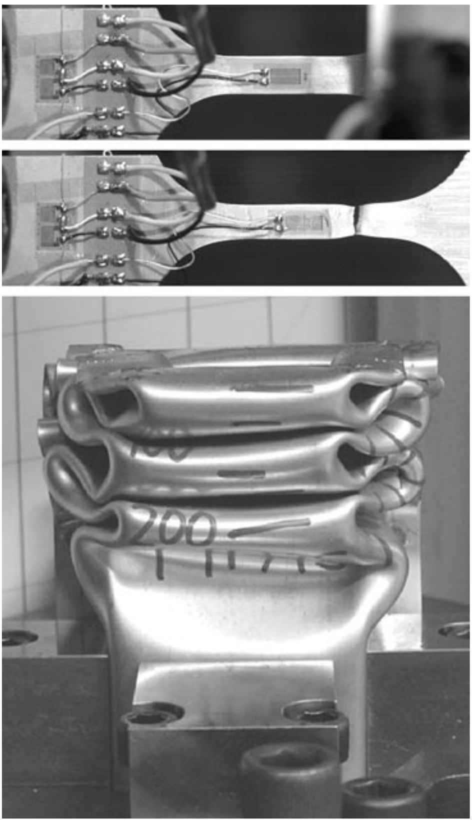
Strain Rate Testing of Metallic Materials and their Modelling for use in CAE based Automotive Crash Simulation Tools (*Recommendations and Procedures*)



P.K.C. Wood
and
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Contents

Annex

1 Aim of Recommendations

To provide guidelines to generate tensile strain rate test data for ferrous and non-ferrous sheet metals for use in finite element based automotive crash simulation tools. Specifically, measurement of the strength hardening in a sheet material resulting from strain rate testing using a high speed servo hydraulic test machine. Additionally, to provide guidelines to process raw test data, fit material model and format this data for application in crash simulation tools. It is not within the scope of these recommendations to advocate a material model to fit strain rate test results, although useful models are referenced. Rather to give guidance on the error allowance in fitting model to test results. These guidelines are expected to have broader application in the transport industry sector.

1.1 Scope

Materials include high and low strength sheet metals and alloys with ductility typically greater than 10% tensile elongation to failure and melting point temperature typically above 500 °C; such materials include steel and aluminium alloys with sheet thickness in the range 0.7 to 5 mm. The design range to develop strain rate test data for application in automotive crash simulation tools is from quasi-static to 500/s. Strain rate testing is designed to generate material data in this range and typically over six decades of strain rate. All tests are conducted at ambient temperature. The tensile strain range for measurement of strain rate induced strength hardening in the material is from yield through to tensile strength, and this range provides the minimum data input for materials modelling in an automotive crash structure.

1.2 Background

The technology and recommendations document was developed under a collaborative project engaging several industry partners whose business activity involves automotive product development with crash safety imperatives. The project was initiated in 2004, called Premium Automotive Research and Development (PARD), and part funded by Advantage West Midlands (Regional Development Agency).

The motivation for the project was determined by end users of this data, with the objective to balance cost and quality in delivering a technology more closely aligned to automotive crash applications. At the outset of this project there were no standards or recommendations in place for developing material strain rate data for ferrous and non ferrous sheet metals. Furthermore there were no practical guidelines to describe the requirements to fit a material model to strain rate test data for use in finite element based crash simulation tools.

1.3 Technology Validation

The technology in this document was validated using a high speed test machine together with supporting processes, e.g., specimen manufacture and measurement techniques that had been established at the IARC under the PARD project. Strain rate testing techniques at leading international laboratories were reviewed [1–17] and some consulted to establish best practice, from which a technical specification for the IARC laboratory was established to support the project.

The technology in this document was validated in the following way;

- Benchmarking of high speed tensile test results obtained at IARC with other labs, to include model fitting, using a common material

- Extensive use of computer-aided engineering (CAE) based simulation to validate specimen designs and measurements derived from dynamic tensile experiments for ferrous and non-ferrous materials

- Low and high speed testing of generic crash structures to validate dynamic material data input to CAE based simulation tools for ferrous and non-ferrous materials

- Participation in relevant technical workshops, and broader publication of technology in journals and conference proceedings [18–29]

1.4 Variation to Documented Guidelines

Strain rate testing procedures have evolved in laboratories in industry and academia concerned with measurement and characterisation of dynamic properties of materials. Such laboratories undertake research in new materials and continue to develop enabling technologies to support the introduction of new materials for industrial application. The technology and recommendations in this document are not intended to replace existing practices in such laboratories, although they may offer improvements to specific aspects for example, local measurement techniques. The intention is to provide a test protocol benchmark for strain rate testing using a high speed servo hydraulic test system, to measure the strength hardening in a sheet metal for automotive crash applications.

2 Abbreviations

CAE	Computer-aided-engineering
DLC	Dynamic load cell
DAQ	Data acquisition
IARC	International Automotive Research Centre
WMG	Warwick Manufacturing Group
DT	Displacement transducer
SEP	Stahl-Eisen-Prüfblälter (SEP) des Stahlinstitiits VDEh

2.1 Symbols

F	Force measurement
s	Engineering stress
σ	True stress
e	Engineering strain
ε	True plastic strain
$\dot{e}$	Conventional or engineering strain rate
$\dot{\varepsilon}$	True strain rate

K	Constant or Coefficient
Li	Original (un-deformed) gauge length
Ai	Original (un-deformed) cross section area of gauge length
t	Thickness
w	Width
T	Time
U	Grip velocity
V	Voltage

3 Test Machine Requirements

3.1 Speed range for strain rate testing

The design range to develop strain rate data for application in automotive crash simulation tools is from quasi-static to 500/s. Strain rate testing is designed to generate material data in this range and typically over six decades of strain rate. Equipment capable of delivering this range of strain rates is a precision high speed servo hydraulic test machine. The test machine will ideally deliver a speed range from 1 mm/s to 20 m/s within the same load frame to test specimens with gauge length dimension described in Section 4.1. An example of such a test machine is shown in Figure 3.1.

The actuator of the high speed servo hydraulic test machine will operate under closed loop control at the lowest speed and typically up to around 1 m/s; above this speed it will operate under open loop control. Closed loop control of actuator is essential at speeds below 1 m/s.

It is desirable that the machine actuator is capable of testing materials at speeds up to 20 m/s, which enables greater flexibility in design of specimen and local strain measurement technique (Section 5.4) used on the specimen gauge length.

3.2 Machine Load Frame

Interaction between machine and specimen during routine testing has a major influence on strain rate that develops in the specimen gauge length [15]. Higher loads will place higher demand on the machine frame.

Figure 3.1 Instron VzHS160/100-20 High Velocity Testing System

The load frame must have sufficient spring stiffness to ensure the machine actuator speed is used to maximum effect, to minimise the strain rate rise time to achieve a near steady condition in specimen gauge length on application of loading.

Different metals, alloys and gauges will introduce different levels of steady strain rate into the specimen gauge length for a given test speed. Although it is desirable to minimise such strain rate variations as a function of specimen resistance, there are practical limitations to what can be achieved. This is why it is important to measure strain directly on the specimen gauge length from which the strain evolving stain rate may be determined for each test. Especially to capture the strain rate induced strength hardening in a material at low strain (at around yield point) then load frame stiffness becomes a more critical design parameter to deliver the requirements.

3.3 Actuator Stroke

The actuator must have sufficient length of stroke to accelerate the moving grip to target speed, maintain speed to deliver target strain rate in specimen gauge length, and then decelerate the actuator on completion of test. For testing metals and alloys at speeds up to 20 m/s in tension, using the specimen gauge length dimension given in section 4.1 to deliver strain rates up to 500/s, it is recommended that at least 250 mm of total actuator travel is available.

3.4 Actuator Speed Droop

Accumulator and valve system must be capable of delivering power to actuator to minimise a drop in speed (actuator speed droop), which develops on load take up under open loop control. Speed droop is greater for speeds which are at the lower end of the open loop control operating window (typically 1 m/s), and of course when testing specimens with higher resistance, see Figures 3.2 and 3.3. The increase in actuator kinetic energy at higher speed typically from 5 m/s and above will reduce speed droop to a tolerable level for both low and higher resistance specimens as shown in the Figures 3.2 and 3.3.

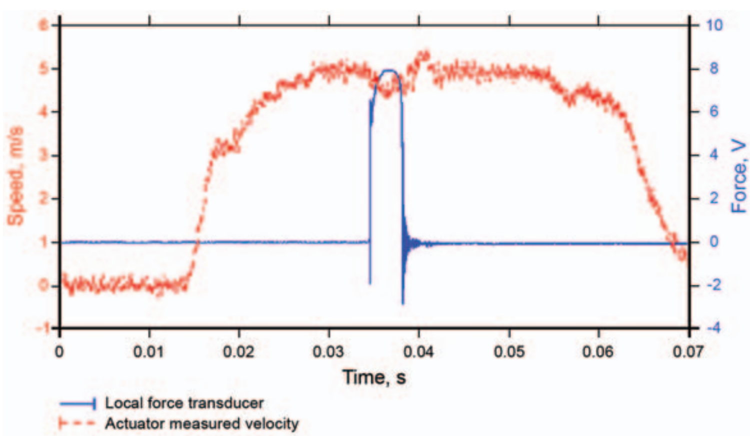

Figure 3.2 Actuator measured speed derived by differentiating displacement transducer with time to check velocity variation during loading for high strength steel specimen tested with target speed set to 5 m/s

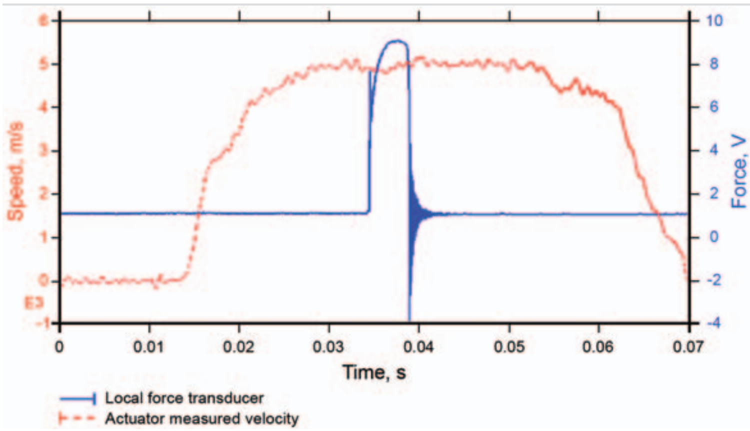

Figure 3.3 Actuator measured speed derived by differentiating displacement transducer with time to check velocity variation during loading for aluminium alloy specimen tested with target speed set to 5 m/s

Speed droop will influence the strain rate measured in the specimen gauge length at lower strain. In developing the test procedure the specimen gauge length and actuator speed are optimised to minimise speed droop; typically increasing specimen gauge length and testing at a higher speed to deliver the target strain rate. It is recommended actuator speed droop is controlled to within –20% deviation of target speed.

3.5 Specimen Gripping

One end of the specimen is connected to a static grip which by definition remains stationary (with the exception of harmonic vibration which is excited by dynamic loading). The static grip is fixed to the body of the machine. The other end of the specimen is free and is coupled to a moving grip, only after actuator reaches target speed.

The system used for gripping the moving side of the specimen is either a slack adapter or fast jaw. In the former method a connecting assembly is attached to the moving side of the specimen before the test is started, such that both stationary mass of specimen and connecting assembly must be accelerated to target speed on load take up. In the later method the grip remains disconnected from the moving side of the specimen until the actuator has reached target speed, such that only the stationary mass of specimen is accelerated to target speed on load take up. The fast jaw is sprung apart using pre-tensioned rods, which are released depending on the machine settings defined by user.

Other techniques to grip moving side of specimen at test speeds typically above 0.1 m/s that are not described in this document, must be treated with caution until adequately proven in application.

3.6 Load Train Components and Strain Rate

The machine components connecting the specimen in the load train influence the strain rate that develops in gauge length. The main load train components are the static and moving grips, dynamic loadcell, actuator and specimen. Load train components are in series such that the same load under a static or low speed condition is carried by all components in load train. The displacement of load train is normally measured by a sensor which monitors position of actuator. Hence, displacement of load train will be the sum of the elastic displacements of each component in the load train, including elastic/plastic displacement of specimen and take-up of slack between connections, e.g., grips and specimen.

To reduce damping in the load train and the associated rise time to transfer strain rate to specimen gauge length, the static grip assembly must be as stiff and light as is practically possible and appropriate for use in high speed testing of specimens with varying resistances. All load train components must be connected in such a way that slip between connections is avoided at load take up, e.g., grip and specimen, and for the duration of specimen loading. It is desirable to minimise the number of connections in the load train to reduce damping introduced to specimen gauge length. The grips (grip faces) must be capable of securing the specimen adequately under load. The grip faces must be designed for durable application. The rate of grip face wear will be dependent on specimen resistance, hardness condition of material as well as the number of tests. As such they are a consumable item which must be routinely inspected for wear, and replaced as necessary and/or periodically depending on demand for testing to maintain quality of results.

4 Specimens

To deliver material strain rate data at decade intervals from quasi-static through to 500/s to measure strength hardening in the material, three specimen configurations are recommended as shown in Figure 4.1.

4.1 Specimen Gauge Length and Strain Rate

The strain rate that develops in the specimen gauge length is proportional to the velocity difference across the gauge length [27]. The starting point for designing specimens is to calculate strain rate using a theoretical based prediction:

$$\dot{e} = \frac{U}{Li}$$

For a fixed grip velocity (U) the prediction suggests engineering strain rate is dependent on the initial gauge length (Li) of specimen; the smaller the gauge length the higher the engineering strain rate. The grip velocity is not however the same as the velocity difference across the gauge length. The simple prediction suggests merely changing gauge length offers wide flexibility in designing a family of specimens to deliver strain rates in the range of interest. Although providing a first approximation, the prediction has been shown to be increasingly inaccurate for specimens with a short gauge length [23].

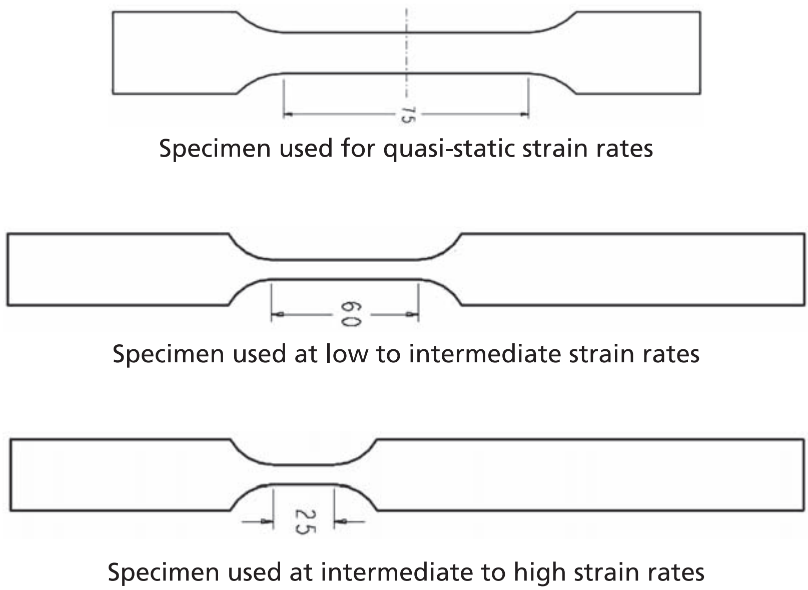

Figure 4.1 Technical drawings of the three specimens configurations used for testing metals and alloys at low through to high speed at the IARC lab are given in Annex E (dimensions in mm)

For a 10 mm gauge length the difference can typically be 50% lower than prediction. The true strain rate provides a small improvement to accuracy since gauge length is not constant under load. However, neither prediction accounts for machine-specimen interaction, e.g., load frame stiffness and damping in load train. Hence, accurate and reliable determination of strain rate can only be determined by direct measurement.

In designing specimens, practical considerations which include direct measurement of strain introduce design constraint. It is recommended that the specimen gauge length is not less than 20 mm for strain rate testing above 100/s (test speeds conducted typically above 5 m/s), and not less than 50 mm for strain rate testing between 0.01 and 100/s (test speeds conducted typically in the range 10 mm/s through to 5 m/s).

For tests conducted at strain rates below 0.01/s (below 10 mm/s) it is recommended to follow the EURONORM standard [1].

4.2 Gauge Width

In designing specimens that have different gauge lengths, it is desirable that a constant relationship between gauge length and gauge width is maintained in accord with Barba's Law for sheet metal specimens [15]:

$$\frac{Li}{\sqrt{Ai}} = \text{Constant}$$

The purpose is to ensure consistency in ductility measurement across the different specimen designs. However, thickness of gauge length also has an effect on ductility, but this parameter is determined by customer requirements and can not be controlled other than to specify lower and upper limits. These recommendations offer guidance for testing sheet metal and alloy thicknesses in the range 0.7 mm to 5 mm.

The material data sought from a tensile test to develop a strain rate dependent model of material to measure strength hardening is in the range of uniform plastic tensile elongation; that is yield point through to tensile strength, and not beyond. Provided the gauge length is not too short [15], percentage elongation is mainly influenced by uniform elongation, and thus it is dependent on the strain hardening capacity of the material. The practical considerations that influence specimen design and especially local strain measurement on gauge length have higher priority. For this reason it is recommended that gauge width is in the following proportions:

- Gauge width not less than 8 mm and not greater than 10 mm (*smaller gauge width is used for materials when tensile strength to yield strength ratio* > 2)
- Gauge width to static grip width < 0.33

4.3 Tolerance Requirements

The width of specimen gauge length must be within +/– 0.03 mm of nominal dimension, although repeatability of width dimension for the batch of specimens to produce the dynamic model of material should be within +/ 0.01 mm. The width of static grip length will be within +/– 0.03 mm of nominal dimension, but repeatability of this dimension for all specimens in the batch should be within +/0.01 mm. The gauge length must be centred in the static grip length to within +/– 0.25 mm. The gauge length and static grip length must be parallel to within 1 degree.

The surface roughness along the edge of the specimen gauge length must be lower than Ra = 1.6 μm for general materials, but is reduced to 0.3 μm for brittle materials. The edge of the specimen gauge length must be free of sharp edges.

