Recent Enhancements to Determine Flow Stress Data in High Speed Compression Tests*

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Abstract

The accuracy in numerical simulation and physical models is increasing continually. For this reason, the attention to the measurement of flow stress fields at hot forming conditions rises presently. The determination of flow curves at small and middle strain rates up to 100 /s has become a standard procedure. In the wide range between strain rates of 100 /s up to 500 /s no accurate experimental data of compression tests by the use of servo-hydraulic testing systems exists to date. In this context, the IBF investigated how compression tests especially on servo hydraulic testing-machines can be developed in order to expand the range of flow-curve fields clearly above 100 /s with strains up to φ = 0.7. The maximum tool speed of the IBF testing machine is 3000 mm/s.

This presentation shows the advances realised in this field. During the research activities, the existing servo-hydraulic high-speed testing machine has been optimised and new post processing techniques have been developed. Hence, valid flow stress values can now be determined up to strain rates of 300 /s in compression tests on the utilised servo hydraulic testing system. Present investigations have the aim to determine absolutely reliably flow stress data even for strain rates up to 500 /s.

Keywords:

Forming, Metal, Flow Stress, Measuring Instrument

1 Introduction

In this research project the fundamentals of the performance, evaluation, and analysis of compression tests on servo-hydraulic systems with completely new test parameters are developed. This was done especially for experiments in the range of high strain rates at

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large strain values in axisymmetric compression tests. Primarily, hot dynamic compression-tests are carried out at temperatures up to 1250 °C. These kinds of tests are important for the determination of flow-stress curves at high temperatures to obtain a basis for the FEM simulation of hot forming processes. Thereby, the progress in the experimental set-up and further possibilities with regard to the realisation of higher strain rates are most important. Tests with strain rates of up to 100 /s are performed on the installed servo hydraulic testing machine SERVOTEST by default. The usability of data determined on standard path controlled test methods in the range of strain rates higher than 50 /s was not assured at the beginning of this research project.

The above mentioned values in strain rates, or even higher strain rates can be found "locally" in modern industrial forming processes, like rod rolling or profile rolling, hammer forging, die forging, as well as extrusion. The goal of this project is to explore how to reach higher strain rates of about 200 /s to 500 /s or even up to 1000 /s. Then, modern industrial forming processes such as tandem mills can be very reliably simulated. Meanwhile, the set-up of the servo-hydraulic testing-machine is optimised to perform compression tests in the range of 100 /s to 300 /s at room temperature. Therefore, the new developed optimised testing methods close the gap in determination of flow curves between tests at low and medium strain rates on servo-hydraulic respectively mechanical machines and experiments at highest strain rates on Split-Hopkinson Pressure Bars (SHPB) [9] or on dynamic expansion test-systems. A further aim is to standardise the measurement of flow curves by compression tests at room temperature and at high temperatures in the range of high strain rates.

2 Used Testing Equipment

2.1 Hydraulic Testing Machine

The used SERVOTEST testing-system was installed at the IBF in 1995, see [6,8]. The servo hydraulic testing machine has a maximum force of 1200 kN and a maximum tool-velocity of 3000 mm/s. A miniaturisation of the specimen geometry down to $h_0 = 6$ mm and $d_0 = 4$ mm enables even tests with maximal nominal strain rates of 500 /s. Further, it was verified to what extend a variation of the specimen geometry influences the determination of flow stress data, e.g. [6,12,13].

2.2 Data Acquisition

The data logging is automatically carried out with separate A/D converters each one for the load, velocity, displacement, and temperature channel. Sample frequencies up to 20.48 kHz can be realised for each of the four channels above mentioned which is sufficient for the regarded high speed compression tests. Furthermore, the recently upgraded system enables the measurement with three additional thermocouples. In general, a standard load cell measures the forces on the basis of resistive wire strains in a shear-web-design. The sensors for velocity and displacement are the so-called Linear Variable Differential Transformer (LVDT) and the Linear Velocity Transducer (LVT). Both sensors operate inductively. The temperature is optionally measured with thermocouples.

