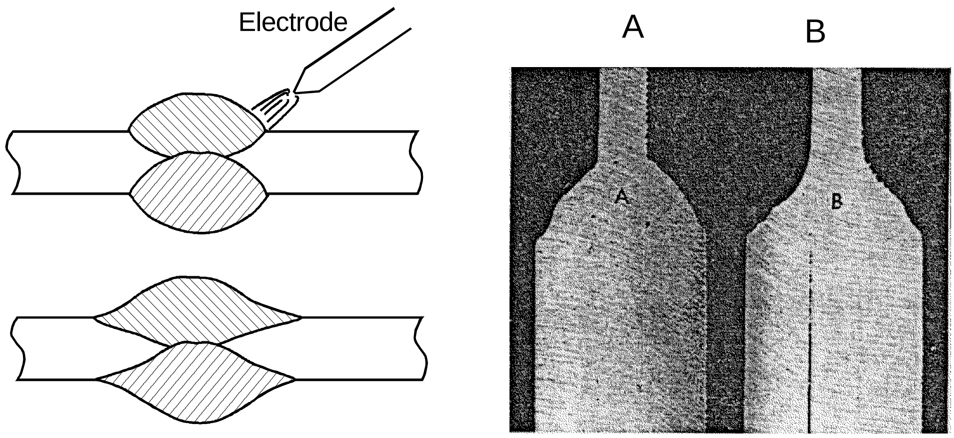
Shape change methods include such techniques as weld reinforcement, water erosion, machining, such as drilling/grinding/peening, remelting of welds. In the sense of post-manufacturing treatments as mentioned above the following three are the ones most widely used.

Grinding

Disc or conical grinding and burr grinding are widely used techniques. Grinding off ≈ 0.5 mm at the toe of a weld has beneficial effects removing sharp notches, cracks.

TIG-Remelting or Dressing

This treatment involves re-melting the toe regions of welds with the aim of improving their profile so that the stress concentration is reduced where the weld bead meets the base metal, see **Figure 2404.03.02**. Besides a certain change in the pattern of the residual stresses may be produced.



(A) undressed and (B) dressed fillet welds.
In (B) an improved profile has been produced.

D. Kosteas, TUM

TALAT Training in Aluminium Application Technologies	TIG Dressing of a Butt Weld	2404.03.02

Peening

The technique may be used for stress control such as in manufacturing repairs or treatment of surfaces subject to stress corrosion, stress relief of weld regions, peening after grinding. Variations of the procedure such as single-point or hammer peening, shot peening, multiple-point or needle peening, rotary flap peening, brush shot peening, etc. are known. Peening not only may change the initial form beneficially, i.e. remove sharp notches, but may also induce substantial residual stresses on the treated surface through cold working. The problem that arises is how to determine how much cold working has been done to the part so that an extrapolation from test data to manufacturing in practice can be achieved. The so called Almen intensity is used as a reference.

Residual Stress Methods

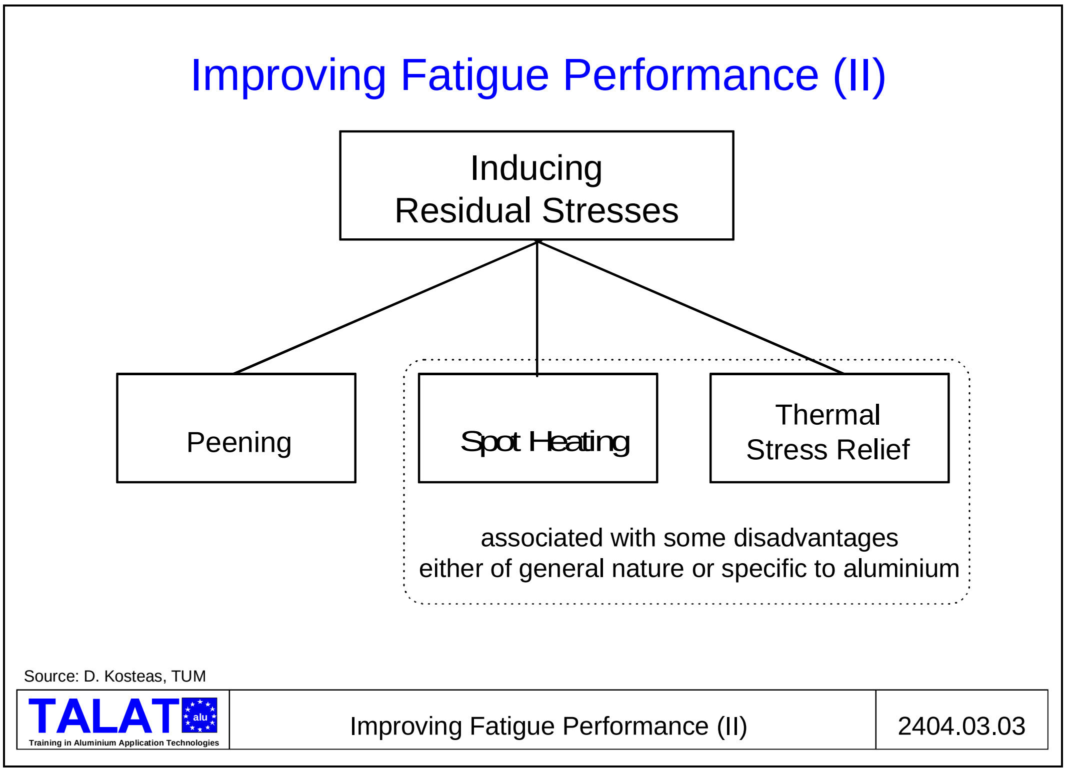
Refer to **Figure 2404.03.03**.