4.4 Pre-Test Measurements

The sheet supplied by the customer to produce tensile specimens for high speed testing must be free of distortion.

After manufacturing specimens, the width of gauge length and thickness of each specimen must be measured at three locations before testing using a micrometer. All measurements must be recorded in the test report.

Each specimen must be placed on a flat table to check for distortion. Ideally there should be no observable distortion (either bend or twist) along the length of specimen. If distortion is present it must be recorded using a rule and entered in the test report. There must be no attempt to reshape the specimen if distortion is noted.

4.5 Specimen Handling and Storage

Long specimens with a narrow wasted length are prone to damage through handling. It is recommended that each batch of specimens produced in preparation for testing are stowed in a purpose made container with adequate supports provided to each specimen to prevent handling damage. The container must a have a lid.

Containment is especially important after specimens have been prepared and strain gauges installed. A transparent container is recommended so the operative can see that specimens are in the container without removing lid.

The environment for storage of the specimen must be dry. Ambient temperature must be generally constant within +/– 2 °C, not dropping below 10 °C, and not rising above 25 °C.

4.6 Specimen Identification

Each specimen must be marked at both ends of the specimen with a durable scribing technique before testing and before each specimen is instrumented. It is recommended that a unique identification is assigned to include target test speed.

4.7 Method of Manufacture

The method of manufacture used to produce specimens must be consistent for each specimen in a batch and consistent from batch to batch.

The method of manufacture must be capable of delivering the tolerances required of the specimens and must not introduce either sharp edges or distortion resulting from a cutting or a general separation process. For example, use of guillotine or shearing machine to separate each specimen before trimming must be avoided even if a generous material surplus is introduced.

Heat must not be introduced to any of the stages in the specimen manufacturing process to include specimen separation from sheet through to the finishing processes to size each specimen. It is essential that mechanical cutting processes do not modify the mechanical properties locally at the edge of a specimen. It is essential that no chemicals come into contact with the specimen during the manufacture that will modify the material properties in the short- or long-term.

To comply with all the stated requirements the IARC process has developed the use of high speed machining to produce a batch of specimens for testing to develop a dynamic model of the material. The machining process is proven for both ferrous and non-ferrous materials.

4.8 Heat Treatment

Heat treatment applied to a batch of specimens, for example to simulate paint bake effect in automotive structures, must be done before the specimens are instrumented. It is recommended that after heat treatment, specimens are tested within 28 days, unless the customer requires a shorter time frame.

It is recommended that just one specimen goes through the heat treatment cycle to check that no distortion results.

In the oven all specimens must be adequately supported to mitigate the likelihood of distortion, and the support system used must not introduce a heat sink to draw heat from specimens.

4.9 Specimen Orientation (Sheet Rolling Direction)

An example of the orientation of specimens to be produced from sheet using a 500 × 500 mm square plaque is shown in Figure 4.2.

For automotive applications, the strain rate dependent model of material is developed using results derived from testing specimens in the transverse direction to sheet roll direction.

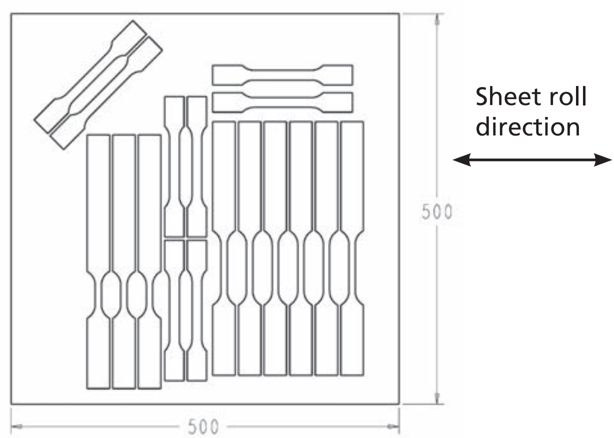

Figure 4.2 Packaging and orientation of specimens to be produced from sheet (dimensions in mm)

Variations in tensile mechanical properties of a material as a function of the orientation of sheet to rolling direction are determined by conducting quasi-static tests in the 0, 45 and 90 degree directions. It is recommended that at least two specimens are tested in each of the 0 and 45 degree directions, and at least four specimens in the 90 degree direction to confirm variations in mechanical properties under quasi-static loading.

In the interests of balancing cost and quality to develop dynamic data for industrial application, it is acceptable to produce one flow curve for each strain rate test providing the high speed testing process is stable in developing stain rate sensitivity data (Section 6.1.6).

5 Measurements

5.1 Machine-Based Force Sensor

The force sensor in the machine is a dynamic load cell (DLC) which is incorporated in the load train. The DLC must be located between the static side of the specimen and the machine to measure load. The DLC is typically located in the static grip assembly, and ideally, the assembly is positioned as close as practically possible to specimen gauge length. Figure 5.1 shows the position of DLC in static grip assembly.

The DLC will have a load range appropriate for testing specimens with varying resistances. The DLC in the IARC machine operates to 100 kN, but smaller load ranges may be selected to maintain accuracy and precision in force measurements. The load range of DLC is set for each test to match the specimen resistance expected using pre-determined calibration files, to deliver a measurement error of less than 0.5% of load range used. Furthermore the DLC time constant appropriate for measurements at different test speeds is set to match the duration of a test.

The DLC will be calibrated annually and at shorter intervals depending on usage of the machine. All calibration files used for different load range settings must be checked immediately following DLC calibration.

The natural frequency of DLC must be as high as possible for dynamic force measurement. The Kistler type DLC used in the IARC machine has a natural frequency of around 30 kHz in the direction of load application. The DLC in the IARC machine is incorporated into the

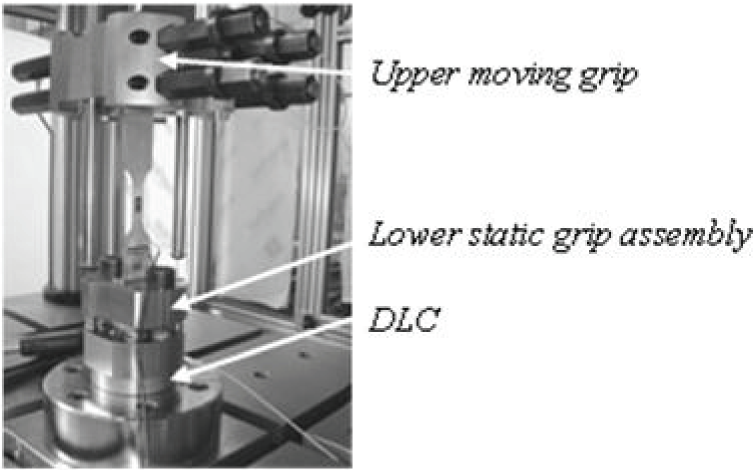

Figure 5.1 Specimen set-up in high speed test machine

static grip assembly; this combination delivers an effective natural frequency of 6 kHz for force measurement [9]. The frequency of static grip assembly with DLC increases to above 7 kHz when loaded by specimen. It is recommended that the frequency response of static grip assembly with DLC is not below 5.5 kHz. DLC is generally restricted to force measurement for strain rate testing below 10/s (test speeds typically under machine closed loop control, i.e., below 1 m/s). Increasing oscillation in force measurement develops in strain rate testing above 10/s (test speeds typically under machine open loop control, i.e., above 1 m/s). Therefore, force measurements obtained from DLC for strain rates above 10/s will not be used in developing a strain rate dependent model of material.

5.2 Actuator Displacement

Machine-based sensors will include an inductive field based displacement transducer (DT) to measure actuator position during loading of specimen, and hence derive the measured speed by differentiating with time.

The DT will not be used to derive strain and strain rate in the specimen gauge length.

The DT confirms the actuator speed droop on take up of load is within the limits recommended.

5.3 Local Force Measurement on Specimen

To maintain accuracy and precision in dynamic load measurement a cleaner force signal is required for strain rate testing above 10/s (test speeds typically above 1 m/s). It is recommended to create a local force transducer on the specimen using strain gauges. Figure 5.2 compares test results from DLC and a local force transducer for strain rate testing at around 70/s.

The strain gauges will be configured as a full bridge circuit to compensate for bending, and the transducer will be located on the wider section of specimen, on the static side, in close proximity to

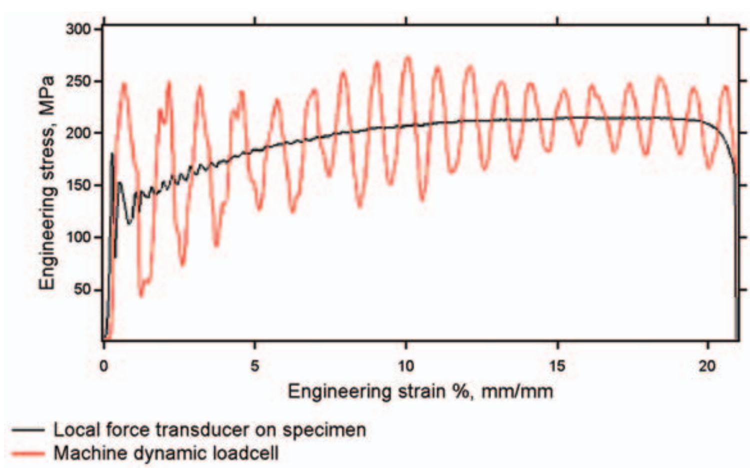

Figure 5.2 Comparing results from DLC and local force transducer for strain rate testing at around 70 /s (test speed 5 m/s)

gauge length. Strain gauges are selected for low strain, high sensitivity and dynamic applications. The measuring grid length is not greater than 5 mm. The active resistance strain gauges are orientated in the direction of load train. The two passive resistance gauges will be orientated in the transverse direction to the load train. It is not recommended to use passive resistors in the bridge circuit in place of stain gauges.

The frequency response of the local force transducer is dependent on the static grip length on which the strain gauges are placed. It is necessary to maximise frequency response of local force transducer. This requires the static grip length to be as short as practically possible. It is essential, however, the transducer on which strain gauges are placed, transducer. The local force transducer is shown in Figure 5.3. A technical drawing of strain gauge positions is given in Annex E.

The following recommendations are proposed in creating a local force transducer on specimen:

- Static grip length is 40 mm
- Transition radius is greater than 10 mm (the dimension selected for transition radius will be consistent within the batch of

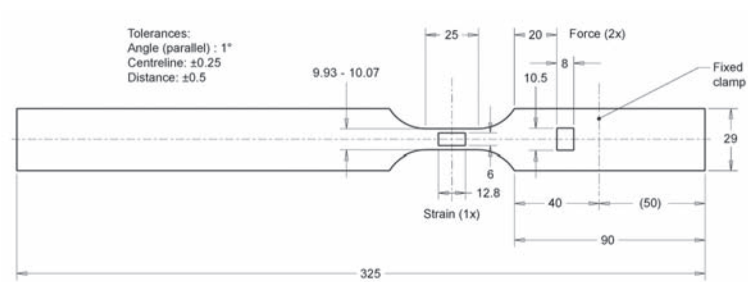

Figure 5.3 Position of strain gauges on specimen for local force measurement

specimens used to develop a model of material, and it should ideally remain consistent for different materials)

Strain gauges will be located to the right of the mid-length of the static grip length, but not to close to the fixed grip. The positioning of strain gauges will be consistent across all specimens used in the batch of specimens to develop a strain rate dependent model of the material. The position accuracy of the strain gauges will be maintained within +/– 0.25 mm and to achieve this, a template is recommended.

5.4 Local Strain Measurement on Gauge Length

Direct measurement of strain on gauge length is recommended for testing at all speeds. An IARC specimen uses one strain gauge configured as a quarter bridge circuit, located midway on the specimen gauge length on one side of the specimen, which provides an analogue signal output of high resolution. The measuring grid length selected is 7 mm. The strain gauge is selected for high strain applications, e.g., 20% elongation. The adhesive must have sufficient ductility at higher strain rates to prevent separation of strain gauge from specimen from low through to intermediate strains. Furthermore, the mechanical wire connections must withstand sudden acceleration.

The positioning of the strain gauge must be consistent across all specimens used in the batch of specimens to develop a dynamic model of the material. The position accuracy of the strain gauge must be maintained within +/– 0.5 mm. A technical drawing is given in Annex E.

The material data sought from these tests to develop a strain rate dependent model of material is in the range of uniform plastic tensile elongation; that is yield point through to tensile strength and not beyond. It is important that the strain gauge provides a reliable strain signal over a significant portion of the strain range of interest.

Two important considerations when using a strain gauge to measure strain on the gauge length. Necking generally initiates outside the measurement length, see Figure 5.4, unlike the Euronorm static test [1], in which necking initiates inside the measurement length of the clip gauge. The tensile strength of the material is determined at the onset of necking instability. Strain measurement using a strain gauge outside the local neck region will generally cease to measure strain beyond tensile strength. Hence, the flow curve derived provides data from yield point up to tensile strength and not beyond; this is sufficient however to provide a strain signal over the strain range of interest.

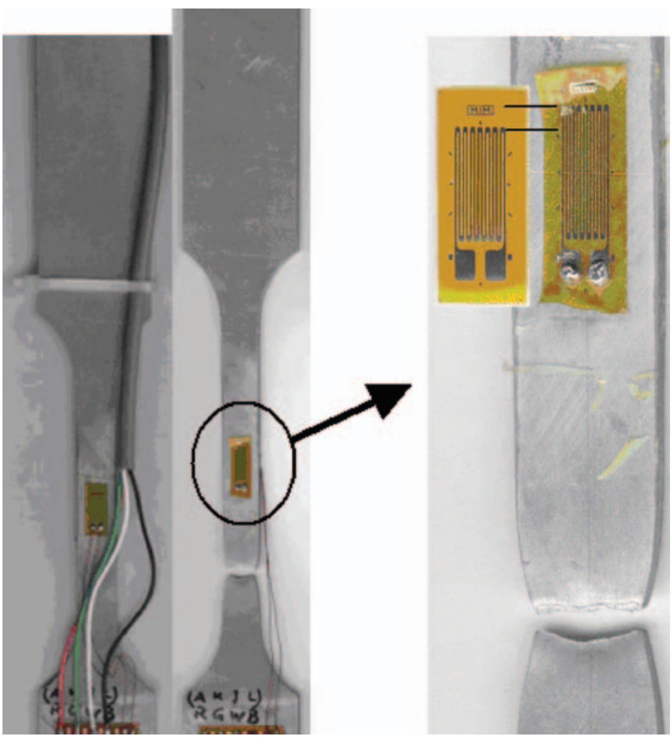

Figure 5.4 Specimen before and after strain rate testing

More often the strain signal fails before the material has reached its tensile strength. Figure 5.4 shows initiation of adhesive failure and delamination of strain gauge at high plastic strain. Where the signal from the strain gauge does not fail the strain signal becomes increasingly non-linear at strain measurement typically above 15% engineering strain, and increasingly unreliable at this level of plastic strain. Section 6.1.2 describes the data processing technique for direct strain measurement using a strain gauge, and a reliable method to determine strain at tensile strength.

5.5 Method of Application of Strain Gauges on Specimen

The IARC has developed a procedure for installing strain gauges on specimens for force and strain measurement appropriate for strain rate testing in the range of interest. The procedure is as follows:

- Place strain gauges on microscope slides, apply Mylar tape, cut and leave one edge with tape
- Sandpaper surface of specimen (grit: 150 – 250 particles per cm)
- Clean surface with acetone/isopropanol
- Condition surface
- Neutralise surface
- Fix strain gauge
- Apply hot curing , two component epoxy adhesive
- Apply pressure and cure at 95 °C for 6 h.

Wiring connections

- Apply solder terminal above force gauge with special superglue
- Connect sockets to solder terminal

5.6 Instrumentation

Data Acquisition (DAQ) requirements will provide signal conditioning for all measurements recorded at 12 bit resolution. Measurements recorded by DAQ will include machine force sensor, DT, DLC and local strain measurement all synchronised to a common time. The frequency of DAQ is set to record a minimum of 2000 data points in the strain range of interest (yield point to tensile strength) at each test speed under machine closed loop control (e.g., below 1 m/s). Under machine open loop control (above 1 m/s), the frequency of DAQ is set to record a minimum of 1000 data points in the strain range from yield point to tensile strength at each test speed.

5.7 Test Procedure

Careful handling is essential in transferring a fully instrumented specimen from storage container to machine for testing. All wiring must be adequately supported so as not to introduce any kind of loading at wiring terminations on specimen. Hand contact between strain gauges and wiring terminations on specimen must be avoided.

The specimen must be correctly aligned to the direction of load train to within +/– 0.1 degree when clamping it in the static grip.

A summary of the machine settings for testing at different speeds to deliver the range of strain rates is given in the table in Annex F.

6 Data Processing

The key stages in processing raw test data are shown in Figure 6.1.

Each stage of data processing is described in turn, in this section.

6.1 Stage 1 Data Processing: Raw Engineering Data

For strain rate testing above 10/s (test speed above 1 m/s in which machine operates under open loop control) the raw signal output from local force transducer is strain in volts *versus* time, see Figure 6.2.

Similarly, the raw signal output from strain sensor on gauge length for all strain rates above 0.01/s (quasi-static test below 0.01/s adheres to EURONORM requirements [1]), is strain in volts *versus* time, see Figure 6.3.

The machine DLC provides direct force measurement for strain rate testing below 10/s (test speed typically below 1 m/s in which the machine is operating under closed loop control). The data output from each strain rate test will remain unfiltered at this stage of data processing.

6.1.1 Calibrating Local Force Measurement

The DLC is used to calibrate the local force measurement device on a specimen in which the strain gauge signal is output as a voltage. The calibration must be done at strain rates below 10/s (test speed typically below 1 m/s), see Figure 6.4.