3 Problem Description

Using the standard test set-up for cold compression tests at high strain rates, the measured load signal (Figure 1a) oscillates with a frequency about 1715 Hz due to the sudden impact [6,7,11,10]. The particular frequencies depend on the specific set-up of the testing system, [6]. No ringing in the load signal (Figure 1b) is recorded for “low” strain rates up to 50 /s, [6].

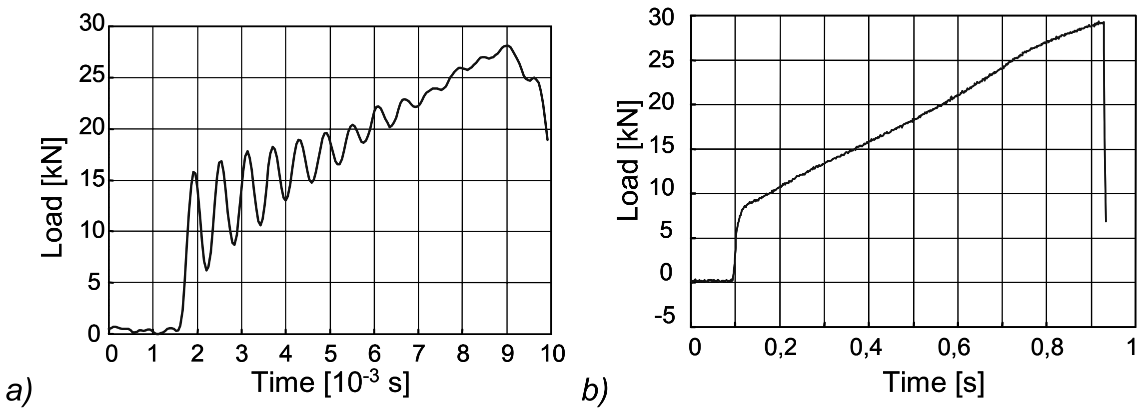


Figure 1: *Load signal of an axisymmetric (uniaxial) compression test, 100Cr6, 25°C,* h_0 *= 10 mm,* d_0 *= 7 mm at a strain rate a) 300 /s and b) 1 /s*

First of all, the reason for the ringing was investigated. Thence, there could not be the possibility to determine accurate flow curve data from measured signal recorded during compression tests at high tool velocities. Insofar, the source of ringing was necessarily spied out. Furthermore, it was verified, in how far the load ringing can influence the actual forming process. The goal was either to suppress the ringing as good as possible or to develop an adequate post processing method in order to filter the ringing. The use of a signal filter is only feasible if the described oscillating phenomena can be separated from the actual forming process.

4 Troubleshooting

Due to the above described problem two tasks were carried out. On the one hand, the used testing set-up actually was analysed and modified. On the other hand, the existing post processing was replaced by a new and better suited method. In the following, the two traced scopes of duties will be described.

4.1 Data Post Processing

The vibration of the load signal is the main problem in determining flow curves by the use of (uniaxial) compression tests at elevated strain rates. Firstly, this problem has to be solved. Subsequently, other influences on the accuracy [4] of determining flow curves - like friction or dissipative heat generation - can be investigated. The use of attenuators in order to reduce the oscillations is not expedient. The reason being that any additional dashpot will absorb a fraction of the force applied on the load cell. Measuring any instantaneous dynamic force value necessarily requires that the frequency response of the force measurement system must be sufficient in order to follow the rapidly changing force [3]. Any supplementary damping downgrades the inherent frequency response of each measurement system. For this reason, the ringing of the load signal has to be filtered out in detail. Standard algorithms used up to now are inapplicable because they falsify the original signal so much that an inference to the underlying excitation caused by the impact and the subsequent deformation of the sample is impossible [1,6].

If standard filtering techniques are used on the ringing load signal, the important information about the rise in the load at the beginning of the test is lost. General filtering techniques, like the use of low pass filters, are not applicable because the frequency response of the measurement system is close to the time scale of the initial load rise. In general, each filtering of signals implicates a delay and a phase shift, whereby in most of the cases the corrected signals are distorted. Hence, investigations to develop new methods of correcting measured data were required (by any means).