Peening

Essentially the same peening methods as above are used.

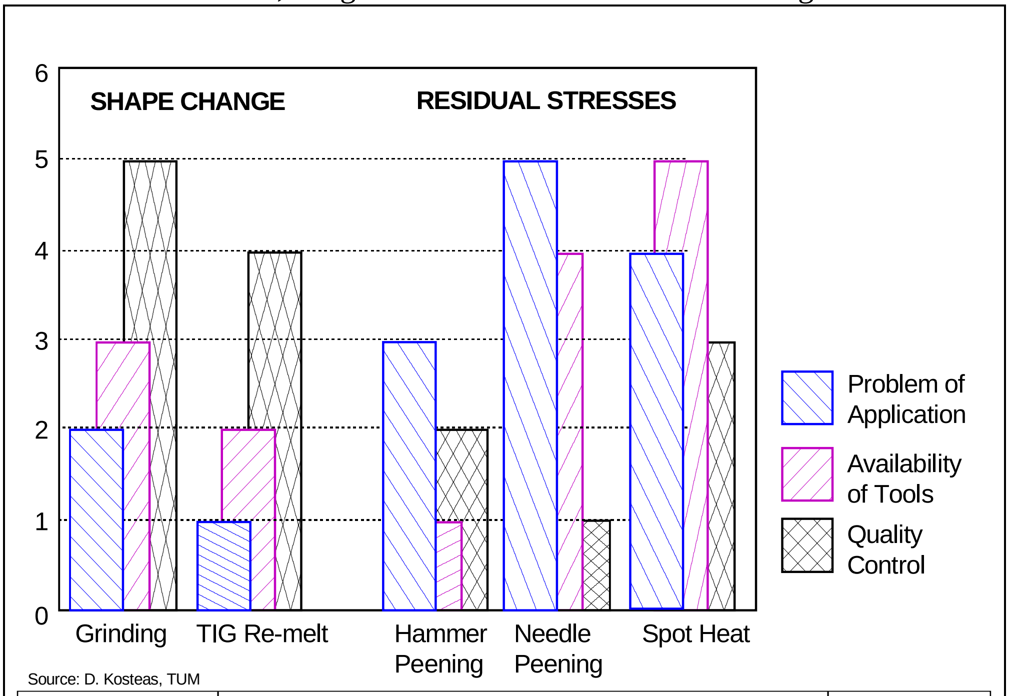
Spot Heating and Thermal Stress Relief

Local heating with two welding guns, treating critical areas from both sides and simultaneously, produces in this part of the component during subsequent cooling tensile residual stresses. These will be counterbalanced by compressive residual stresses at the remaining parts of the component. The method is applied in such a way that critical locations with notches, such as a weld profile, will fall into the area of compressive residual stresses. The technique has a general and a specific disadvantage, though. The rather difficult fixation of areas to be heat treated and the fact that it is applicable only in such cases when the critical area where compressive stresses are to be induced is small relative to the rest of the cross section. This is the case typically at the end of longitudinal fillet welds of an attachment. The second disadvantage is specific to aluminium alloys where welding is detrimental to strength. So this method is not in use. A general thermal stress relief is of course beneficial to welded structures in general and specifically for aluminium, since enhancement factors may be activated due to a reduction of initial tensile residual stresses, see Lecture 2402 on the effect of R-ratio or the ERAAS Fatigue Design rules.