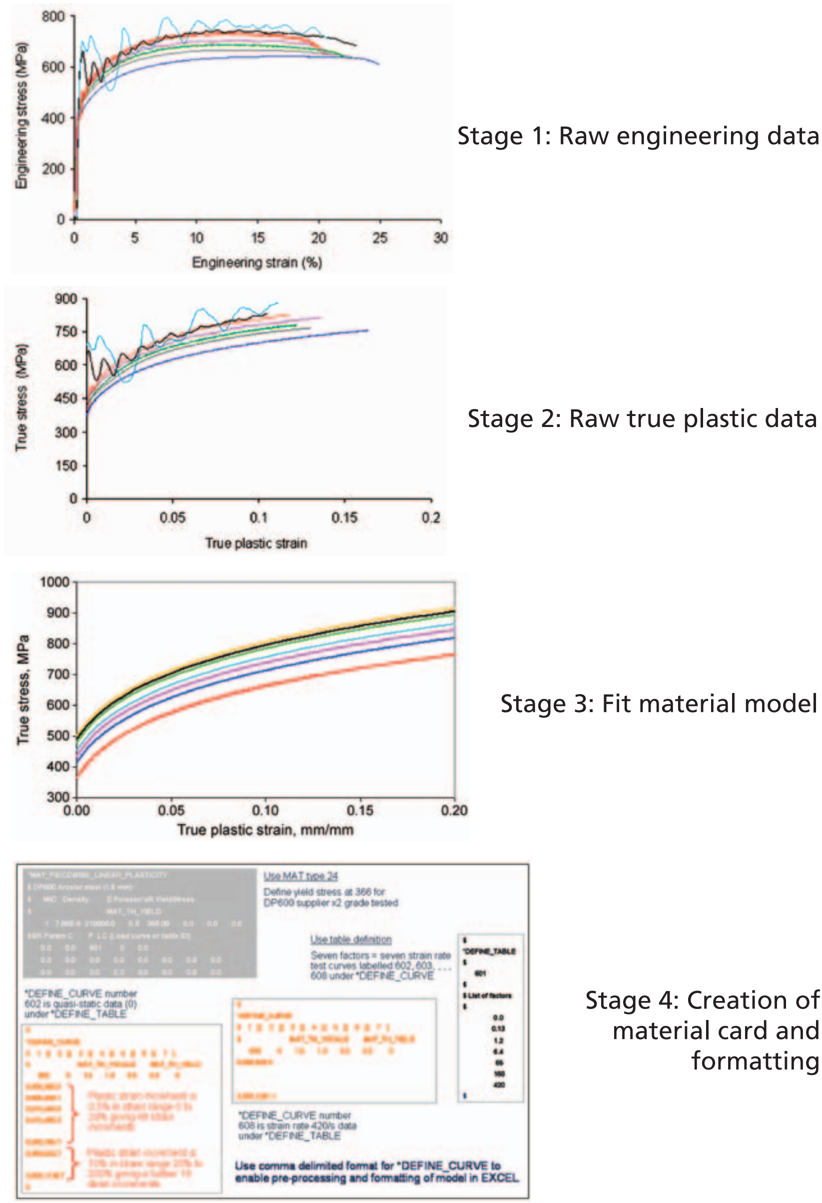

Figure 6.1 Stages in processing raw strain rate test data.

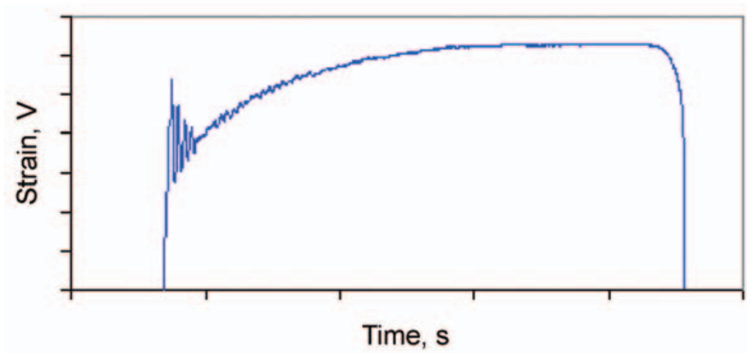

Figure 6.2 Local force measurement on specimen given as voltage *versus* time for strain rate testing at 70 /s

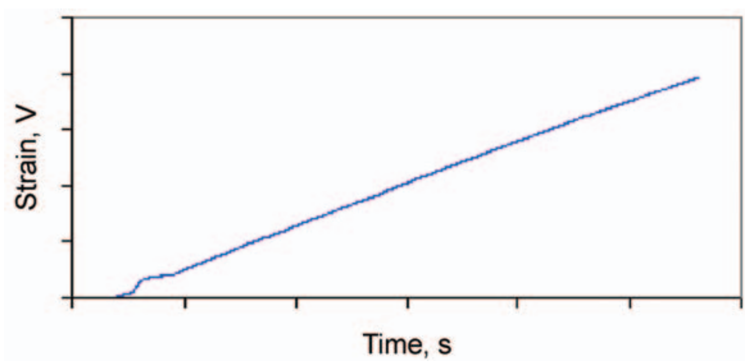

Figure 6.3 Local strain measurement on specimen gauge length given as voltage *versus* time

6.1.2 Strain Measurement on Gauge Length

The calibration factor to convert voltage to engineering strain measurement is determined by conducting one low speed test of a high strain rate test specimen with a strain gauge on the gauge length, together with a standard clip gauge device used in quasi-static tensile testing.

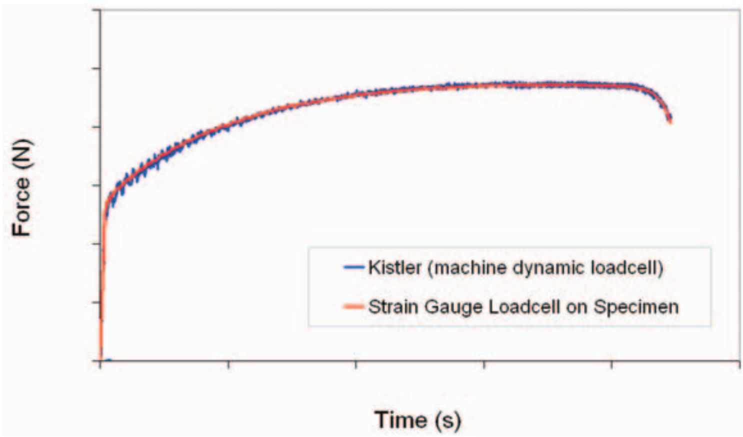

Figure 6.4 Calibrating local force measurement device using machine DLC

At increasing test speed, the signal from the strain gauge measuring device is lost before the loading of specimen has terminated, typically between 10% and 20% engineering strain. In such cases it is necessary to extrapolate strain to the end of loading by linear regression. These recommendations propose calculating the slope between 3% and 10% engineering strain for material type A, see Figure 6.5, which does not exhibit a clearly defined yield point. For material type B, which exhibits a clearly defined yield point, the slope must be calculated from the start of the plastic hardening curve, e.g., when constant yielding has terminated, typically at 3% or 4% engineering strain, see Figure 6.5.

If the strain gauge signal is lost below 5% engineering strain for material type A, the result will be discarded, and a repeat test is necessary. Similarly if the strain gauge signal is lost below 7% engineering strain for material type B the result will be discarded and a repeat test is necessary. Marks will be placed on the specimen at both ends of gauge length using a soft pencil before testing to confirm total elongation to failure.

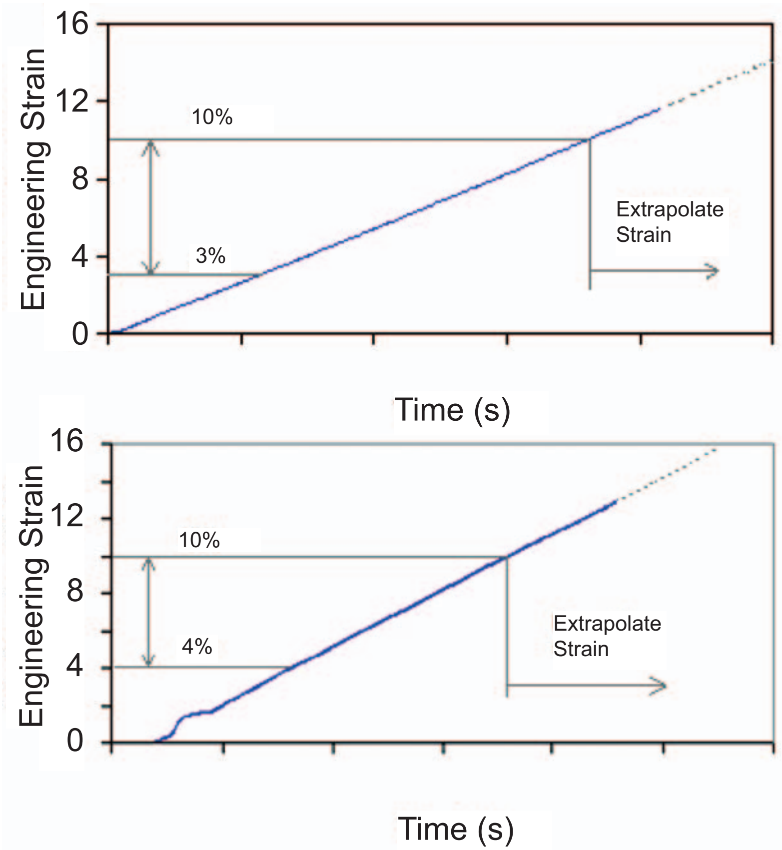

Figure 6.5 Method to extend strain measurement to tensile instability for material type A (above) and material type B (below).

6.1.3 Strain Rate Measurement

Figure 6.6 shows the measured engineering strain output from strain sensor on gauge length for testing an aluminium alloy. The target strain rate in gauge length is 83.3/s for the specimen type tested (shown in Figure 4.1) together with test speed set to 5 m/s. This strain measured from the sensor is differentiated and filtered, giving the derived strain rate.

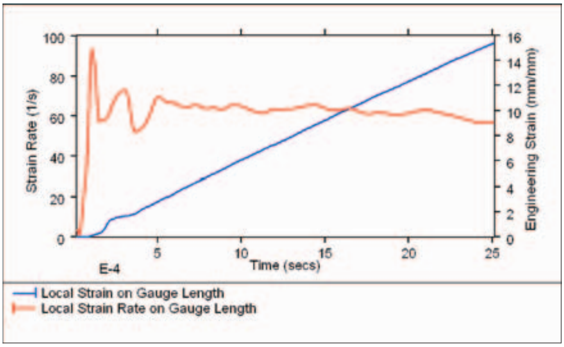

Figure 6.6 Measured engineering strain and strain rate (filtered) derived by differentiating strain by time

A consistent approach to computing the average engineering strain rate must be adopted. The most practical approach to calculating average engineering strain rate is simply to compute the average in the strain range 0 to 10% for material types A and B. Figures 6.7 and 6.8 show derived strain rate as a function of strain, to deliver target strain rates 83.3 and 600/s using test speeds 5 and 15 m/s, respectively, and specimen types shown in Figure 4.1.

6.1.4 Raw Engineering Stress

The raw force *versus* time data as described in Section 6.1.1 obtained for each test result is converted to engineering stress using:

$$s = \frac{F}{wt}$$

Where w and t are the nominal values of the specimen.

6.1.5 Engineering Stress, Strain and Strain Rate

To complete the requirements of stage 1 data processing, the raw engineering stress *versus* engineering strain for each strain rate test result are displayed in one graph. An example graph is shown in Annex A.

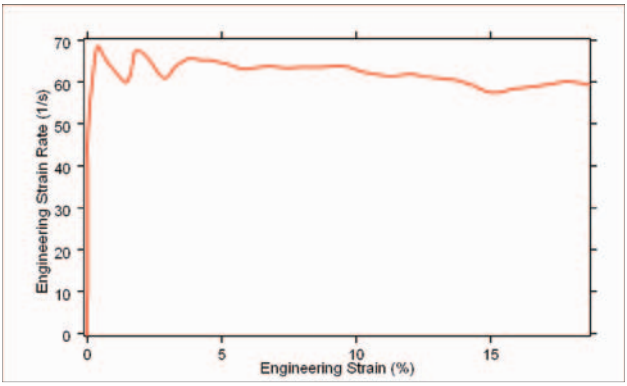

Figure 6.7 Engineering strain rate (filtered) *versus* engineering strain for aluminium alloy and target test speed set to 5 m/s

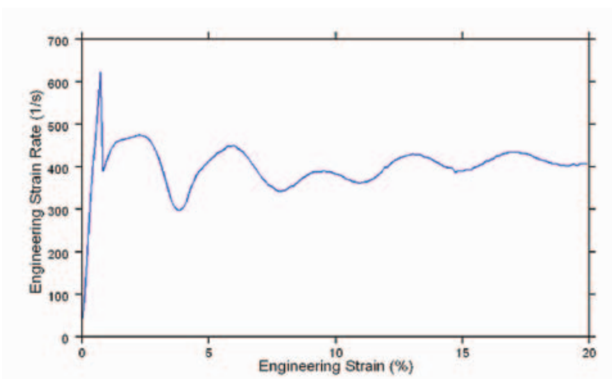

Figure 6.8 Engineering strain rate (filtered) *versus* strain for high strength steel and target test speed 15 m/s

6.1.6 Analysis of Engineering Stress versus *Strain Data*

Inspecting the graph of engineering stress *versus* strain it is expected the raw strain rate test curves are consistent for conventional metallic materials to include steel and aluminium alloys with a melting point above 500 °C. That is, as strain rate increases the general trend for strength hardening is expected to increase in the entire strain range up to tensile strength for these materials.

6.1.7 Crossing of Strain Rate Curve Trends at Low Strain

If the test curves derived at higher strain rate dip below the quasi-static test curve at low strain, typically below 5% strain, it is suspected that either yielding has occurred in the local force measurement device, or the strain rate sensitivity of the material may be so low that it is considered insensitive to strain rate at ambient temperature. The former requires a modification to the test procedure. In the latter case the measured strength hardening in the material over the range of strain rates approximates to the typical variation in strength derived from quasi-static tests. See also Section 6.4.3.

6.1.8 Adiabatic Thermal Softening in Strain Rate Testing

Thermal softening will develop in the gauge length with increasing strain rate and plastic strain. At very low strain rates the thermodynamic process in the material is considered isothermal. At higher strain rates typically above 10/s the thermodynamic process in the material is considered adiabatic; the heat has little time to dissipate, which manifests as a steady reduction in strength hardening with increasing plastic strain.

For conventional steel materials which have a low thermal heat capacity, the thermal softening effect is generally not significant in comparison to the strain rate induced strength hardening effect in the plastic strain range to tensile strength.

For aluminium alloys the effect can be more significant. For those grades which exhibit no measurable strength hardening resulting from strain rate testing, the trend of the flow curves derived at higher strain rate will gradually dip below the quasi-static flow curve at higher plastic strain, typically approaching the tensile strength, see example in Annex C. For such materials in which the thermal softening effect is present but the reduction in strength hardening is marginal, it is not necessary to account for the thermal softening effect in the material model if tensile strength develops below 20% true plastic strain (see also Section 6.4.3).

6.2 Stage 2 Data Processing: Raw True Plastic Data

For each strain rate test result, identify the region of uniform plastic elongation of gauge length using the engineering stress *versus* strain curve. The start of uniform plastic elongation will be defined by the yield point. To identify the yield point for material type A determine 0.2% strain offset and using Young's modulus for the material, locate the yield point on the test curve, see Figure 6.9. For material type B which exhibits a clearly defined initial yield point, material yielding is assumed to coincide with the start of the hardening curve for CAE input, e.g., when constant yielding has terminated, typically at 3% or 4% engineering strain, see Figure 6.9.

The end of uniform plastic elongation of gauge length will be determined by the maximum tensile strength of the material (onset of necking in the tensile specimen), see Figure 6.10.

The data to the left and right of the region of uniform plastic elongation is removed and a new data set created.

6.2.1 Raw True Plastic Data

For the region of uniform plastic elongation, the raw engineering test results obtained for each strain rate curve are converted to true plastic data using these equations for true stress σ and true strain (e):

$$\sigma = s(1 + e)$$

$$\varepsilon = \ln(1 + e)$$

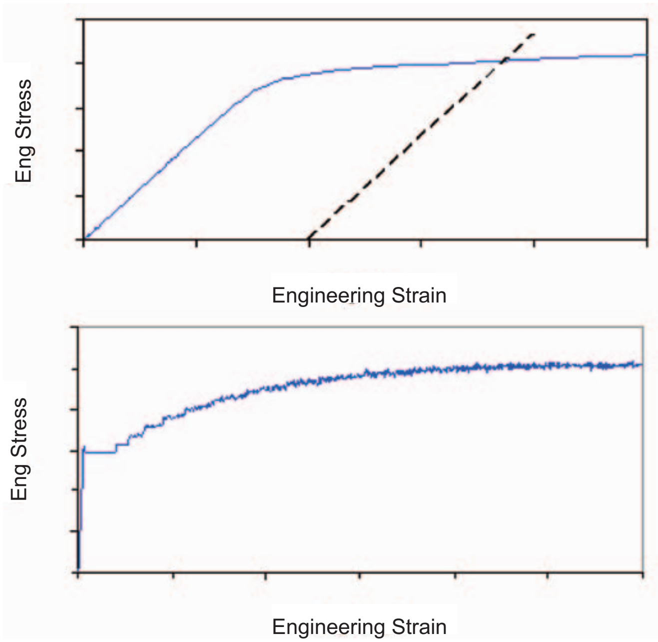

Figure 6.9 Method to identify yield point for material type A (above) and material type B (below).

The true test curve obtained for each strain rate may be shifted left on the true strain axis so that the start of loading coincides with the zero true plastic strain. This completes the requirements of stage 2 data processing and an example result is shown in Annex sections A, B and C.