Another strategy of filtering the data is based on an idea by SERVOTEST [2]: To simplify the problem, a single undamped harmonic oscillation is assumed. This supposition corresponds to the above-mentioned model of a non-damped harmonic oscillation. Then the answer of the load sensor is

$$F_a(t) = F_e(t) + F_0 \cdot sin(\omega_0 t) \tag{1}$$

Hence, F_a is the answer signal detected by the load cell, F_e is the excitation force belonging to the underlying compression of the specimen, F_0 is the initial ringing amplitude, and ω_0 is the specified harmonic frequency.

Using the second derivate of (1) and combining the result with the original equation (1) an algebraic transposition results in

$$\frac{1}{\omega_0^2} \cdot \left(\frac{d^2}{dt^2} F_a(t) - \frac{d^2}{dt^2} F_e(t) \right) = F_e(t) - F_a(t) \tag{2}$$

Regarding now the direct neighbourhood of a single data point in the digitally recorded load signal. It can be assumed that the second derivative of the real excitation force source is negligible, so that the excitation force can be calculated from the recorded signal of the load sensor F_a and the determined excited natural frequency ω_0, according to

$$F_e(t) = F_a(t) + \frac{1}{\omega_0^2} \cdot \left(\frac{d^2}{dt^2} F_a(t) \right) \tag{3}$$

The thus corrected answer signal of the sensor F_a is the first approximation of the real force F_e which is necessary to compress the specimen with high impact tool velocities. The problem of an unknown amount of masses added to the sensor system is successfully avoided with this method (3).

The described calculation considers neither damping effects nor multiple frequencies in the oscillating signal. Consequently, the described method was optimised.

The results of the system analysis show that the oscillations in the load signal of high speed compression tests contain only the excited natural frequencies of the whole experimental set-up [6,7,10]. The number and amplitudes of registered frequencies depend mainly on the initial impact forces and the different set-up principles. The recorded signal is a superposition of damped harmonic oscillations with linear independently excited natural frequencies $\omega_{0,i}$.

$$F_a(t) = F_a(t) + \sum_i F_{0,i} \cdot e^{\delta_i \cdot t} \cdot sin(\omega_{0,i} \cdot t) \quad (4)$$

The above described correction (3) can easily be applied to signals with more than one excited natural frequency separately for each estimated natural frequency in different steps. Further investigations also indicated that a multiple exertion of this correction calculation can sufficiently reconstruct the exciting force out of damped oscillations in the answer load signal as well.

Even the new extension of the frequency correction method does not consider the load cell's inertia correctly, i.e. the delayed answer of the sensor due to the sudden impact. The answer time of the load cell limits the detection of the generally steep ascending slope of the (deforming) load during a high speed compression test. In comparison to the determined stress-strain curves at low strain rates, the stress curves at high strain rates show a gradient slope that is too low if they are smoothed. Because the most important aspect of the analysis is a precise definition of the yield point, the correction of the signal must maintain the information of the initial load gradient. Therefore, the correction algorithm was again optimised. Because of the delayed answer of each used sensor, the real excitation force will be only followed by the recorded signal due to the physical limits of the used sensors. The quality of this effect depends mainly on the reaction time of the used sensor-system. Therefore, no sensor will be able to exactly reproduce the original unknown excitation source.

Regarding a thought experiment where the excitation force applied on the sensor is a rectangle signal, each sensor containing masses would also respond oscillating to this theoretical excitation by delay [6]. In order to have a reproducible correction, the first turning point after the initial load rise is chosen where the correction of the answer signal should start. With reference to a plain sine curve, this position is a neutral point, i.e. the first overshoot is kept out of the maintained uncorrected signal for all times. Applying this method, much better results in determining high speed flow curves were achieved [6]. Up to the present, the above discussed correction methods are the best technique to extract the “real” compression force for this special problem. Therefore, this algorithm has been implemented in the standard post processing software *FlowStressUtilities* which is currently being developed. High speed compression test data is now handled using this method by default.