Comparison of Techniques

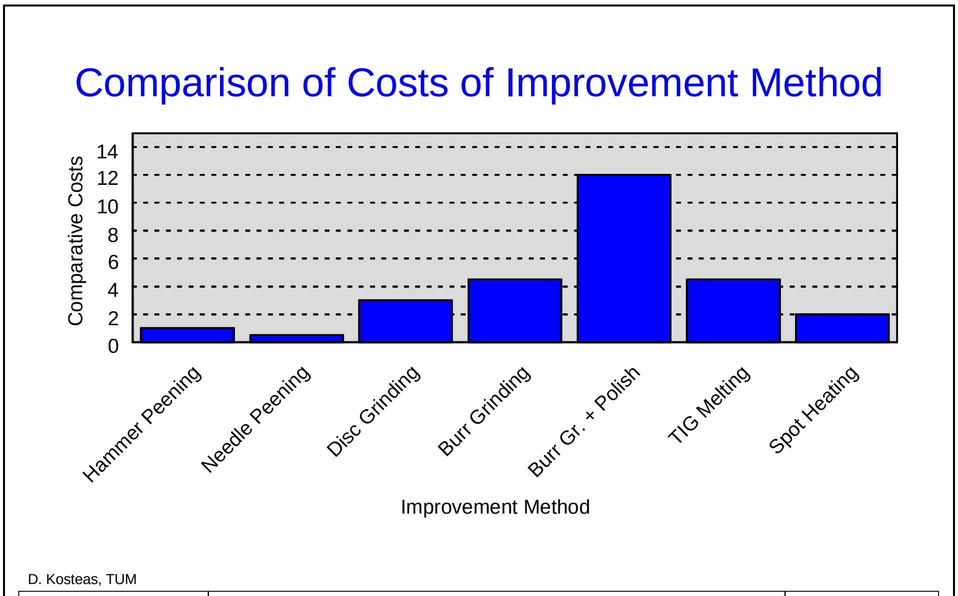
A qualitative evaluation of some commonly used techniques, **Figure 2404.03.04**, on the basis of "application", accounting for the difficulties in using the method especially on-site, "tools", accounting for availability of devices and degree of knowledge in using them, "quality control", accounting normally for the greatest scatter since there are not yet any universal, easy-to-use, standardised procedures available. The general result is that the easiest the method, the greatest the difficulties in controlling it.



Comparison of Improvement Techniques 2404.03.04

Comparison of Cost

Peening methods are rather inexpensive. Evaluations from literature referring to manufacturing and application of improvement methods to laboratory welded small specimens (attachments made with fillet welds) show the following cost relation (see also **Figure 2404.03.05**).



Comparison of Costs of Improvement Method 2404.03.05

Method	Comparative Costs
Single-point (hammer) peening	1
Disc grinding	2 to 4
Burr grinding	4.5
Burr grinding and polishing	12
As previously plus measurement grinding depth	110
TIG remelting	3 to 4.5
Spot heating	2
Multiple-point (needle) peening	0.5

For comparison, welding costs, without cutting, handling and fitting, are approximately equivalent to TIG remelting.

It must be pointed out though that in a real structure the number and extent of areas to be treated by improvement methods would be small in relation to the whole structure and accordingly the cost of the improvement methods will be definitely lower than in these examples with small specimens, where each one has been treated.

Applicability

Peening methods improving both the shape and the residual stress situation besides being rather economical are also easy to apply. TIG dressing is also an interesting method when welding is possible, but may show disadvantages if not sufficiently controlled.

When using peening methods the depth of maximum compressive stress as well as the total depth of influence are related to the diameter of the surface indentation rather and not so much to the tool diameter. Literature studies evaluating shot/needle/hammer peening show approximately the following respective diameters for the surface indentation: 0.7/1.4/3.9 mm. The total extent (depth) of residual stress modification is in a ratio of 1:1 to these values, but the depth of the cold worked layer or the depth of the maximum value of compressive stress is at a ratio of 1:10 to the indentation diameters.

Another interesting observation referring to the shaking down of very high compressive stresses near the surface with cyclic loading has been reported. After 1000 cycles the originally different values for each peening method relax to approximately half the yield strength of the material. This has been observed in steel and a verification in the case of aluminium alloys should be undertaken. First observations made with aluminium weldments in full-size components should be studied in more detail to clarify whether and to what extent the magnitude of residual stresses induced by improvement methods is reduced by fatigue cycles, the influence of the weld type or of the stress concentration gradient, the possibility to apply analytical models of damage accumulation, like the Palmgren-Miner rule, to components improved by different techniques.