6.3 Stage 3 Data Processing: Fitting Material Model

In commercial CAE simulation tools table definitions are available to input material flow curves, for example LS-DYNA (Livermore Software, Livermore, CA, USA) will allow input of true plastic data [30, 31]. Raw, true plastic data, however, are not input directly to simulation tool. Instead, the material data input to simulation

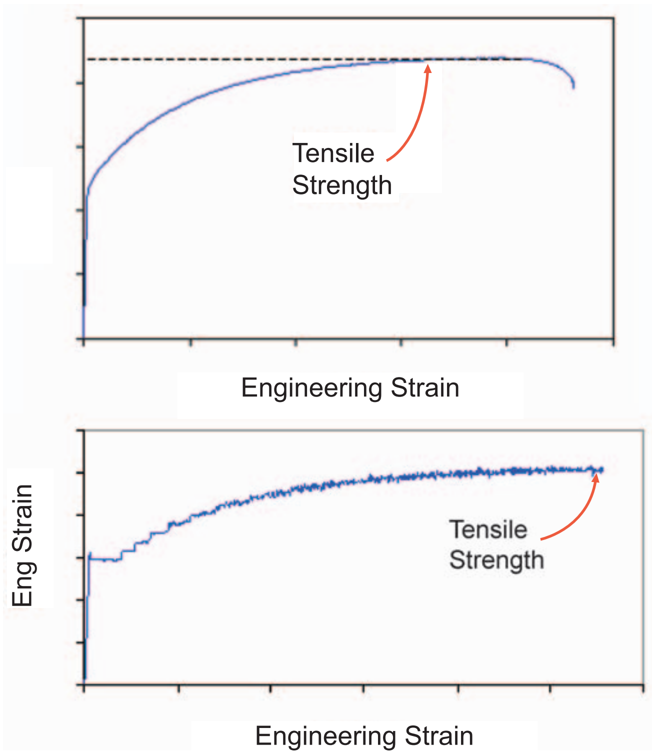

Figure 6.10 Method to identify the tensile strength of a material with pronounced necking before fracture (above) and marginal necking before fracture (below)

tool describing each test curve will be smooth and monotonically increasing. For this, a model of the material is necessary to meet the requirements of stability in CAE applications.

It is not within the scope of these recommendations to advocate a material model to fit to raw true plastic data. Rather to specify the accuracy of fit (or error allowance) in fitting model to raw plastic data. A requisite is a model together with fitting algorithm that has the functional capability to deliver the necessary quality of fit to raw test results.

6.3.1 Definitions

<u>2-D Model Set</u>: Collection of model test curves in which each is fitted to one test result obtained at a given average engineering strain rate. There is no relationship existing between each of the test curves in the 2-D model set. The model of each test curve has two parameters, stress and strain for a given average strain rate.

<u>3-D Model</u>: Family of test curves fitted to strain rate test results such that a relationship exists between the curves. The model contains three parameters, stress, strain and strain rate, and is often referred to as either a constitutive law or surface. For convenience the term surface is used in this document.

The IARC algorithm works by fitting a smooth and monotonically increasing test curve to each of the raw true plastic data curves obtained at each strain rate. The algorithm uses either least squares, spline curves or filtering, whichever provides the best fit to test result, in effect creating a 2-D Model Set. At strain rates typically below 10/s, the fit accuracy of each curve in the 2-D Model Set and its respective raw true plastic flow curve will be within 2%. At strain rates greater than 10/s, the trained eye is used to check quality of fit because of the presence of increasing force oscillation at higher strain rates in the raw test results, see examples in Figures 6.11 and 6.12.

6.3.2 Error Allowance

In fitting a surface the accuracy of model fit will be determined by the deviation between each strain rate curve in the surface and the associated curve derived in the 2-D Model Set. The fit allowances proposed based on practical testing are listed in Table 6.1.

An example of surface model fitted to test results in the low to intermediate strain range is shown in Figure 6.13.

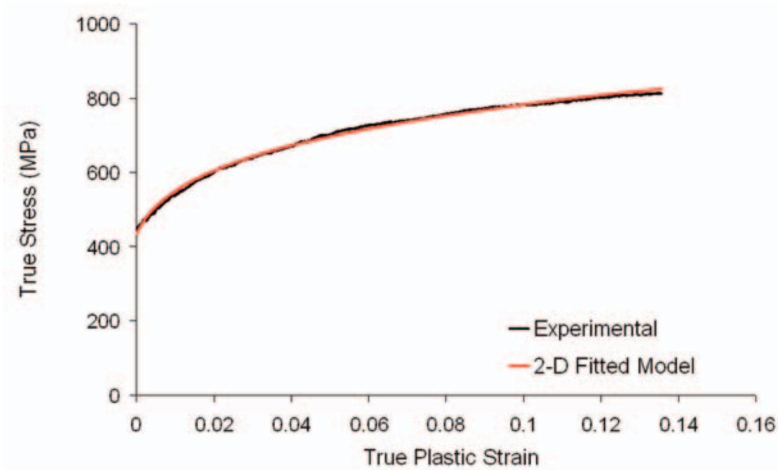

Figure 6.11 Target strain rate 8.33 /s. Model fit error using least squares less than 2% deviation from test result. Measured average engineering strain rate = 6.4014 /s

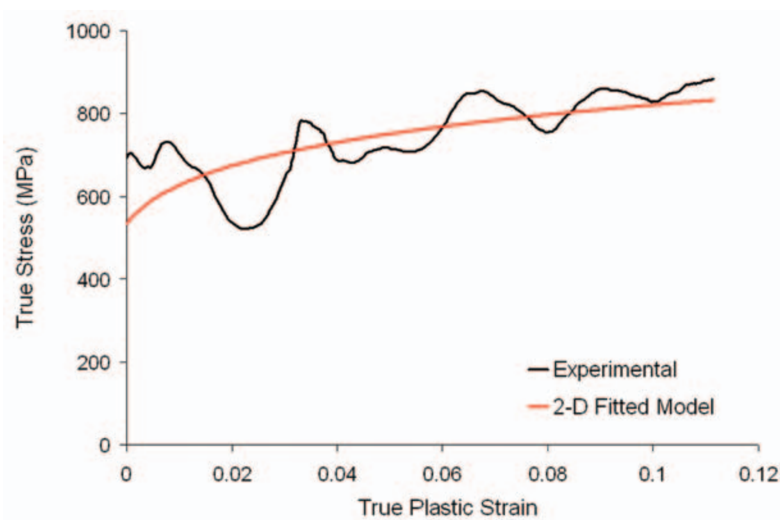

Figure 6.12 Target strain rate 600/s. Model fit error using least squares demonstrates a good approximate fit to oscillating curve. Measured average engineering strain rate = 420.43 /s

Table 6.1 Table of allowable deviations in fitting surface model to raw true plastic data							
True Plastic Tensile Strain	Theoretical Strain Rate (l/s)						
	0.001	0.1	1.33	8.33	83.3	240	600
0%	2.0%	3.0%	3.0%	3.0%	0	0	0
2%	2.0%	3.0%	3.0%	3.0%	0	0	0
5%	2.0%	3.0%	3.0%	3.0%	0	0	0
10%	2.0%	3.0%	3.0%	3.0%	0	0	0
15%	2.0%	3.0%	3.0%	3.0%	0	0	0
20%	2.0%	3.0%	3.0%	3.0%	0	0	0

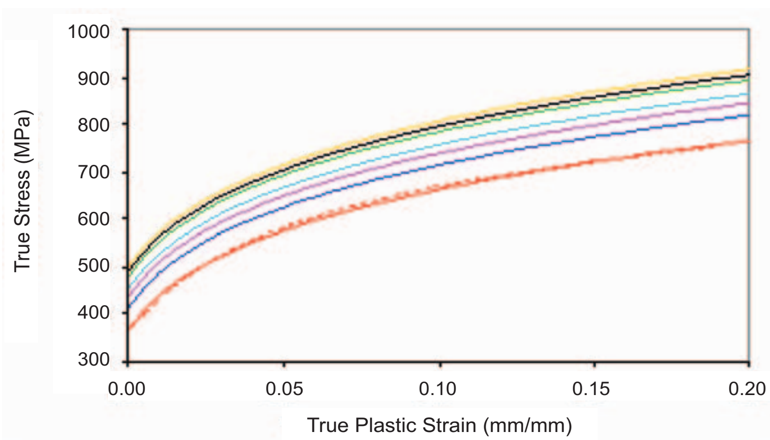

Figure 6.13 Surface model fitted to raw true plastic data

6.3.3 Model Extension to High Plastic Strain

In CAE applications, it is necessary to extend the range of true plastic data to 100% true plastic strain (and in some cases 200%) to ensure material stability in implicit and explicit solver solution schemes. Various techniques have been applied to achieve this such as linearly extending the slope at the end of the curve. There are others each having merits and drawbacks, and the latter is emphasised when considering several curves in one data set such as material data with strain rate dependency. It is recommended that a consistent approach be adopted, and one such approach is elucidated next.

The IARC surface [18] contains a multiplicative hyperbolic term, which may be used explicitly to force the extended curves of a surface model to converge to a target saturation stress using this expression:

$$\sigma = \left[1 - \tanh\left(\frac{\varepsilon}{k}\right)\right] \times \sigma_{surface}$$

This term may be applied with other models. The expression has little influence in the strain range for which the test data was derived, but can exert a significant influence at higher plastic strain by simply changing the value of the coefficient k (either – or + ve) to achieve the desired effect. An example is given in Figure 6.14.

Some materials, e.g., aluminium alloys, converge to a saturation stress at an intermediate plastic strain normally beyond the tensile strength of the material but significantly below 100% true plastic strain, as shown by a quasi-static plane strain compression test. The hyperbolic

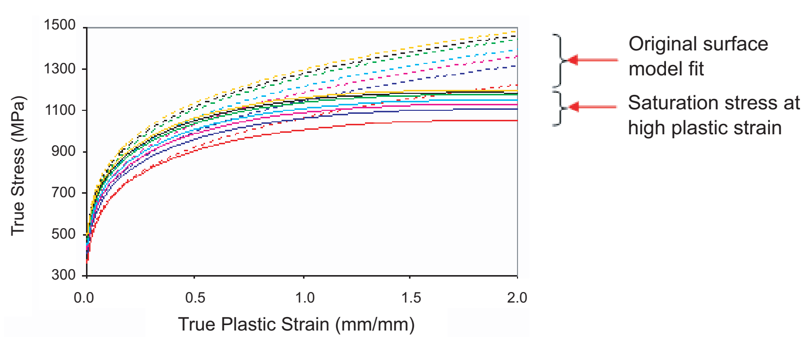

Figure 6.14 IARC surface model adjusted to achieve a saturation stress at higher plastic strain

term described may be used in the same way to achieve saturation stress of the surface at intermediate levels of true plastic strain.

Essential requirements of building a model test curve is that true stress will increase with true plastic strain until saturation stress is reached. Further, the slope (or plastic modulus) derived between each stress and strain co-ordinate in the table definition will gradually reduce until saturation stress is reached. The plastic modulus will not oscillate. The true plastic strain range used in the table definition will not be increased beyond 200%.

6.4 Stage 4 Data Processing: Formatting Material Model and Creation of Material Card

The surface model is formatted in accordance with the following recommendations for input to CAE based simulation tools. For each test curve:

The ordinate (Y) axis of each test curve is true stress and the abscissa (X) axis is true plastic strain.

Low to intermediate strain range: Increments of true plastic strain will be defined at 0.5% in the plastic strain range 0 to 20% giving 40 co-ordinates for true stress *versus* true plastic strain. The start of true stress coincides with zero on the true plastic strain axis. An example using comma delimited format often called table definition in simulation software tools is shown next:

X,	Y
0,	200.000
0.005,	250.000
0.01,	280.000
0.2,	350.000

Intermediate to high plastic strain: Increments of true plastic strain will be defined at 10% in the plastic strain range 20% to 200% giving a further 18 co-ordinates for true stress *versus* true plastic strain. The example table definition given previously is extended to include intermediate to high plastic strain and is shown next. A worked example is given in Annex D.

X,	Y
0,	200.000
0.005,	250.000
0.01,	280.000
0.2,	350.000
0.3,	380.000
0.4,	395.000
2,	430.000

It is recommended that a test curve is generated from the surface model for each of the strain rate test results using the table definition format. A total of seven true plastic flow curves will be formatted, each flow curve using common increments for true plastic strain previously described, and each flow curve requiring a separate table definition for input to CAE tool. Smaller plastic strain increments in the low to intermediate true plastic strain range is generally not necessary.

6.4.1 Formatting for Input to Simulation Tool

Commercial CAE based simulation tools enable material test curves with strain rate dependency to be input to material card using a table definition [30, 31] in accord with the format given in Section 6.4.1. This table definition containing the coordinates of each strain rate test curve is cross-referenced to another table (see example next) which identifies the strain rate for each flow curve, and in turn, to the material card by a user defined number:

0.0000000 (quasi-static test speed)
0.1321400
1.2655000
6.1792000
59.256000
146.14000
394.36000

Table of strain rates to cross reference each flow curve (*note first flow curve tested at quasi-static test speed is set effectively to zero strain rate*)

Essential mechanical properties of the material independent of strain rate, e.g., Young's modulus and Poisson ratio, are entered in the field spaces provided in the material card, in which the simulation tool user manual [30, 31] should be consulted for details.

6.4.2 Exception to Defining Seven Strain Rate Flow Curves

Where the material exhibits relatively low strength hardening dependency on strain rate, the number of test curves used in the table definition (Section 6.4.1) is reduced from seven to two test curves. It is recommended that strain rate sensitivity is calculated using the data in the table definition (Section 6.4.1) as follows:

$$m = \frac{\log(\sigma_2/\sigma_1)}{\log(\dot{\varepsilon}_2/\dot{\varepsilon}_1)}$$

Suffix 1 = value of true stress from quasi-static strain rate curve at 1% true plastic strain

Suffix 2 = value of true stress from strain rate curve nearest 1/s at 1% true plastic strain

In the case where the strength hardening effect in the material measured across the strain rate range is greater than the typical variation in strength derived from quasi-static tests, and the m value is typically below 0.01, two test curves are sufficient, one at quasi-static and the other at 100 s^{-1} or greater.

In the case where the measured strength hardening in the material from testing over the range of strain rates approximates the typical variation in strength derived from quasi-static tests, it is sufficient to use only the quasi-static test curve to model material for input to the simulation tool.

An example of a non-ferrous material in which strength hardening is dependent on strain rate is given in Annex B. An example of a non-ferrous material in which strength hardening is considered independent of strain rate is also given in Annex C.

6.4.3 Significant Figures and Decimal Places

The number of decimal places is dependent on the unit system of measurement selected in the simulation tool. The number of decimal places is less important than the number of significant figures. It is recommended that at least five significant figures are consistently used to describe all mechanical property data relating to the material input to simulation tool, including all table definitions holding true plastic data.

6.4.4 Material Units

The units for material data input to simulation tool must be consistent with the dimensions of structural elements together with external loadings applied to structural elements. The simulation tool user manual should be consulted to confirm the unit system for material.

6.5 Numerical Stability

Explicit-based finite element simulation tools such as LS-DYNA include features in the dynamic model of material, which reduce noise and improve stability of material model in numerical analysis. Such a feature in LS-DYNA [30, 31] is the visco-plasticity option which introduces a small amount of damping to the dynamic material model.

6.6 Model Quality Checks

Material model will be tested in a suitable application such as the sub-system test described in references [19] and [26].

7 General Definitions

Gauge length: Distance of parallel length between transition radii

Gauge width: Width of parallel length between transition radii

Static grip length: Distance between static grip end and specimen lower transition radius

Static grip width: Width of static grip length

8 Strength Hardening Constitutive Relations to Model Material Strain Rate Dependency

It is not within the scope of these recommendations to advocate a material model to fit strain rate test results for use in simulating automotive crash applications, although references for several useful models are given next, but the list is not exhaustive.

Some of the models listed are empirical based, providing a description of strain rate hardening and the adiabatic heat softening on the developed plastic strain in the material, such as [3, 4, 5]. They are so described because the models are mathematical descriptions that are developed to fit the observed test results. Material testing is designed to match the application design range of interest in which the material will be considered. For example through either tension, compression or plane strain testing, or a combination of these.

Whilst other models listed have a physical basis which attempts to couple the effects of strain rate and heat that develops with plastic deformation in a metal structure, for example through dislocation theory and thermodynamic considerations. They still ultimately provide a mathematical description of the material under conditions of special interest, and the inputs to the model still require strain rate and temperature testing.

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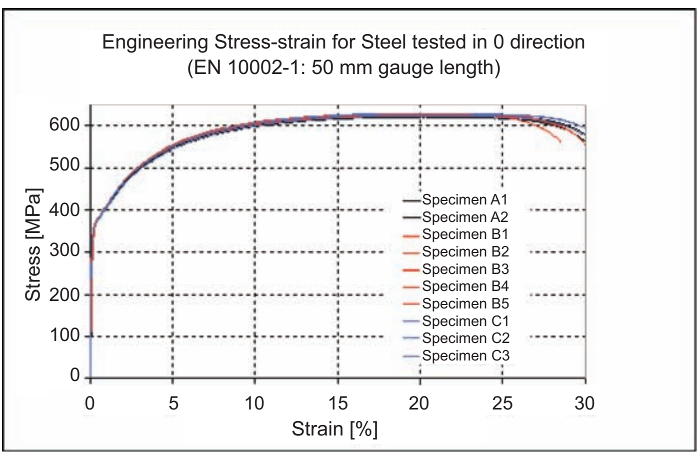
29) P.K.C. Wood and C.A. Schley, *Material Data Management Tool – Models and Processes to Transform Raw Material Data for Input to CAE Tools* (proprietary software), Flat 41, Brindley Point, 20 Sheepcote Street, Birmingham, B16 8AE

30) J.O. Hallquist, *LS-DYNA – Keyword User's Manual,* Version 971, Volumes 1-2, Livermore Software Technology Corporation, Livermore, 2007.

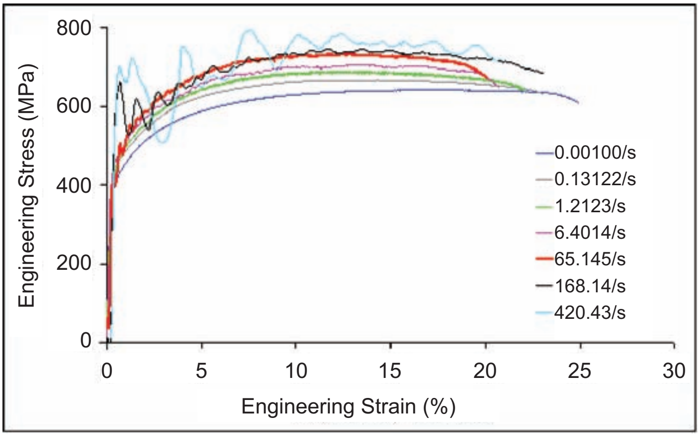
31) *OASYS LS-DYNA ENVIRONMENT*, Ove Arup and Partners, The Arup Campus, Blythe Valley Park, West Midlands, UK.