4.2 Testing Set-Up

The unavoidable ringing in the load signal was analysed for the standard experimental set-up in order to develop an optimised measurement. Neither velocity nor displacement signals show a ringing behaviour during high speed compression tests [6,7,10]. Both the high speed compression test as well as a stroke with a copper-hammer result in a frequency of 1715 Hz in the load signal [6,10]. Therefore, it is safe to say that the oscillation is pure load cell ringing. Furthermore, measurements with strain gauges affixed directly to a specimen proved this assumption to be true [6].

A recorded load signal (Figure 1a) of a high strain rate compression test can be described as a combination of the following two effects. On the one hand, the forming force as a result of the proper compression of the sample acts on the load sensor. Secondly, the load cell ringing due to the impact of the specimen onto the upper die overlays the above described signal component. In a first approximation the oscillation in the load signal can be described as a rigid body movement considered as free vibrations around the changing equilibrium position corresponding to the forming force of the sample [6].

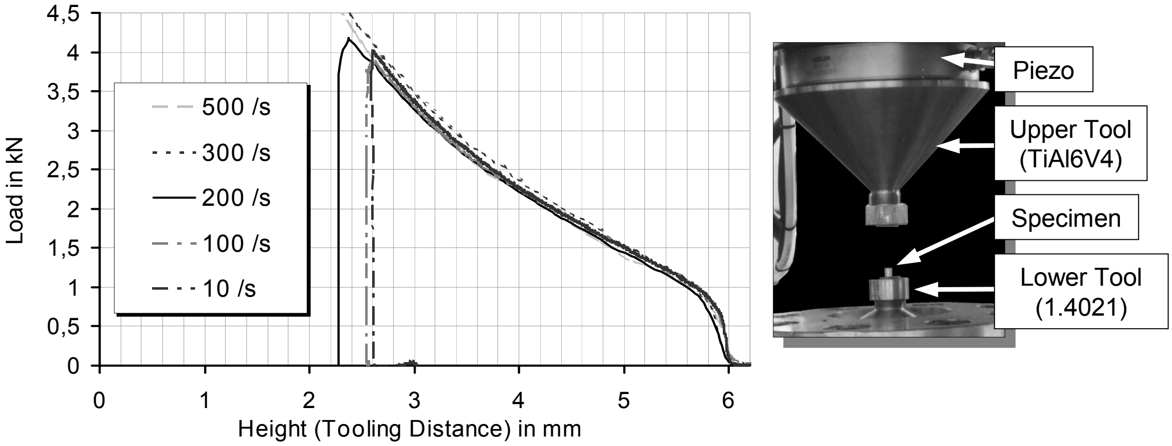


***Figure 2:** Load signals and testing set-up of uniaxial compression tests on aluminium; 25°C; initial height h_0 = 6 mm, initial diameter d_0 = 4 mm; nominal strain rates 10/s to 500 /s*

The answer of each oscillating system to the excitation source depends on the natural frequencies . The higher the frequencies, the faster the reaction of the system will be [6].
If the masses (tools, cooling devices etc.) which are connected with the load cell can be reduced, the natural frequencies will be shifted to higher values [6,11]. In the first instance, the measuring system for room temperatures was reconstructed. The motive for optimising tests firstly at room temperature is mainly the easier examination of the modifications and their effects. Additionally, in this set-up high speed videotaping is possible. In order to reduce the masses as much as possible, an upper die was constructed using TiAl6V4 as tool material. The geometry of this die was adapted to the handling of reduced sample sizes (initial height h_0 = 6 mm, initial diameter d_0=4 mm). Furthermore, a stiffer and faster piezo force sensor [6] was installed (Figure 2).

Tests and the recorded video sequences using the described set-up show no oscillations for all velocities (Figure 2) in the case of nominal strain rates from 100 /s to 500 /s. The actual input is not sufficient to excite the first natural frequency of 5000 Hz determined by a FEM calculation. The necessary forming forces for the small specimen with maximum values of 4 kN as well as the decreased necessary testing speeds reduce the input to the sensor. These two facts are desired and positive secondary effects of the modification task. The optimised tests at room temperature can be used to determine flow stress data up to high strain rates.