Peening creates surface marks which act as stress concentrations. Only if the stress concentration due to these peening marks is lower than the original stress concentration of the component an improvement in life or fatigue strength can be achieved. The degree of cold working will grow from the lowest to the highest values from shot peening, over multiple-point peening and single-point peening, to deformation cracking. The degree of improvement depends on the type of detail. It will be the highest for a plain plate in the lowest region of cold working, i.e. for shot peening. Butt welds reach a maximum improvement for multiple-point (needle) peening. Fillet welds show a growing improvement with growing degree of cold working and reach their maximum just prior to deformation cracking. These observations have been made on steel welds.

Again on steel welds some fracture mechanics observations show that cracks at fillet weld toes begin to grow within a small percentage of total fatigue lives for peened welds. Also defects which are equally as severe as those found at weld toes of unimproved welds have been observed at the toes of peened welds. Therefore fatigue strength improvement due to peening methods seems to be achieved only through retardation in crack propagation. The use of crack-initiation models together with crack-propagation models cannot be justified.

An improvement in fatigue strength and accordingly an increase in fatigue classification cannot be justified for all structural details. For instance structural details in which cracks initiate from a weld root cannot be influenced by the improvement methods described above. A maximum improvement classification probably exists. If a design requires greater strength then another manufacturing or joining method must be chosen. Prototype testing on the other hand could enable higher than recommended values.

Fatigue Improvement - Research Results

In the following a collection of characteristic published test results is presented demonstrating the effect of peening and/or TIG-remelting on aluminium welds.

Improving 5086 Welds for Ship Construction by Peening

Studies in the seventies had shown serious degrading of 5086 alloy by welding such as softening of the weld bead, presence of weld microporosity at levels either undetectable by radiography or allowable by current standards. Fatigue strengths were reduced at 10^7 cycles for weldments in air to $\approx ^1/3$ and for weldments in seawater to $\approx ^1/8$ of the respective lower boundary value (σ_a=20 ksi=138 MPa) for base metal in air. The material for the investigations was 6.4 and 15. 9 mm thick 5086 H116 butt and fillet welds with 5356 filler metal and welded automatically in the flat position by the GMAW (or MIG) process in the spray mode.

After machining the test sections of the specimens with transverse welds (butt with weld reinforcement removed and transverse one-side attachment with fillets) were given a rotary wire brush finish.

Shot peening with two types of rotating brushes, a cast steel shot brush and a tungsten carbide shot brush, was investigated. This type of peening has a potential for use as a portable, manual or automatic method of controlled peening. The initial material, butt or fillet weld fatigue strengths were ≈20/12/8 ksi for 10^6 cycles and 16/8/6 ksi (1ksi=6.895MPa) for 10^7 cycles respectively.

Fatigue cracks initiated and propagated through the weld metal for butt welds. In fillet welds they initiated at weld toes and propagated through the HAZ.

The butt-welded 15.9 mm thick specimens with weld reinforcements removed were brush peened (cast steel shot brush with 20.3 or 30.5 mm dia) to different intensities and subsequently fatigued. Some specimens were overpeened to intensities of Almen 0.0080 in (0.2 mm) to indicate any degradation in fatigue performance. The overall result is that peening significantly improves the fatigue strength of butt-welded 5086-H116. In the high-cycle region values for the base metal are reached or surpassed. In the low-cycle regime peened specimens are somewhat lower than the base metal. It is also significant that maximum peening intensities did not lead to any deleterious overpeening.

During the postweld peening of the fillet welds areas further than 9.5 mm from the toe of the weld were masked with cloth adhesive tape to prevent inadvertent peening of these areas. In some specimens only the toes of the welds were peened, in others both the toes and the plate surface opposite the stiffener (underside) were peened.

Peening with the broad cast steel shot brush did not prove to be universally beneficial though. Moving the brush parallel to the tee attachment formed rolled lips at the free edges of some specimens which sometimes acted as crack initiation sites. In other cases local weld irregularities masked weld toes from the peening brush. Finally, peening only the weld toe moved the crack initiation location to the back or unwelded side. A 100% peening coverage was attained at fillet welds by using the small tungsten carbide peening brush, specifically designed for peening in restricted areas. The brush could be manipulated for peening either parallel or perpendicular to the stiffener and thus removing any irregularities at the weld toe. The improved fatigue performance of such specimens, an enhancement of fatigue strength at 10^7 cycles by the factor 1.8, is significant.