Annex

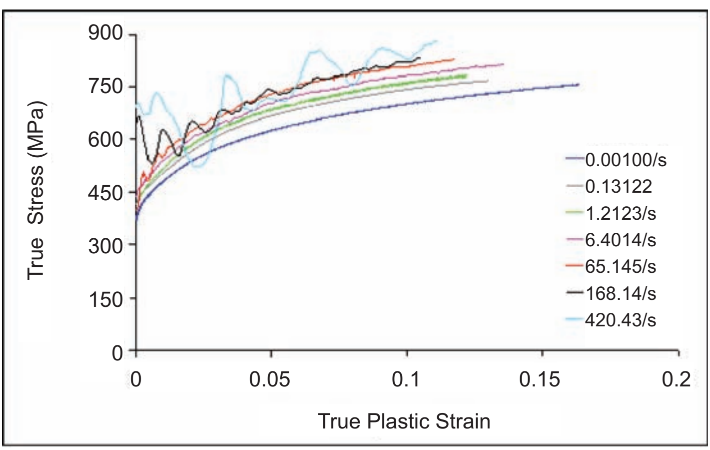
Annex A: Examples of quasi-static and strain rate data derived for a ferrous material with measurable strain rate induced strength hardening dependency, and fitted model



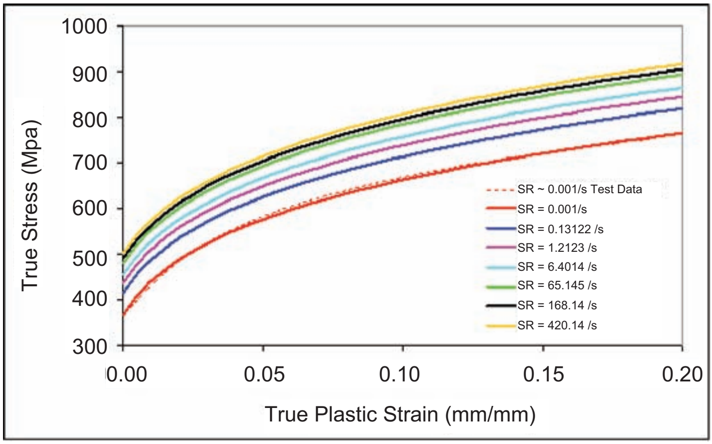
Quasi-static tests conducted on a ferrous material using specimens produced from the same sheet. Measured variability is low



Strain rate tests conducted on same ferrous material in which strength hardening is observed to have measurable dependency on strain rate

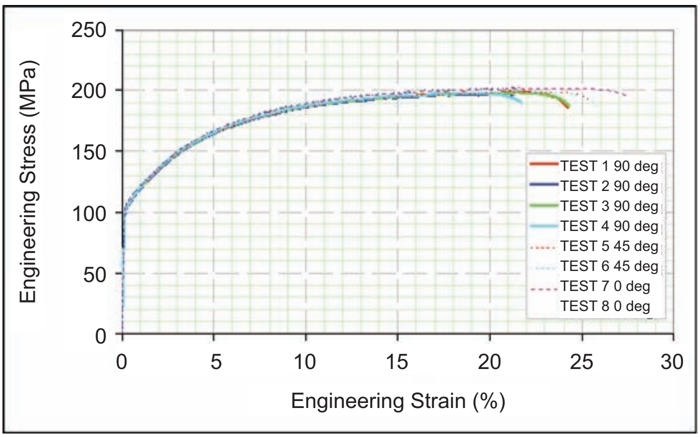


Strain rate test results for same ferrous material converted to true plastic data in which strength hardening is observed to have measurable dependency on strain rate

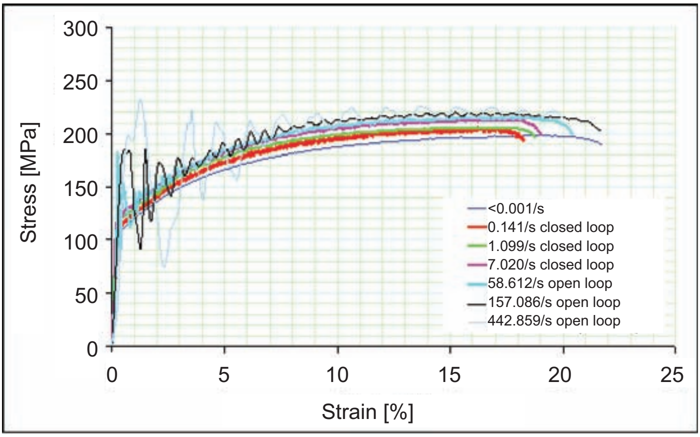


Strain rate dependent model fitted to true plastic test data for same ferrous material

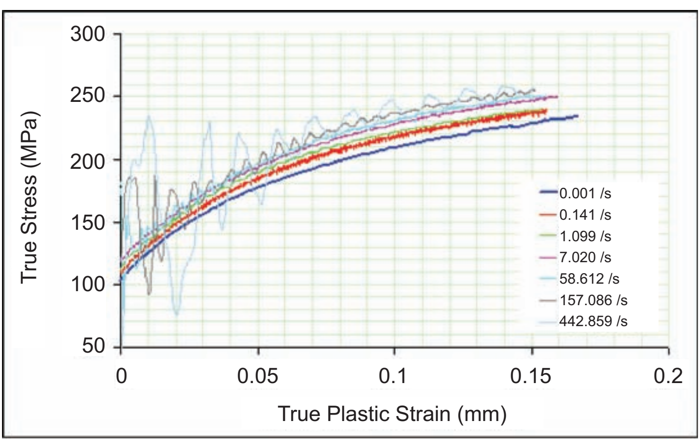
Annex B: Example of quasi-static and strain rate data derived for a non-ferrous material with measurable strain rate induced strength hardening dependency, and fitted model



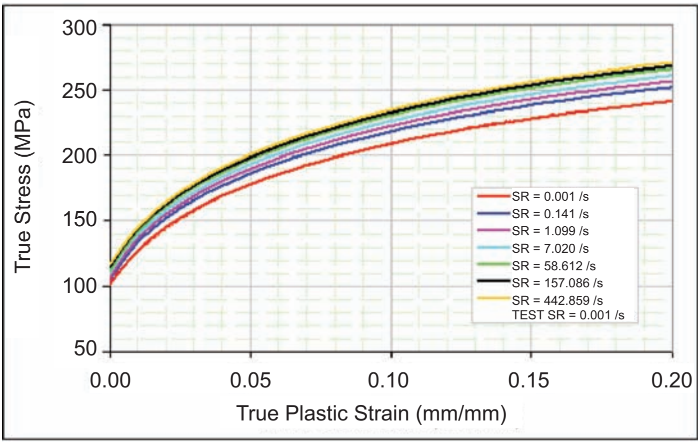
Quasi-static tests conducted on a non-ferrous material using specimens produced from the same sheet. Measured variability is low



Strain rate tests conducted on same non-ferrous material in which strength hardening is observed to have measurable dependency on strain rate

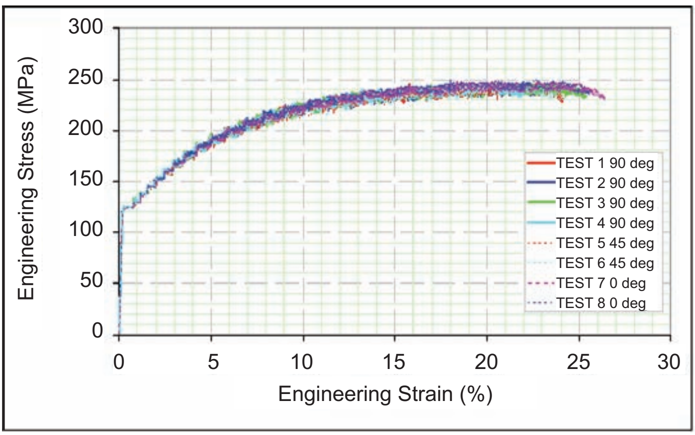


Strain rate test results for same non-ferrous material converted to true plastic data in which strength hardening is observed to have measurable dependency on strain rate

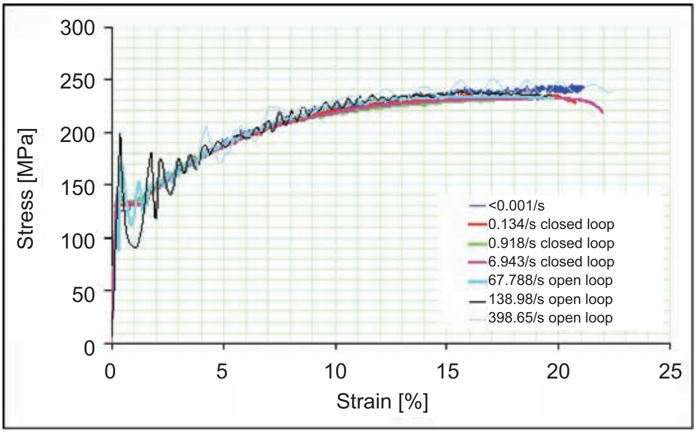


Strain rate dependent model fitted to true plastic test data for same non-ferrous material

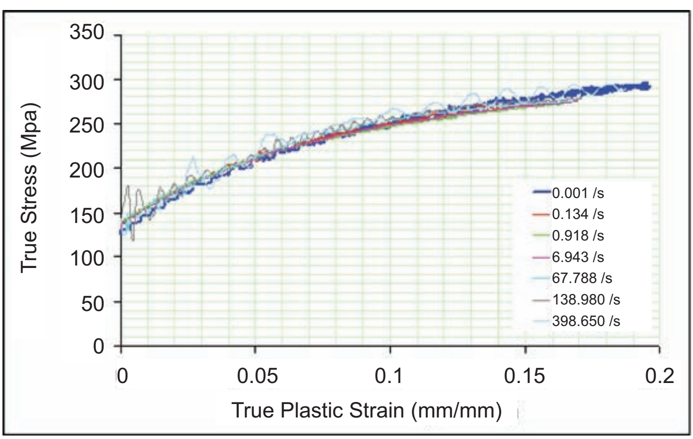
Annex C: Example of quasi-static and strain rate data derived for a non-ferrous material in which there is no measurable strain rate induced strength hardening dependency, and fitted model



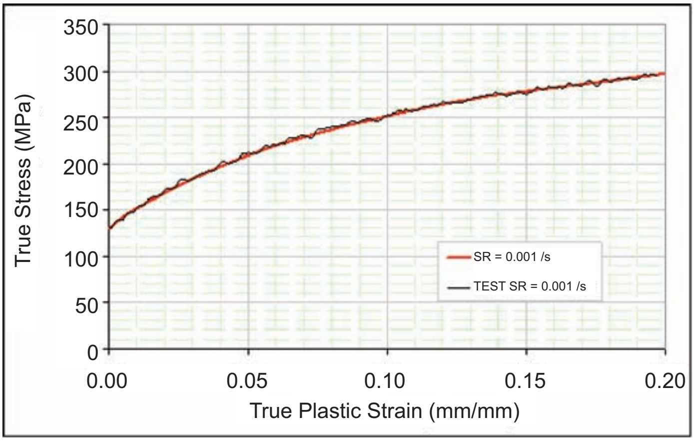
Quasi-static tests conducted on a non-ferrous material using specimens produced from the same sheet.
Measured variability is low



Strain rate tests conducted on same non-ferrous material in which strength hardening is observed not to have a measurable dependency on strain rate

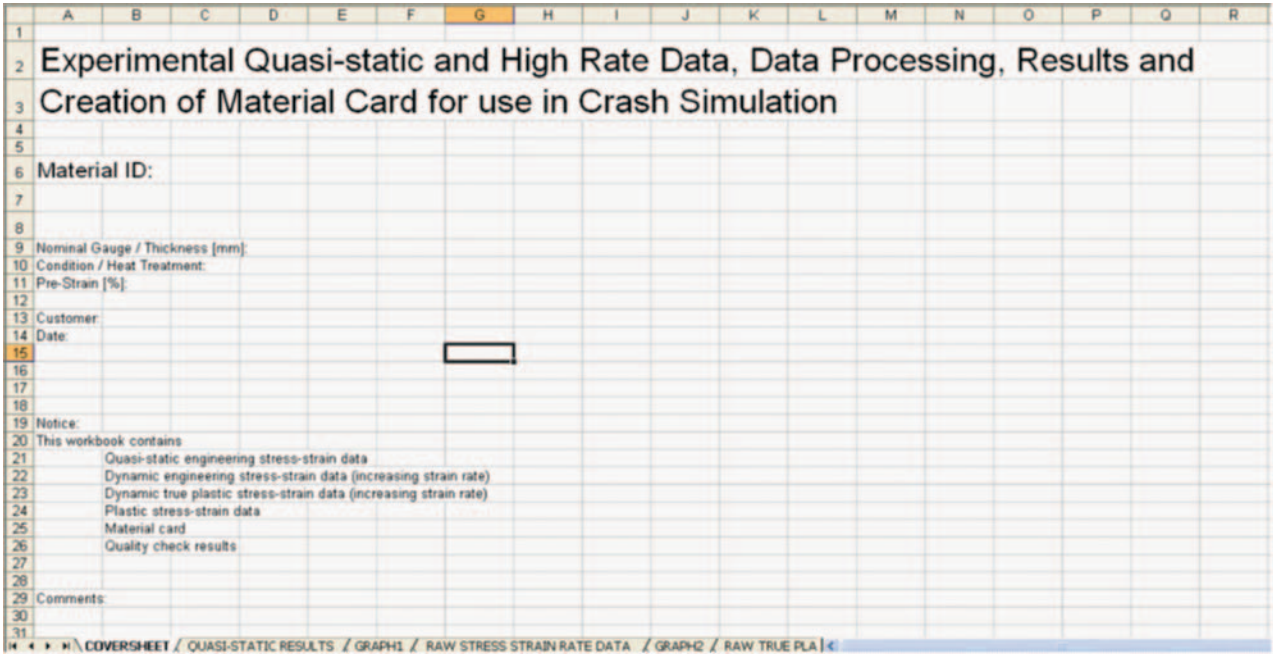


Strain rate test results for same non-ferrous material converted to true plastic data in which strength hardening is observed not to have measurable dependency on strain rate

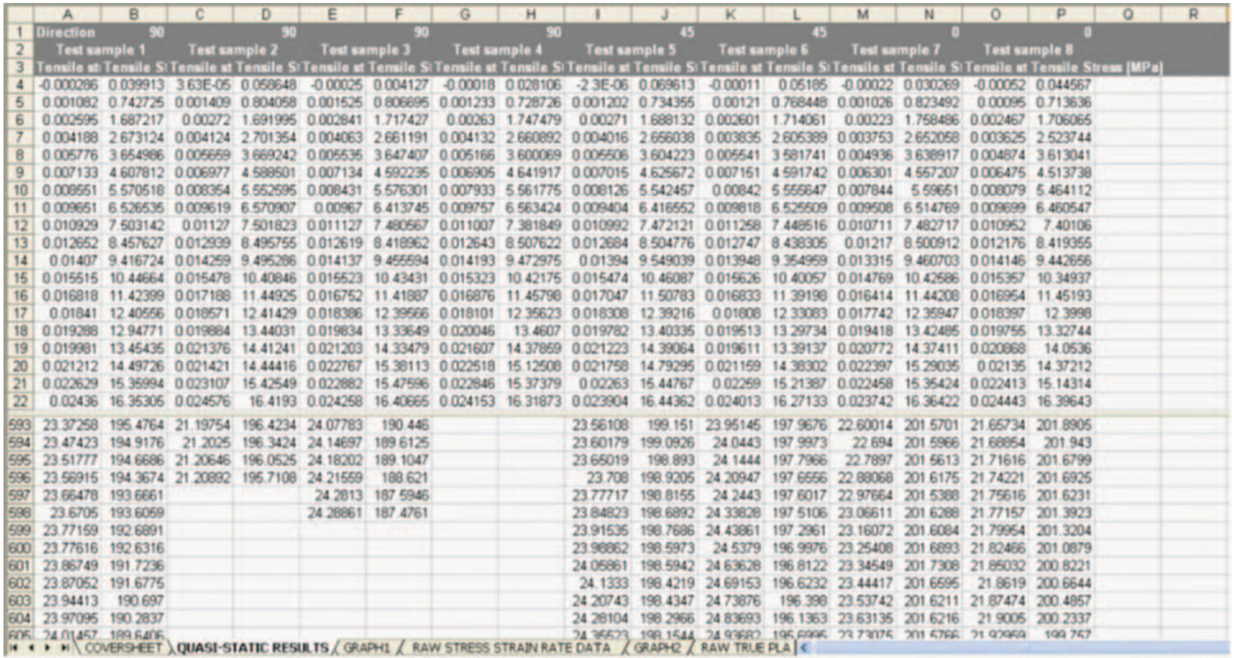


Model fitted to quasi-static true plastic test data for same non-ferrous material