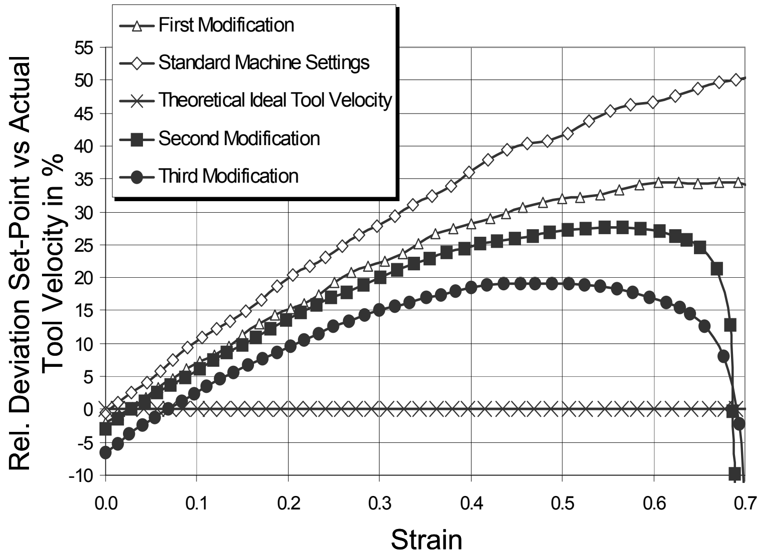


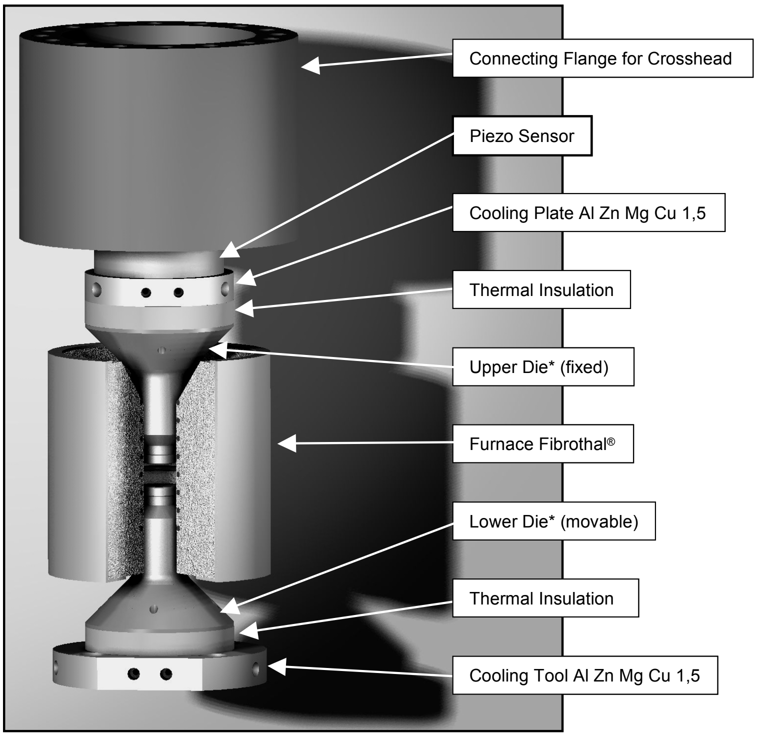
Figure 3: *Summary of velocity deviations for strain rate 300 /s tests. Variations of machine control parameters and the effect on the valve closing*