The ability to conduct the peening operation in an aluminium ship structure makes brush peening an attractive method for treating areas susceptible to fatigue cracking both in new construction and during repair in ships or other high performance craft.

Following an earlier study on the influence of shot peening on welded aluminium alloys such as 5086, 6082, and 7020, and the general statement of 80% improvement upon fatigue behaviour due to peening, a more detailed recent study in France has undertaken the task to define the improvement in fatigue for shot-peened 5086-H111 butt and fillet welds. The fillet welded cruciform joints in 6 mm thickness were welded (a) without any edge preparation and (b) with a groove preparation. In case (a) peening effects on a weld with internal defects could be studied. An automatic MIG process with 5356 filler metal was used.

The shot peening was undertaken with three different kinds of shot/ dia [µm]/ Almen intensity French Standard: glass/300/F10N-F30N, ceramic/425/F20A-F25A, mild steel/800/F45A-F50A. Induced residual stresses were recorded by X-ray diffraction. They reached a value at the surface depending on the shot, 150/120/80 MPa for glass/ceramic/steel. The maximum stress value was with 200 MPa the same for the three cases as related to the mechanical properties of the alloy itself. The depth of the maximum was at 20/80/200 µm and the depth affected by shot peening was 300/600/1000 µm for glass/ceramic/steel.

Specimens were fatigued at R = +0.1 at a frequency of 100 Hz and maxσ = 90 MPa. The same value was adopted for both butt and fillet welds on the experience that an one-side butt weld has a lower fatigue strength than a double-side butt weld and similar to the strength of a fillet weld.

Comparing results at the 90 MPa level for the butt weld it may be stated that shot peening with glass had a slight improvement upon life, but ceramic or steel improved life by a factor of 15 over the values for untreated specimens. A maximum improvement is reached for a depth of ≈ 600 µm, beyond this value no further improvement is obtained. The greater depth reached with steel shot did not contribute thus to any further improvement and it must be noted that the shot diameter with 800 µm may have been the cause of detrimental effects, reducing the overall positive influence of shot peening. For practical applications a diameter of 400 µm is recommended. Fatigue cracks initiated on the surface, at weld toes or in zones with undercut. The life enhancement from shot peening is obvious.

Analogous comparisons can be drawn for the fillet welds. Naturally all results for specimens with a groove preparation were better than those without edge preparation. At joints with a groove preparation cracks initiated again most probably at weld toes on the specimen surface. The life improvement was ≈10 times in relation to respective unpeened specimens and it was greatest for the glass or steel shot and somewhat lower for the ceramic shot.

Fillet welds without a groove preparation exhibited a crack initiation in the weld when unpeened and when shot peened a fracture at half depth (weld root?) propagating to the outer surface before any crack initiation from the outside could be detected - thus explaining the lower fatigue behaviour in relation to the above case with a groove preparation and fatigue cracks emanating from external weld toes. A fatigue life improvement through shot peening was significant in all three cases relative to the unpeened specimens, the lower values for glass shot, an improvement of ≈ 7 times for ceramic and even more than 25 times for steel shot. Parallel investigations with TIG-remelted fillet welds gave the following results. Smoothing the surface by TIG-remelting meant a significant improvement for fillet welds with groove preparation of the joint, indicating that surface geometrical conditions play a significant role when cracks emanate from external sites such as the weld toe. But the improvement was lower than the effect of shot peening. For fillet welds without groove preparation TIG-remelting had no practical effect since the crack initiation site, the internal weld root, was not affected by the external geometrical smoothing effect.

Improving Fatigue in Rail Cars by Peening and TIG-Remelting

Similar results have been reported in investigations a decade ago with weld details in Australian rail cars. Laboratory tests have shown needle peening the toes of aluminium alloy 5083 fillet welds is an effective method for improving fatigue performance over a wide range of applied stresses. In this regard, greater benefit is obtained if the peening operation is carried out after, rather than before, the application of any preload or mean stress. Field trials on welded aluminium wagons over periods of up to eight years have confirmed that peening the toe regions of critical welds both delays the onset of fatigue cracking and reduces the number of cracks that form. Laboratory tests have shown that TIG dressing of MIG fillet and butt welds may be even more effective than peening in improving fatigue performance of aluminium alloy weldments. This statement does not seem to hold though in the light of the more recent French investigations reported above.

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