Annex D: Workbook example of data processes to create material card



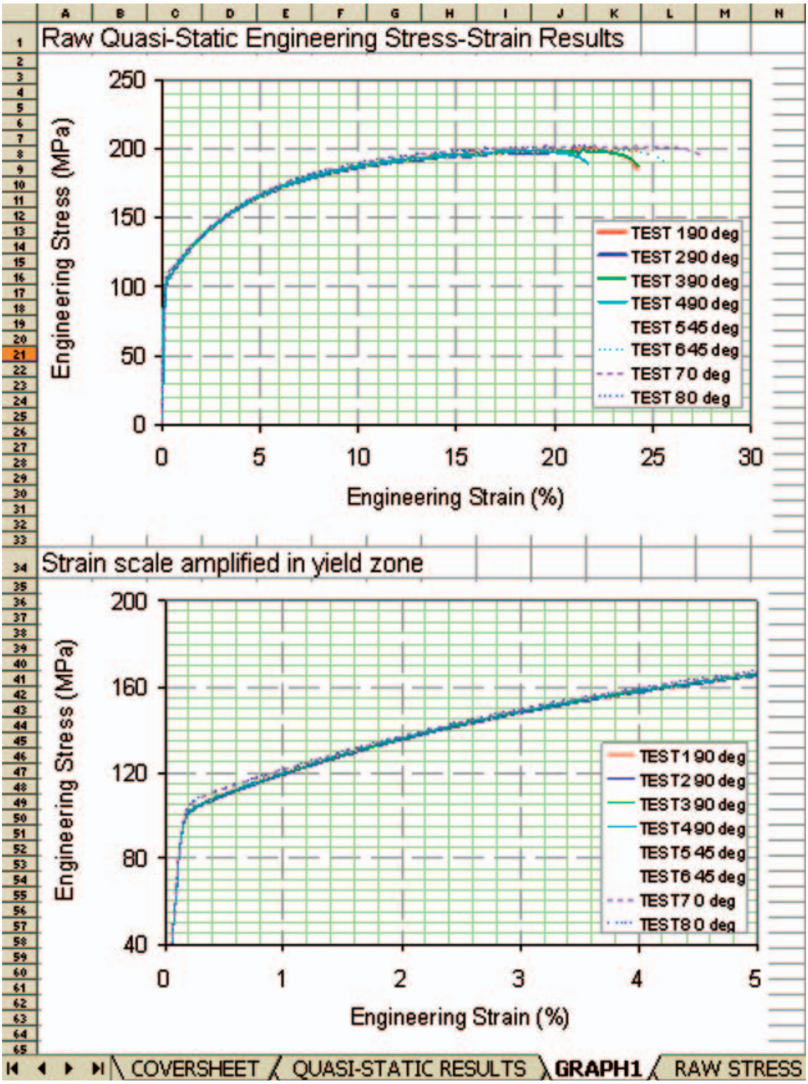
D1: Layout of first tab in workbook



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Direction	90		90		90		90		45		45		0		0
2	Test sample 1		Test sample 2		Test sample 3		Test sample 4		Test sample 5		Test sample 6		Test sample 7		Test sample 8	
3	Tensile st	Tensile S	Tensile st	Tensile S	Tensile st	Tensile S	Tensile st	Tensile S	Tensile st	Tensile S	Tensile st	Tensile S	Tensile st	Tensile S	Tensile st	Tensile Stress [MPa]
4	-0.000286	0.039913	3.63E-05	0.058648	-0.00025	0.004127	-0.00018	0.028106	-2.3E-06	0.069613	-0.00011	0.05185	-0.00022	0.030269	-0.00052	0.044567
5	0.001082	0.742725	0.001409	0.804058	0.001525	0.806695	0.001233	0.728726	0.001202	0.734355	0.00121	0.768448	0.001026	0.823492	0.00095	0.713636
6	0.002595	1.687217	0.00272	1.691995	0.002841	1.717427	0.00263	1.747479	0.00271	1.688132	0.002601	1.714061	0.00223	1.758486	0.002467	1.706065
7	0.004188	2.673124	0.004124	2.701354	0.004063	2.661191	0.004132	2.660892	0.004016	2.656038	0.003835	2.605389	0.003753	2.652058	0.003625	2.523744
8	0.005776	3.654986	0.005659	3.669242	0.005535	3.647407	0.005166	3.600069	0.005506	3.604223	0.005541	3.581741	0.004936	3.638917	0.004874	3.613041
9	0.007133	4.607812	0.006977	4.588501	0.007134	4.592235	0.006905	4.641917	0.007015	4.625672	0.007151	4.591742	0.006301	4.557207	0.006475	4.513738
10	0.008551	5.570518	0.008354	5.552595	0.008431	5.576301	0.007933	5.561775	0.008126	5.542457	0.00842	5.555647	0.007844	5.59651	0.008079	5.464112
11	0.009651	6.526535	0.009619	6.570907	0.00967	6.413745	0.009757	6.563424	0.009404	6.416652	0.009818	6.525509	0.009508	6.514769	0.009699	6.460547
12	0.010929	7.503142	0.01127	7.501823	0.011127	7.480567	0.011007	7.381849	0.010992	7.472121	0.011258	7.448516	0.010711	7.482717	0.010952	7.40106
13	0.012652	8.457627	0.012939	8.495755	0.012619	8.418962	0.012643	8.507622	0.012684	8.504776	0.012747	8.438305	0.01217	8.500912	0.012176	8.419355
14	0.01407	9.416724	0.014259	9.495286	0.014137	9.455594	0.014193	9.472975	0.01394	9.549039	0.013948	9.354959	0.013315	9.460703	0.014146	9.442656
15	0.015515	10.44664	0.015478	10.40846	0.015523	10.43431	0.015323	10.42175	0.015474	10.46087	0.015626	10.40057	0.014769	10.42586	0.015357	10.34937
16	0.016818	11.42399	0.017188	11.44925	0.016752	11.41887	0.016876	11.45798	0.017047	11.50783	0.016833	11.39198	0.016414	11.44208	0.016954	11.45193
17	0.01841	12.40556	0.018571	12.41429	0.018386	12.39566	0.018101	12.35623	0.018308	12.39216	0.01808	12.33083	0.017742	12.35947	0.018397	12.3998
18	0.019288	12.94771	0.019884	13.44031	0.019834	13.33649	0.020046	13.4607	0.019782	13.40335	0.019513	13.29734	0.019418	13.42485	0.019755	13.32744
19	0.019981	13.45435	0.021376	14.41241	0.021203	14.33479	0.021607	14.37859	0.021223	14.39064	0.019611	13.39137	0.020772	14.37411	0.020868	14.0536
20	0.021212	14.49726	0.021421	14.44416	0.022767	15.38113	0.022518	15.12508	0.021758	14.79295	0.021159	14.38302	0.022397	15.29035	0.02135	14.37212
21	0.022629	15.35994	0.023107	15.42549	0.022882	15.47596	0.022846	15.37379	0.02263	15.44767	0.02259	15.21387	0.022458	15.35424	0.022413	15.14314
22	0.02436	16.35305	0.024576	16.4193	0.024258	16.40665	0.024153	16.31873	0.023904	16.44362	0.024013	16.27133	0.023742	16.36422	0.024443	16.39643
593	23.37258	195.4764	21.19754	196.4234	24.07783	190.446			23.56108	199.151	23.95145	197.9676	22.60014	201.5701	21.65734	201.8905
594	23.47423	194.9176	21.2025	196.3424	24.14697	189.6125			23.60179	199.0926	24.0443	197.9973	22.694	201.5966	21.68854	201.943
595	23.51777	194.6686	21.20646	196.0525	24.18202	189.1047			23.65019	198.893	24.1444	197.7966	22.7897	201.5613	21.71616	201.6799
596	23.56915	194.3674	21.20892	195.7108	24.21559	188.621			23.708	198.9205	24.20947	197.6556	22.88068	201.6175	21.74221	201.6925
597	23.66478	193.6661			24.2813	187.5946			23.77717	198.8155	24.2443	197.6017	22.97664	201.5388	21.75616	201.6231
598	23.6705	193.6059			24.28861	187.4761			23.84823	198.6892	24.33828	197.5106	23.06611	201.6288	21.77157	201.3923
599	23.77159	192.6891							23.91535	198.7686	24.43861	197.2961	23.16072	201.6084	21.79954	201.3204
600	23.77616	192.6316							23.98862	198.5973	24.5379	196.9976	23.25408	201.6893	21.82466	201.0879
601	23.86749	191.7236							24.05861	198.5942	24.63628	196.8122	23.34549	201.7308	21.85032	200.8221
602	23.87052	191.6775							24.1333	198.4219	24.69153	196.6232	23.44417	201.6595	21.8619	200.6644
603	23.94413	190.697							24.20743	198.4347	24.73876	196.398	23.53742	201.6211	21.87474	200.4857
604	23.97095	190.2837							24.28104	198.2966	24.83693	196.1363	23.63135	201.6216	21.9005	200.2337
605	24.01457	189.6406							24.35523	198.1544	24.93682	195.6995	23.73075	201.5766	21.92969	199.757

COVERSHEET | QUASI-STATIC RESULTS | GRAPH1 | RAW STRESS STRAIN RATE DATA | GRAPH2 | RAW TRUE PLA

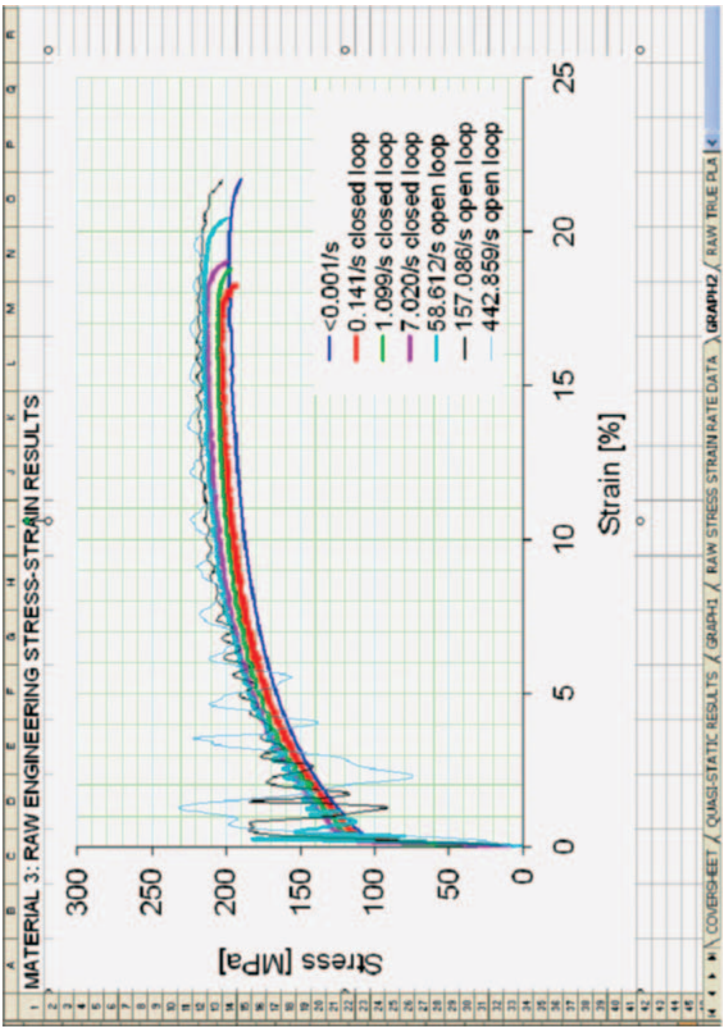
D2: Layout of raw quasi-static results on second tab in workbook



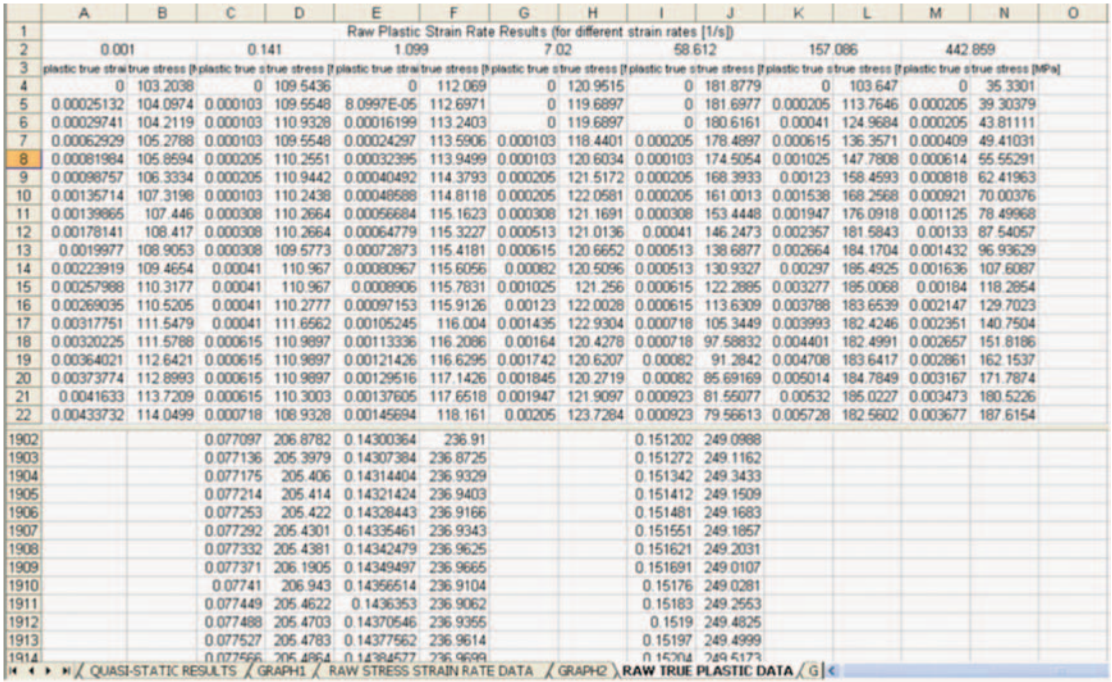
D3: Layout of graphs of raw quasi-static results on third tab in workbook

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	QUASI-STATIC CURVE			SR = 0.141 / s			SR = 1.099			SR = 7.020				SR = 58.612			157.086			SR = 442.859	
2	Clip Gauge	achine load cell		Strain Gauge	Kistler		Strain Gauge	Kistler		Strain Gauge	Kistler	Strain Gauge		Strain Gaug	train Gauge		Strain Gaug	train Gauge		Strain Gaug	train Gauge
3	Strain [%]	Stress [MPa]		Strain [%]	Stress [MPa		Strain [%]	Stress [MPa		Strain [%]	Stress [MPa	Stress [MPa]		Strain [%]	Stress [MPa		Strain [%]	Stress [MPa		Strain [%]	Stress [MPa
4	-0.00017975	0.028106221		0.05129004	0.690382		0	0		0	-0.6863552	-0.36051109		0.010258	4.506391		0.010258	3.785368		0	3.965624
5	0.00123316	0.728726233		0.05129004	0.001438		0.0081	8.01091		0	-0.6863552	-0.901278095		0.010258	4.506391		0.010258	4.14588		0.010258	3.965624
6	0.00263033	1.747478815		0.05129004	0.001438		0.0162	13.8969		-0.010258004	-0.6863552	-0.540767005		0.010258	3.965624		0.010258	5.047158		0.010258	4.14588
7	0.00413163	2.66089185		0.06154805	0.690382		0.0243	17.7951		0	0	-0.36051109		0	3.785368		0.010258	5.76818		0.010258	4.14588
8	0.00516553	3.60006898		0.06154805	1.379326		0.0324	22.2944		-0.010258004	2.05906554	0		0.010258	3.965624		0.030774	7.02997		0.010258	4.14588
9	0.00690501	4.641916686		0.06154805	-1.37645		0.0405	28.0407		0	1.37271036	0.901278095		0.010258	3.965624		0.020516	8.291759		0	3.965624
10	0.00793329	5.561775357		0.05129004	0.690382		0.0486	36.939		-0.010258004	0	0.901278095		0.010258	3.785368		0.030774	9.373293		0	4.686646
11	0.00975682	6.563423663		0.05129004	0.001438		0.0567	44.2113		-0.010258004	4.11813109	1.08153364		0.010258	3.244601		0.041032	10.81534		0.010258	4.866902
12	0.01100749	7.381849391		0.05129004	1.379326		0.0648	50.2141		0.010258004	3.43177591	1.622300645		0	3.244601		0.041032	12.61789		0.010258	5.227413
13	0.01264322	8.507621908		0.06154805	0.001438		0.0729	55.821		-0.010258004	2.74542072	1.982812105		0.010258	3.244601		0.041032	14.96122		0.010258	5.587925
1307				4.8828125	173.6154		10.5542	199.563		12.57337711	210.024682	208.9162839		11.3401	209.4571		20.38826	214.324			
1308				4.8930705	172.2375		10.5623	199.618		12.5831977	209.338329	208.9162839		11.34822	209.6373		20.40321	214.324			
1309				4.8930705	171.5485		10.5704	199.685		12.59303232	209.338329	209.276795		11.35634	209.8176		20.41816	214.324			
1310				4.8930705	171.5485		10.5785	199.698		12.6028529	208.651975	209.4570506		11.36446	209.9978		20.43311	214.6845			
1311				4.90332851	172.2375		10.5866	199.704		12.61268752	208.651975	209.4570506		11.37258	209.8176		20.44806	214.6845			
1312				4.90332851	171.5485		10.5947	199.709		12.6225081	209.338329	209.0965395		11.3807	209.9978		20.46301	214.5042			
1313				4.90332851	172.2375		10.6028	199.756		12.63234272	210.711036	209.4570506		11.38882	209.9978		20.47796	214.5042			
1314				4.91358653	172.2375		10.6109	199.831		12.64216331	210.711036	209.276795		11.39694	209.8176		20.49291	214.324			
1315				4.91358653	172.2375		10.619	199.885		12.65199793	210.711036	209.6373065		11.40506	209.9978		20.50786	214.324			
1316				4.91358653	171.5485		10.6271	199.953		12.66181851	211.397405	209.276795		11.41318	209.9978		20.52281	214.324			
1317				4.92384454	172.2375		10.6352	199.932		12.67165313	211.397405	209.276795		11.4213	209.9978		20.53776	214.324			
1318				4.92384454	172.9264		10.6433	199.928		12.68147371	211.397405	209.6373065		11.42942	210.1781		20.55271	214.1437			
1319				4.92384454	172.2375		10.6514	200.015		12.69130833	211.397405	209.4570506		11.43754	210.1781		20.56766	213.9634			
1320				4.93410254	172.2375		10.6595	200.071		12.70112891	211.397405	209.817562		11.44566	210.1781		20.58261	213.9634			
1321				4.93410254	172.2375		10.6676	200.139		12.71096354	210.711036	209.817562		11.45378	209.9978		20.59756	213.7832			
1322				4.94436055	172.2375		10.6757	200.207		12.72078412	210.024682	209.817562		11.4619	209.9978		20.61251	213.7832			
1323				4.94436055	172.2375		10.6838	200.236		12.73061172	210.024682	209.4570506		11.47002	209.8176		20.62746	213.6029			
1324				4.95461857	172.9264		10.6919	200.31		12.74043932	209.338329	209.817562		11.47814	209.8176		20.64241	213.4227			
1325				4.95461857	172.9264		10.7	200.404		12.75026692	210.711036	209.6373065		11.48626	209.6373		20.65736	213.6029			
1326				4.95461857	173.6154		10.7081	200.474		12.76009452	209.338329	209.9978176		11.49438	209.6373		20.67231	213.4227			
1327				4.96487658	172.2375		10.7162	200.54		12.76992212	209.338329	210.1780731		11.5025	209.9978		20.68726	213.0622			

