Characterisation of high strain rate material behaviour for high-speed forming and cutting applications

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Abstract. Determination of the material behaviour for high speed forming processes is challenging due to high process velocity and small specimen geometry in experimental analysis. This paper proposes two different material characterisation concepts for high strain rates at $10^3$ s$^{-1}$ and higher, namely a pneumatically driven device and an electromagnetically accelerated hammer, for obtaining experimental values. Furthermore, two measuring principles of the hammer velocity and displacement are presented and compared. The authors describe a measurement system with an acceleration sensor for the pneumatic device and a shadowing principle for the electromagnetically driven concept. Using the measured data, material parameters are iteratively adapted in an optimisation procedure until an objective function, comparing the difference between numerical and experimental results, is satisfied. In this case the parameter identification is applied on a strain rate dependant flow curve approximation based on Johnson-Cook.

1. Introduction

High speed processes can lead to economical and technological benefits [1]. As described in [2] high speed effects enable the manufacturing of products with higher quality and without any additional finishing in contrast to conventional processes as confirmed in the investigations of Jana and Ong in [3]. Furthermore, forming at high velocity enables improved material utilisation, reduction of needed process forces and allows to form materials that are not formable with conventional processes as described in [1]. High strain rates of $500$ s$^{-1}$ and higher can result in scaling up the flow stresses compared to quasi-static forming or cutting of strain rate depending materials. Regarding strain rate depending material behaviour Psyk et al. has shown in [4] that forming with high strain rates can lead to extended forming limits. In addition, high velocity allows much more geometrically complex shapes [5]. Modelling high speed processes in detail requires suitable data of the plastic flow and failure behaviour for high strain rates [6].

The difficulty in high-speed material characterisation is the measurement of material characterising quantities due to the limited size and accessibility of the specimen. An alternative approach to direct measurement of stress and strain is an inverse parameter identification for determination of material characteristics. This paper proposes two test setups for a wide range of strain rates from $500$ up to $10^5$ s$^{-1}$. The setup for strain rates of up to $1000$ s$^{-1}$ is based on a pneumatic accelerator, developed for high-speed
cropping, which was first reported in [7] and the second setup uses an electromagnetic acceleration for strain rates up to $10^5$ s$^{-1}$.

2. High Speed Testing Concepts

The pneumatic driven setup based to [7] allows high-speed material characterisation on conventional presses. The test setup, presented in Figure 1, is filled with compressed air and reaches a hammer velocity up to 20 m/s depending on the initial pressure. When pressurised air streams into the piston it moves to its upper limit. While the press pushes the piston downwards, the air between the piston and the hammer cover is compressed. Now the hammer is supported by air pressure acting on the hammer flange. Continuing the stroke, the highly compressed air streams into the hammer chamber, the space between hammer cover and hammer, through the neck of the lifting rod. Subsequently the hammer moves downwards and the compressed air rushes through the air inlet ports into the hammer chamber. Consequently, the hammer is accelerated and impacts the specimen at very high speed.

The electromagnetic test setup depicted in Figure 2 consists of a cylindrical coil including a special field shaper, a solid rod for force measurement, an electromagnetically driven flyer equivalent to the pneumatically driven hammer and the housing of the complete setup. Due to the induced magnetic field and the corresponding current in the flyer, the flyer is accelerated according to the resulting Lorentz force and impacts the specimen after a distance of acceleration.

![Figure 1. Pneumatically driven setup](image1)

![Figure 2. Electromagnetically driven setup](image2)

2.1. Force Measurement

Due to the different physical principles and strain rates of the two presented accelerators, different measuring concepts are used for the experimental measurement of displacement and force data. For precise recording of the measuring signals, all sensors are characterised by a sample rate of 50 kHz for the pneumatic accelerator and 2 MHz for the electromagnetically one. For measuring the force affecting the specimen, the pneumatic accelerator is equipped with a piezo load cell (9041A, KISTLER) mounted in the specimen holder. The piezo load cells with a natural frequency up to 65 kHz is essential in fact of the high hammer speed of up to 20 m/s. Due to the high speed impact in case of the EM accelerated system the usage of piezo load cell is not reasonable. For this reason, a solid rod with a strain gauge half bridge with bending compensation allows measuring the fast rising force signal.

2.2. Displacement Measurement

The displacement of the electromagnetically driven hammer is measured via a shadowing principle where a parallel shaped laser beam is directed through the hammer route. After passing the specimen, the parallel light affects a photoelectric cell, which emits a current proportional to the light intensity. According to the hammer position, the laser beam is shaded by the hammer and the signal of the photoelectric cell changes. In order to prevent the magnetic field from affecting the measurement signal a
plastic optical fibre bundle is used to guide the light to the photoelectric cell placed out of the magnetic field range. The displacement of pneumatically accelerated hammer is measured by an acceleration sensor (KD91, MMF Radebeul) with a maximum measurable acceleration of 25,000 m/s². The time dependent displacement is calculated by integrating the measured signal twice. Advantage in contrast to the EM acceleration regarding the position of the sensors is that the measured signal is not superimposed by an interfering electromagnetic field. The simple mounting of the accelerometer by screwing is advantageous compared to shadowing principle setup that needs a complicated installation. It is necessary that the laser beam is parallel to the specimen geometry and horizontal oriented to capture the correct hammer displacement. The exact positioning of the shadowing principle setup regarding the specimen geometry is important for measuring exactly the displacement due to the kinematic of the pneumatic accelerator. However, the signal of the acceleration sensor is affected by vibrations caused by movement of the press and by the strong impulse when the hammer impacts the specimen. Due to the necessary integration of the accelerometer signal the displacement-time course is smoothed. For evaluating the two measurement principles both setups are mounted on the pneumatic setup, depicted in Figure 3.