Comparing the required and the recorded strain rates leads to the next step of the optimisation task. In order to assure a constant strain rate during the whole test duration, a tool velocity profile according to

$$v_w(t) = h_0 \cdot |\dot{\varphi}| \cdot e^{-|\dot{\varphi}| \cdot t}, \quad \dot{\varphi} = \text{constant} \tag{5}$$

is necessaryly demanded. Because the testing machine is designed for loads of up to 1200 kN, sufficiently large, and thus not satisfactorily fast valves are installed. Ignoring the effects of oil compressibility for the moment, for a strain of 1 at 300 /s the velocity - and hence the valve opening – needs to be reduced to about 30% of the initial value in 3 ms. The maximum rate of change of each main valve spool position is about 10% per millisecond. In order to maximise the deceleration, all 4 main valves of the actuator must be used, so that the initial opening of each valve is as small as possible. Therefore, special machine parameters have been changed to allow the best closing procedure of all valves with an optimised pre-closing at the beginning of the compression. So, the maximum and the average relative deviation in tool velocity between the actual and set point values could be successfully reduced (Figure 3).

If experiments with the new construction for hot compression tests (Figure 4) are performed the recorded load signals still show ringing for strain rates above 100 /s (Figure 5). The used materials and the necessary installation of a cooling system as well as heat insulation put on more weight compared to the new set-up for room temperature. Anyway, with the new optimised construction, the natural frequency of the force measurement chain could be raised to a value of 2500 Hz. Combining the new construction with the new post processing correct data interpretation for flow stress values up to strain rates of 300 /s is possible.



*ODS Superalloy PM 2000: 1.4768 dispersion strengthened, Plansee AG

Figure 4: *Optimised new set-up for hot uniaxial compression tests and high strain rates*

4.3 Discussion of the results

The modifications carried out for the testing set-up for experiments at room temperature and high temperature range show that the main influencing variables are the stiffness and the masses connected to the sensor.

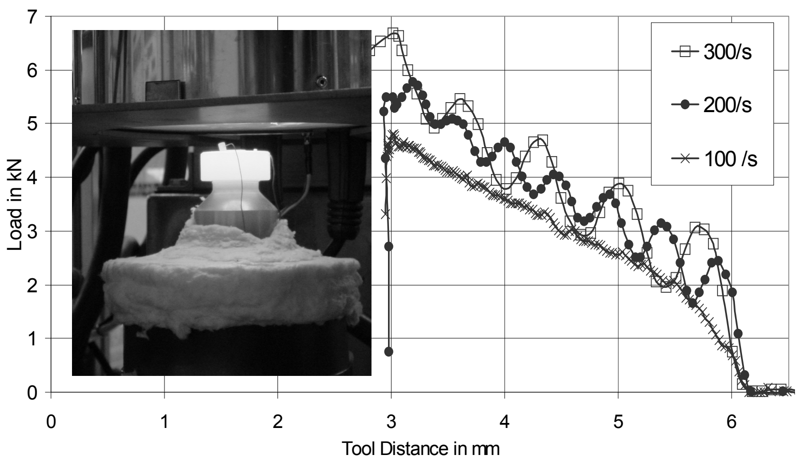


Figure 5: *Load signals of uniaxial compression tests on 16MnCr55; 1000 °C; h_0=6 mm; d_0=4 mm; nominal strain rates 100 /s to 300 /s*

Moreover, the input of kinetic energy exerts an important influence on the excited frequency response (magnitude of the ringing amplitude). The frequency is independent of the used specimen material and tool velocity [6,10]. Temperature effects are minimal due to the fact that the stiffness does not change much with the temperature. Even if the strain rate cannot be held strictly constant during the whole testing procedure, the variations of the real strain rates could be successfully minimised. Further optimisations may lead to a better dynamic behaviour of the well investigated versatile servo hydraulic testing machine. Furthermore, it is now possible to start the examination of the dynamic material behaviour by the use of common metallographic methods.

5 Summary

In the research project presented here, the strain rate (range) spectrum of path controlled axisymmetric compression tests was successfully expanded to 300 /s. By now, an adapted algorithm has been developed. With this new calculation rule, ringing measured load data can be used to determine ringing free flow curves. Further on, the measurement set-up was optimised by the use of a broad system analysis. Therefore, measurement readings are allocated which are not any more, or at least only insignificantly affected by ringing. These results allow a broader applicability in the strain rate range of industrial forming processes.

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