D4: Layout of raw quasi-static and strain rate results on forth tab in workbook

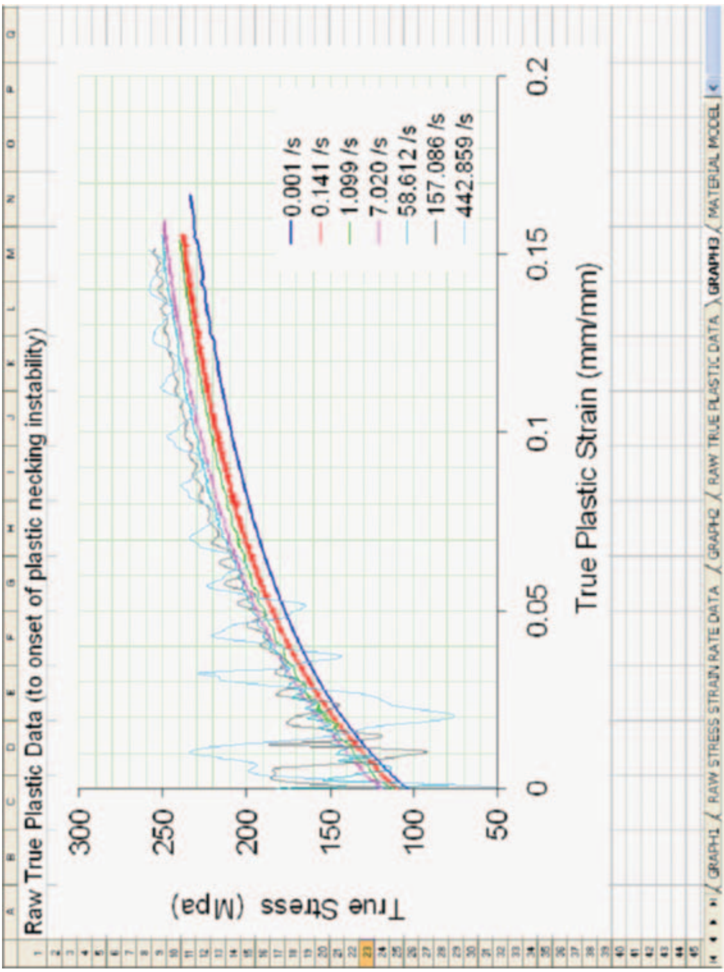


D5: Graph of raw quasi-static and strain rate results on fifth tab in workbook

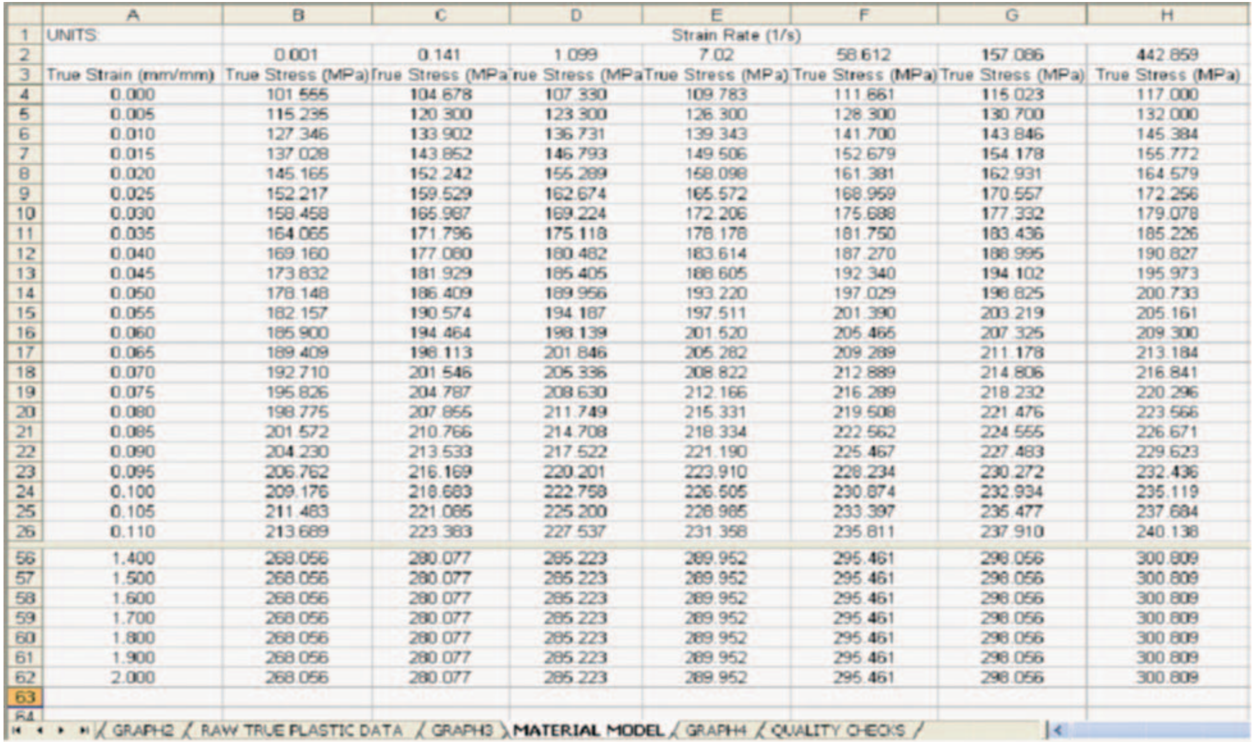


	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Raw Plastic Strain Rate Results (for different strain rates [1/s])														
2	0.001		0.141		1.099		7.02		58.612		157.086		442.859		
3	plastic true strai	true stress [l	plastic true s	true stress [	plastic true strai	true stress [l	plastic true s	true stress [	plastic true s	true stress [	plastic true s	true stress [	plastic true s	true stress [MPa]	
4	0	103.2038	0	109.5436	0	112.069	0	120.9515	0	181.8779	0	103.647	0	35.3301	
5	0.00025132	104.0974	0.000103	109.5548	8.0997E-05	112.6971	0	119.6897	0	181.6977	0.000205	113.7646	0.000205	39.30379	
6	0.00029741	104.2119	0.000103	110.9328	0.00016199	113.2403	0	119.6897	0	180.6161	0.00041	124.9684	0.000205	43.81111	
7	0.00062929	105.2788	0.000103	109.5548	0.00024297	113.5906	0.000103	118.4401	0.000205	178.4897	0.000615	136.3571	0.000409	49.41031	
8	0.00081984	105.8594	0.000205	110.2551	0.00032395	113.9499	0.000103	120.6034	0.000103	174.5054	0.001025	147.7808	0.000614	55.55291	
9	0.00098757	106.3334	0.000205	110.9442	0.00040492	114.3793	0.000205	121.5172	0.000205	168.3933	0.00123	158.4593	0.000818	62.41963	
10	0.00135714	107.3198	0.000103	110.2438	0.00048588	114.8118	0.000205	122.0581	0.000205	161.0013	0.001538	168.2568	0.000921	70.00376	
11	0.00139865	107.446	0.000308	110.2664	0.00056684	115.1623	0.000308	121.1691	0.000308	153.4448	0.001947	176.0918	0.001125	78.49968	
12	0.00178141	108.417	0.000308	110.2664	0.00064779	115.3227	0.000513	121.0136	0.00041	146.2473	0.002357	181.5843	0.00133	87.54057	
13	0.0019977	108.9053	0.000308	109.5773	0.00072873	115.4181	0.000615	120.6652	0.000513	138.6877	0.002664	184.1704	0.001432	96.93629	
14	0.00223919	109.4654	0.00041	110.967	0.00080967	115.6056	0.00082	120.5096	0.000513	130.9327	0.00297	185.4925	0.001636	107.6087	
15	0.00257988	110.3177	0.00041	110.967	0.0008906	115.7831	0.001025	121.256	0.000615	122.2885	0.003277	185.0068	0.00184	118.2854	
16	0.00269035	110.5205	0.00041	110.2777	0.00097153	115.9126	0.00123	122.0028	0.000615	113.6309	0.003788	183.6539	0.002147	129.7023	
17	0.00317751	111.5479	0.00041	111.6562	0.00105245	116.004	0.001435	122.9304	0.000718	105.3449	0.003993	182.4246	0.002351	140.7504	
18	0.00320225	111.5788	0.000615	110.9897	0.00113336	116.2086	0.00164	120.4278	0.000718	97.58832	0.004401	182.4991	0.002657	151.8186	
19	0.00364021	112.6421	0.000615	110.9897	0.00121426	116.6295	0.001742	120.6207	0.00082	91.2842	0.004708	183.6417	0.002861	162.1537	
20	0.00373774	112.8993	0.000615	110.9897	0.00129516	117.1426	0.001845	120.2719	0.00082	85.69169	0.005014	184.7849	0.003167	171.7874	
21	0.0041633	113.7209	0.000615	110.3003	0.00137605	117.6518	0.001947	121.9097	0.000923	81.55077	0.00532	185.0227	0.003473	180.5226	
22	0.00433732	114.0499	0.000718	108.9328	0.00145694	118.161	0.00205	123.7284	0.000923	79.56613	0.005728	182.5602	0.003677	187.6154	
1902			0.077097	206.8782	0.14300364	236.91			0.151202	249.0988					
1903			0.077136	205.3979	0.14307384	236.8725			0.151272	249.1162					
1904			0.077175	205.406	0.14314404	236.9329			0.151342	249.3433					
1905			0.077214	205.414	0.14321424	236.9403			0.151412	249.1509					
1906			0.077253	205.422	0.14328443	236.9166			0.151481	249.1683					
1907			0.077292	205.4301	0.14335461	236.9343			0.151551	249.1857					
1908			0.077332	205.4381	0.14342479	236.9625			0.151621	249.2031					
1909			0.077371	206.1905	0.14349497	236.9665			0.151691	249.0107					
1910			0.07741	206.943	0.14356514	236.9104			0.15176	249.0281					
1911			0.077449	205.4622	0.1436353	236.9062			0.15183	249.2553					
1912			0.077488	205.4703	0.14370546	236.9355			0.1519	249.4825					
1913			0.077527	205.4783	0.14377562	236.9614			0.15197	249.4999					
1914			0.077566	205.4864	0.14384577	236.9699			0.15204	249.5173					

D6: Layout of raw true plastic quasi-static and strain rate results on sixth tab in workbook

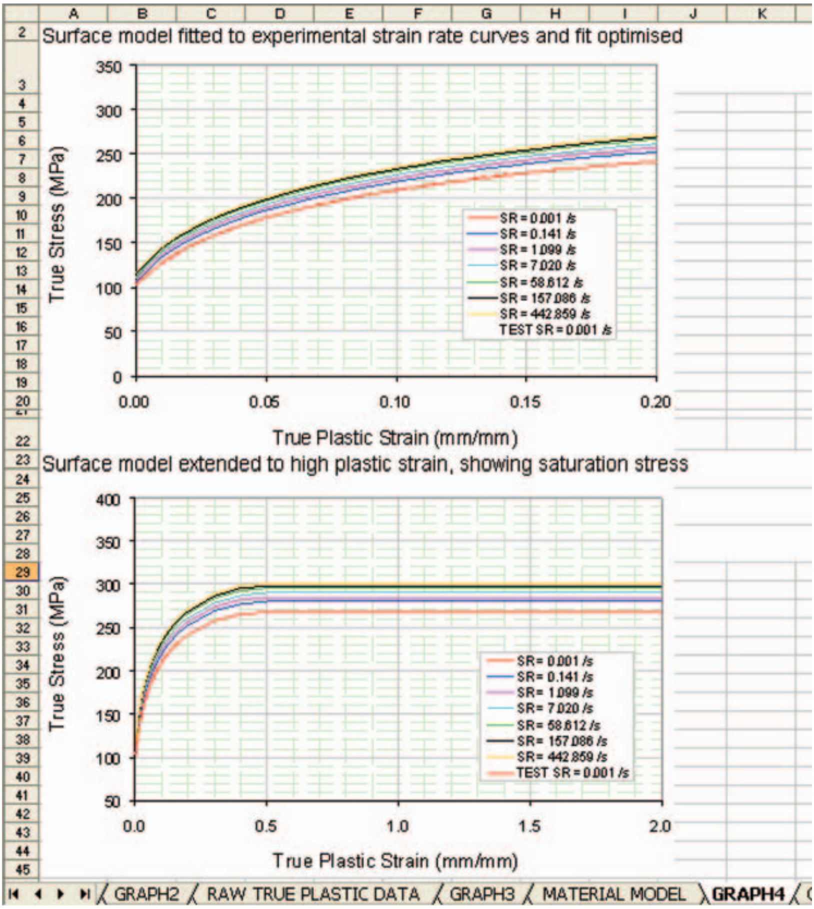


D7: Graph of raw true plastic quasi-static and strain rate results on seventh tab in workbook

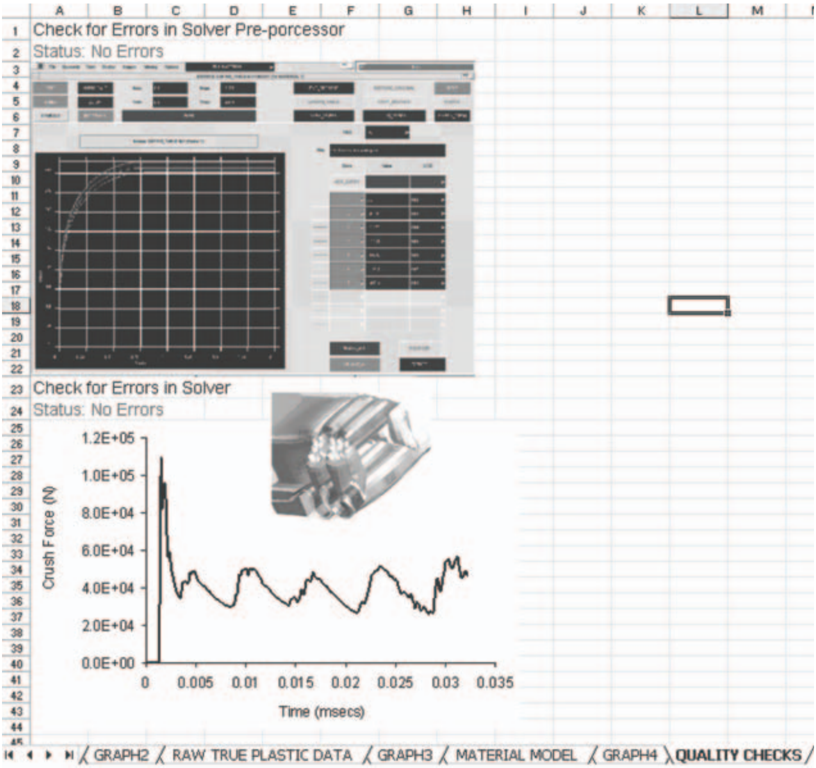


	A	B	C	D	E	F	G	H
1	UNITS:				Strain Rate (1/s)			
2		0.001	0.141	1.099	7.02	58.612	157.086	442.859
3	True Strain (mm/mm)	True Stress (MPa)	True Stress (MPa	rue Stress (MPa	True Stress (MPa)	True Stress (MPa)	True Stress (MPa)	True Stress (MPa)
4	0.000	101.555	104.678	107.330	109.783	111.661	115.023	117.000
5	0.005	115.235	120.300	123.300	126.300	128.300	130.700	132.000
6	0.010	127.346	133.902	136.731	139.343	141.700	143.846	145.384
7	0.015	137.028	143.852	146.793	149.506	152.679	154.178	155.772
8	0.020	145.165	152.242	155.289	158.098	161.381	162.931	164.579
9	0.025	152.217	159.529	162.674	165.572	168.959	170.557	172.256
10	0.030	158.458	165.987	169.224	172.206	175.688	177.332	179.078
11	0.035	164.065	171.796	175.118	178.178	181.750	183.436	185.226
12	0.040	169.160	177.080	180.482	183.614	187.270	188.995	190.827
13	0.045	173.832	181.929	185.405	188.605	192.340	194.102	195.973
14	0.050	178.148	186.409	189.956	193.220	197.029	198.825	200.733
15	0.055	182.157	190.574	194.187	197.511	201.390	203.219	205.161
16	0.060	185.900	194.464	198.139	201.520	205.466	207.325	209.300
17	0.065	189.409	198.113	201.846	205.282	209.289	211.178	213.184
18	0.070	192.710	201.546	205.336	208.822	212.889	214.806	216.841
19	0.075	195.826	204.787	208.630	212.166	216.289	218.232	220.296
20	0.080	198.775	207.855	211.749	215.331	219.508	221.476	223.566
21	0.085	201.572	210.766	214.708	218.334	222.562	224.555	226.671
22	0.090	204.230	213.533	217.522	221.190	225.467	227.483	229.623
23	0.095	206.762	216.169	220.201	223.910	228.234	230.272	232.436
24	0.100	209.176	218.683	222.758	226.505	230.874	232.934	235.119
25	0.105	211.483	221.085	225.200	228.985	233.397	235.477	237.684
26	0.110	213.689	223.383	227.537	231.358	235.811	237.910	240.138
56	1.400	268.056	280.077	285.223	289.952	295.461	298.056	300.809
57	1.500	268.056	280.077	285.223	289.952	295.461	298.056	300.809
58	1.600	268.056	280.077	285.223	289.952	295.461	298.056	300.809
59	1.700	268.056	280.077	285.223	289.952	295.461	298.056	300.809
60	1.800	268.056	280.077	285.223	289.952	295.461	298.056	300.809
61	1.900	268.056	280.077	285.223	289.952	295.461	298.056	300.809
62	2.000	268.056	280.077	285.223	289.952	295.461	298.056	300.809
63								