![Figure 3. Pneumatic accelerator equipped with accelerometer and shadowing principle setup](image)

The typical course of the measurement signal is depicted in Figure 4 for both principles. The shadowing principle delivers a simple evaluable signal with easy detectable stages of the hammer displacement, Figure 4b. The laser recipient is fitted on the specimen holder that the lower edge of the beam defines the lowest hammer position equal to the end of the maximum forming stage. Based on the geometry of the laser beam and the known specimen geometry the starting position of the forming process is known. In contrast, the signal of the accelerometer is complex and the stages of the hammer displacement are not clearly apparent only based on the acceleration signal. For determination of the specimen affecting hammer displacement the signal of the hammer affecting hammer force is necessary. The moment of the raising force signal characterises the beginning deformation of the specimen. The end of the forming stage is described by the velocity equal to zero when the force signal reaches its maximum value. The integration of the acceleration signal delivers the hammer velocity and finally the hammer displacement. It is necessary to detect the beginning and end of the forming stage to get the right displacement of the specimen by integration. Figure 4a depicts the time depending course of the measured signals force and acceleration and the resulting hammer speed and displacement. The stages of the hammer during the high speed process from the first acceleration till the end of deformation are of contrasting colour. The acceleration signals results in a displacement of 2.40 mm while the shadowing measurement delivers 2.75 mm. The measured displacement at the specimen amounts 2.60 mm. The differences are due to the orientation of the laser beam and the scattered light which influences the receiver of the
shadowing setup. In case of the acceleration measurement is the detecting of the beginning deformation need a critical look and how far the vibrations of the press influence the accelerometer signal.

![Graphs showing measurement signals](image)

**Figure 4:** Measurement signal of a) the accelerometer and b) shadowing principle

### 3. Inverse Parameter Identification

As explained in [8], an inverse numerical simulation is applied in order to identify constitutive parameters for the material hardening and failure.

In order to investigate the sensitivity of the measurement signals, which serve as input data for the inverse simulation, extensive pre-simulations of the test setup have been carried out in advance [9]. These numerical sensitivity tests were completed by simulations of the inverse parameter identification problem using LS-OPT [10] to test the capability of this optimization software for our specific problem. Due to the complexity of high speed problems we focused on the electromagnetic driven test setup with a hammer velocity of up to 50m/s assuming that pneumatic accelerated test setup having a lower velocity of 5-10m/s is less problematic. **Figure 5a** depicts the used FEM model in the optimization. It consists of the measurement body, the specimen and the hammer, the latter assumed as rigid body. Measurement points where displacement and elastic strain is determined in the simulation, are the bottom of the hammer and the application position of the strain gauges on the measurement body. The constitutive model of the specimen is Johnson-Cook with an additional non-stress-state dependent failure strain $\varepsilon_f$.

The test curve, **Figure 5b**, blue curve, is calculated using an initial simulation of the problem with an assumed optimisation parameter set $P_{\text{e}}[A=87.6 \text{ MPa, } B=434 \text{ MPa, } n=0.43, \varepsilon_f=0.3]$ as target parameters. The failure strain $\varepsilon_f$, assumed as independent of the stress state describes the failure behaviour of the material. This value influences the decreasing force curve or elastic strain curve in simulation, see **Figure 5b**. Therefore, virtual measurement data serves as input during this investigation which will be replaced by real measurement data in the ongoing project step. In order to consider non-ideal virtual
curves, the ideal curve was changed by smoothing. Figure 5b, red curve, which is considering conceivable deviations in the measurement. The black dotted curve in Figure 5b is the resultant curve of a simulation with the optimal target parameters found if the non-ideal curve (red) is assumed as test curve. The good accordance of the test curve and the resultant curve points to a flat objective function with small gradients around the minimum.

The optimization was performed by LS-OPT which offers a beneficial interaction to LS-DYNA and different optimization algorithms. Various tests have been carried out including direct gradient based optimization algorithms, Monte-Carlo procedures and gradient based meta model algorithms. It turned out that the meta model algorithm was the most effective and finds the optimum in less than 15 optimization steps. Figure 6 depicts exemplary the optimization history of the parameters A and B of the Johnson-Cook constitutive model, whereby the starting values were set far away from the optimum. The red optimization history in Figure 6 based on the non-ideal smoothed test curve and the blue one on the ideal test curve.
4. Conclusion
The paper shows an approach for an inverse parameter identification at high strain rates. Two different acceleration setups were built to cover a large range of strain rate for upcoming test. The realized measuring strategy is explained and the challenges concerning the measurement of the displacement are described. Especially the kinematics of the pneumatic accelerator combined with an accelerometer for determination of the displacement is difficult. The shadowing principle is more complicate in mounting but it is significant easier in evaluating the measurement signal. Additionally, the analysis of the acceleration signal shows a deceleration of the pneumatically driven hammer due to friction in the device. On this account an optimization of the pneumatic accelerator is necessary regarding the aspired maximum hammer velocity of up to 20 m/s. Nevertheless, the developed experimental and inverse numerical approach in combination enables the identification of material model parameters at high strain rates.

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