D8: Layout of material model results on eighth tab in workbook



D9: Layout of graphs of material model on ninth tab in workbook



D10: Layout of graphs on tenth tab in workbook

Annex D11: Example layout of material card for use in LS-DYNA software

```
$
$ =====================
$ MAT24 Material Card
$ =====================
$
$
*MAT_PIECEWISE_LINEAR_PLASTICITY_TITLE
TITLE ….MATERIAL DETAILS .........
$      MID   Density         E Poisson'sR YieldStress
$                                    MAT_TH_YIELD
         1   2.75E-9   69000.0       0.3  101.5546       0.0       0.0       0.0
$SR Param C         P  LC (Load curve or table ID)
       0.0       0.0         1         0       1.0
       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0
       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0
$
*DEFINE_TABLE
$
         1
$
$ List of factors:
$
               0.000
               0.141
               1.099
               7.020
              58.612
             157.086
             442.859
$
*DEFINE_CURVE
$    1   ][    2   ][    3   ][    4   ][    5   ][    6   ][    7   ]
$                          MAT_TH_YSCALE        MAT_TH_YIELD
         2         0       1.0       1.0       0.0       0.0         0
0,101.5546489
0.005,115.2347299
0.01,127.3461175
0.015,137.0284152
0.02,145.1653003
0.025,152.2171803
0.03,158.4578075
0.035,164.0646584
0.04,169.1600808
0.045,173.8323879
0.05,178.1476493
0.055,182.1567318
0.06,185.8997286
0.065,189.4088683
0.07,192.7104917
0.075,195.826438
0.08,198.7750397
0.085,201.5718543
0.09,204.2302118
0.095,206.7616318
0.1,209.1761462
0.105,211.4825517
0.11,213.6886105
```

```
0.115,215.8012112
0.12,217.8264989
0.125,219.7699818
0.13,221.6366191
0.135,223.4308939
0.14,225.1568741
0.145,226.8182641
0.15,228.4184481
0.155,229.9605274
0.16,231.447352
0.18,236.8917499
0.185,238.1379878
0.19,239.3421023
0.195,240.505781
0.2,241.6306027
0.3,257.7349345
0.4,265.5114256
0.5,268.056209
0.6,268.056209
0.7,268.056209
0.8,268.056209
0.9,268.056209
1,268.056209
1.1,268.056209
1.2,268.056209
1.3,268.056209
1.4,268.056209
1.5,268.056209
1.6,268.056209
1.7,268.056209
1.8,268.056209
1.9,268.056209
2,268.056209
$
*DEFINE_CURVE
$    1   ][    2   ][    3   ][    4   ][    5   ][    6   ][    7   ]
$                          MAT_TH_YSCALE        MAT_TH_YIELD
         3         0       1.0       1.0       0.0       0.0         0
0,104.6777702
0.005,120.3
0.01,133.90192
0.015,143.8524199
0.02,152.2420976
0.025,159.5287716
0.03,165.9870806
0.035,171.7961697
0.04,177.0800945
0.045,181.9287109
0.05,186.409427
0.055,190.5742557
0.06,194.4642695
0.065,198.1125357
0.07,201.5461166
0.075,204.7874753
0.08,207.8554873
0.085,210.7661849
0.09,213.533316
0.095,216.1687694
0.1,218.6829054
0.105,221.0848138
0.11,223.3825195
```

```
0.115,225.5831478
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0.13,231.6629641
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0.145,237.0630724
0.15,238.7309762
0.155,240.3384249
0.16,241.8883752
0.165,243.3835523
0.17,244.8264744
0.175,246.2194739
0.18,247.5647156
0.185,248.8642137
0.19,250.1198455
0.195,251.3333642
0.2,252.5064099
0.3,269.3060289
0.4,277.4211904
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0.7,280.0767847
0.8,280.0767847
0.9,280.0767847
1,280.0767847
1.1,280.0767847
1.2,280.0767847
1.3,280.0767847
1.4,280.0767847
1.5,280.0767847
1.6,280.0767847
1.7,280.0767847
1.8,280.0767847
1.9,280.0767847
2,280.0767847
$
*DEFINE_CURVE
$    1    ][    2    ][    3    ][    4    ][    5    ][    6    ][    7    ]
$                          MAT_TH_YSCALE          MAT_TH_YIELD
         4         0       1.0       1.0       0.0       0.0          0
0,107.3299584
0.005,123.3
0.01,136.7312226
0.015,146.7932865
0.02,155.2887073
0.025,162.6739587
0.03,169.2239
0.035,175.1182871
0.04,180.4818371
0.045,185.405018
0.05,189.9557771
0.055,194.1865927
0.06,198.1389382
0.065,201.8462256
0.07,205.335815
0.075,208.630428
0.08,211.7491654
0.085,214.7082573
0.09,217.5216258
0.095,220.201314
0.1,222.7578194
```

```
0.105,225.2003547
0.11,227.5370551
0.115,229.775145
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0.125,233.9806239
0.13,235.9590068
0.135,237.8609342
0.14,239.690684
0.145,241.4521533
0.15,243.1489037
0.155,244.7842006
0.16,246.3610457
0.165,247.8822059
0.17,249.3502384
0.175,250.7675116
0.18,252.1362243
0.185,253.4584223
0.19,254.7360123
0.195,255.9707753
0.2,257.1643777
0.3,274.2604551
0.4,282.5199874
0.5,285.2226683
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0.7,285.2226683
0.8,285.2226683
0.9,285.2226683
1,285.2226683
1.1,285.2226683
1.2,285.2226683
1.3,285.2226683
1.4,285.2226683
1.5,285.2226683
1.6,285.2226683
1.7,285.2226683
1.8,285.2226683
1.9,285.2226683
2,285.2226683
$
*DEFINE_CURVE
$    1    ][    2    ][    3    ][    4    ][    5    ][    6    ][    7    ]
$                          MAT_TH_YSCALE        MAT_TH_YIELD
         5         0       1.0       1.0       0.0       0.0         0
0,109.7833679
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0.01,139.3433113
0.015,149.5062265
0.02,158.0975395
0.025,165.5723726
0.03,172.2057088
0.035,178.1778128
0.04,183.6139738
0.045,188.6051982
0.05,193.2199107
0.055,197.5110049
0.06,201.5203125
0.065,205.281555
0.07,208.8223605
0.075,212.1656835
0.08,215.3308285
0.085,218.3342041
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0.125,237.9001206
0.13,239.909073
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0.14,243.6986018
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0.155,248.871462
0.16,250.4729541
0.165,252.0179272
0.17,253.5089737
0.175,254.948495
0.18,256.338721
0.185,257.681726
0.19,258.979444
0.195,260.2336813
0.2,261.446128
0.3,278.814009
0.4,287.2058866
0.5,289.9516491
0.6,289.9516491
0.7,289.9516491
0.8,289.9516491
0.9,289.9516491
1,289.9516491
1.1,289.9516491
1.2,289.9516491
1.3,289.9516491
1.4,289.9516491
1.5,289.9516491
1.6,289.9516491
1.7,289.9516491
1.8,289.9516491
1.9,289.9516491
2,289.9516491
$
*DEFINE_CURVE
$    1   ][    2   ][    3   ][    4   ][    5   ][    6   ][    7   ]
$                          MAT_TH_YSCALE        MAT_TH_YIELD
         6         0       1.0       1.0       0.0       0.0         0
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0.005,128.3
0.01,141.7
0.015,152.6791581
0.02,161.3806512
0.025,168.9586365
0.03,175.6881491
0.035,181.7499846
0.04,187.2700574
0.045,192.3399715
0.05,197.0286872
0.055,201.3895662
0.06,205.4648464
0.065,209.2886008
0.07,212.8887631
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0.11,235.8112357
0.115,238.1234588
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0.15,251.9445406
0.155,253.6349982
0.16,255.2651198
0.165,256.8377545
0.17,258.3555359
0.175,259.8209037
0.18,261.2361233
0.185,262.6033025
0.19,263.9244064
0.195,265.2012709
0.2,266.4356134
0.3,284.1193584
0.4,292.6650101
0.5,295.4607276
0.6,295.4607276
0.7,295.4607276
0.8,295.4607276
0.9,295.4607276
1,295.4607276
1.1,295.4607276
1.2,295.4607276
1.3,295.4607276
1.4,295.4607276
1.5,295.4607276
1.6,295.4607276
1.7,295.4607276
1.8,295.4607276
1.9,295.4607276
2,295.4607276
$
*DEFINE_CURVE
$    1   ][    2   ][    3   ][    4   ][    5   ][    6   ][    7   ]
$                          MAT_TH_YSCALE        MAT_TH_YIELD
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0.02,162.931227
0.025,170.5573554
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0.04,188.9949618
0.045,194.1017275
0.05,198.8251159
0.055,203.2187039
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0.075,218.2322815
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0.085,224.5553315
0.09,227.483149
0.095,230.2723613
0.1,232.9337999
0.105,235.4769768
0.11,237.910296
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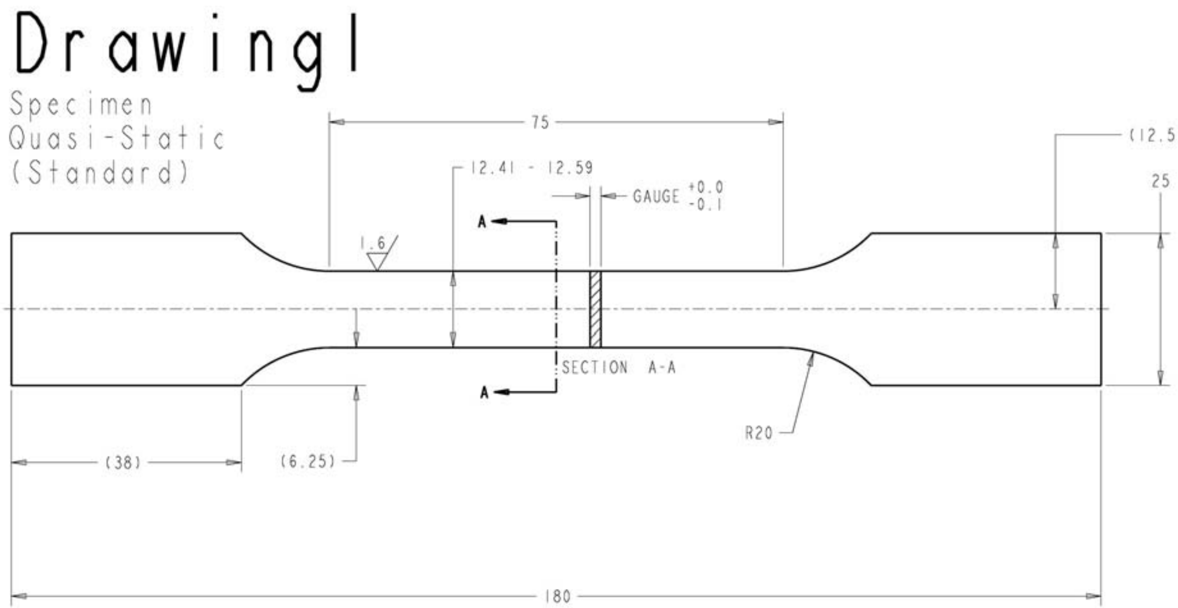
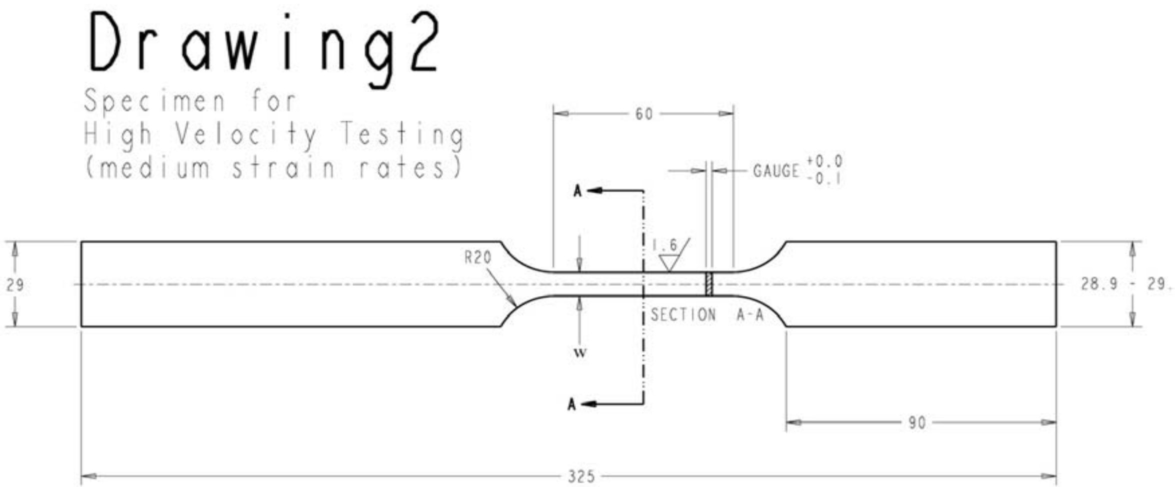
Annex E: Technical Drawings of Test Specimens



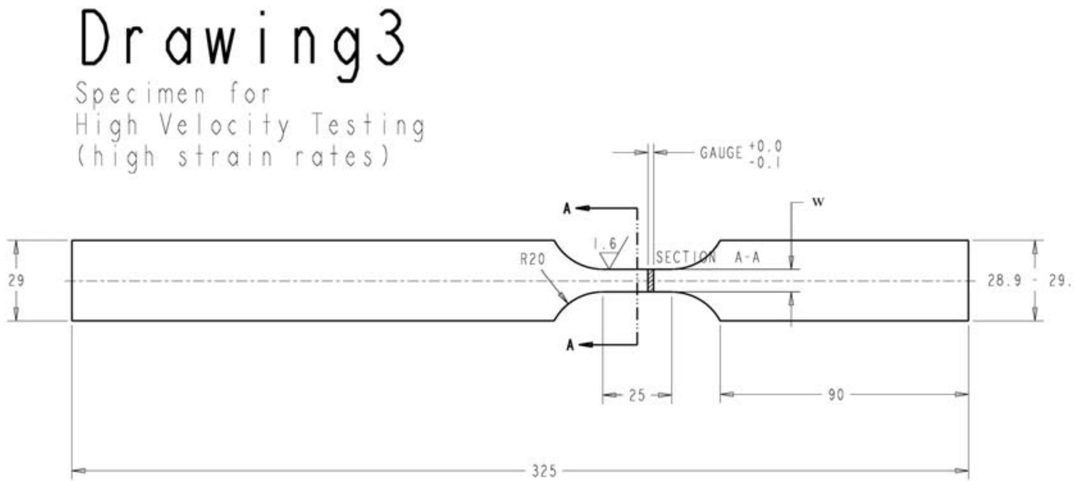
Specimen used for quasi-static strain rates (dimensions in mm)

Annex E: Technical Drawings of Test Specimens



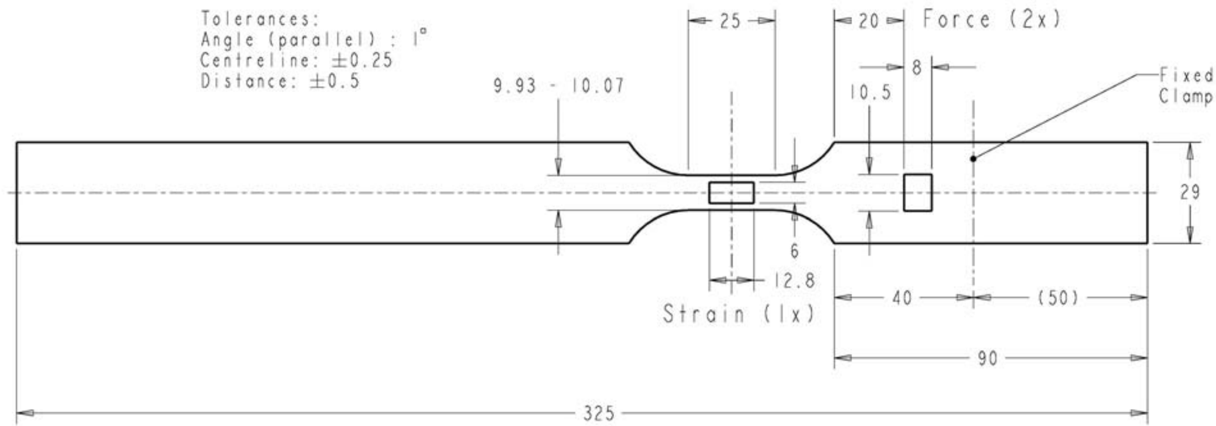
Specimen used at low to intermediate strain rates (dimensions in mm)

Annex E: Technical Drawings of Test Specimens



Specimen used at intermediate to high strain rates (dimensions in mm)

Annex E: Technical Drawings of Test Specimens



Position of instrumentation on test specimen (dimensions in mm)

Annex F: Summary of IARC Machine Settings used for Strain Rate Testing

Test Speed [mm/s]	0.05	10	80	500	5000	6000	15000
Gauge Length [mm]	75	60	60	60	60	25	25
Theoretical Strain Rate [1/s]	0.001	0.17	1.33	8.33	83.3	240	600
Approximate Measured Strain Rate (0.5 to 5 % Strain) [1/s]		0.13	1.2	6.4	65	170	425
Actuator Accel. [mm]	Clamped	Clamped	40	80	80	100	105
Machine Control	Displ. Control	Closed Loop	Closed Loop	Closed Loop	Closed Loop	Open Loop	Open Loop
Trigger	auto	Position	Position	Position	Drive	Drive	Drive
Strain Sensor	Clip Gauge	Strain Gauge	Strain Gauge	Strain Gauge	Strain Gauge	Strain Gauge	Strain Gauge
Force Sensor	Load Cell	Kistler Piezo	Kistler Piezo	Kistler Piezo & 2 Strain Gauges	2 Strain Gauges	2 Strain Gauges	2 Strain Gauges
DAQ Frequency	1/20 N or 1/s	50000 / total actuator displ.	50000 / total actuator displ.	50000 / total actuator displ.	50000 / total actuator displ.	50000 / total actuator displ.	50000 / total actuator displ.
Specimen							

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The aim of this book is to provide guidelines to generate tensile strain rate test data for ferrous and non-ferrous sheet metals for use in finite element based automotive crash simulation tools. Specifically, measurement of the strength hardening in a sheet material resulting from strain rate testing using a high speed servo hydraulic test machine. Additionally, to provide guidelines to process raw test data, fit material model and format this data for application in crash simulation tools.

It is not within the scope of these recommendations to advocate a material model to fit to strain rate test results, although useful models are referenced. Rather to give guidance on the error allowance in fitting model to test results. These guidelines are expected to have broader application in the transport industry sector.

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