Size effects at flow stress behaviour under compressive loading

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In order to measure the flow stress behaviour of materials in small specimen sizes and additionally at high strain rates, starting from the manufacturing up to testing, special care is required.

A test method is introduced to measure the flow stress- deformation behaviour of metallic materials under compressive loading in a range of strain rates from 100 to about 1000 s^{-1}. FE-simulation is applied to optimise the test set-up to measure high quality force signals. Furthermore, the amount of residual stresses and their effect on the measured flow behaviour is measured and discussed

1 Introduction

When manufacturing technologies like cutting and forming are applied to small dimensions and sizes, scaling effects may occur. Scaling effects are defined by the occurrence of a not directly predictable change of the process parameters, if a process was scaled in correct similarity relations. Therefore, the influence of size appearing at the scaling on manufacturing processes has to be clarified where plastic shape-changing of metal material takes a central part, and thereby influence the result of the process.

The observed changes in material properties are a consequence of strong effects that size introduces on the material behaviour, e.g. flow stress and failure. Therefore, the consideration of different scale levels is important to understand physical features and mechanisms. Furthermore, the mechanical behavior at high strain rates differs considerably from that measured at quasi-static or intermediate strain rates. Because many processes occur at higher strain rates the knowledge about the material behaviour at different length and time scales is essential. To provide suitable material data, mechanical testing of samples with reduced dimensions is necessary.

To determine material properties for high speed cutting or forming operations, the dynamic compression test is widely applied. Drop weight test set-ups or more popular split Hopkinson Pressure Bar (SHPB) systems are traditionally used for determining the plastic properties of metals at strain rates in the range of 100 to 10000 1/s [1].

For high speed cutting processes the knowledge about stress and failure behaviour at even higher strain rates of 2 ... $4*10^4$ s^{-1} is required.

The nominal strain rate in the specimen can be approximated by $\dot{\varepsilon} = v / l_s$, where v is the velocity of deformation, and l_s is the length of the specimen. As a consequence, reduced gauge lengths and / or increased deformation velocities are needed, if high strain rates are required.

However, special care is necessary, if high strain rate properties have to be measured. In comparison with quasi-static loading rates inertia and wave propagation effects become more pronounced at higher strain rates. The measurement of force are affected by stress wave propagation. Using thinner specimens are suitable to achieve a more uniform deformation state more quickly, but will increase the effect of friction [2]. Sample size requirements also include a sufficient large number of grains to ensure the measurement of bulk properties.

Additionally, to measure size effects on material behaviour, samples are much smaller compared with the dimension usually used for quasi-static and dynamic testing. Therefore, residual stresses, surface qualities, and other quality-requirements on samples become an important consideration and affect the test validity.

The objective of the paper is to measure the influence of manufacturing of samples by grinding on the occurrence of residual stresses and their possible effect on the flow properties. A novel method is introduced to measure the flow stress behaviour at a range of strain rate between 100 and 1000 s^{-1} by using small specimen geometries of 4 mm or less. Finally, experiments were done to determine the effect of residual stresses on the flow behaviour of a quenched an tempered steel deformed under compressive loading at different strain rates at room temperature. Both, size effects and the effect of the strain rate on flow stresses are discussed.

2 Materials and Methods

The material used in this study is a tool steel 30 CrMnMo 7 (German grade 1.2311, AISI 20P). After austenitization for 15 min at 850 °C, quenching in oil, the steel was tempered at 650 °C for 1 h and cooled down slowly. This procedure resulted in a hardness of 33 HRC.

After the final heat treatment the compression samples were electro discharge machined and ground to a diameter of 9 and 1 mm, respectively.

The residual stresses on grinded and additionally annealed (640 °C / 1 h) steel were determined with CrKα-radiation using the $\{211\}$- interference lines. The analysis was based on the $\sin^2\psi$ – method for which the lattice spacing d were measured at thirteen ψ–angles between $-60° \le \psi \le 60°$ with $\Delta\psi=10°$. In order to calculate the residual stresses from the observed lattice strains a Young's modulus of $E^{\{211\}}=220000$ MPa and a Poisson's ratio of $\nu^{\{211\}}= 0.28$ were used.

For compression tests, cylindrical specimen with an height-diameter aspect ratio (l/d) of 1 were used. Although, requirements on the specimen geometry and test conditions at low test velocities are already specified, requirements like parallelism of the specimen and exact loading conditions become even more important if tests are performed at high loading rates.

The uniaxial compression tests, conducted in a range of strain rates from 10^{-3} s^{-1} to 10 s^{-1}, were performed in a special compression device to ensure exact axial deformation, loaded with servohydraulic testing machine with an additional piezoelectric force sensor. Tests at higher strain rates were done in a specially designed drop weight test set-up to receive high quality force signals. For low strain rate tests the displacement was measured with inductive devices. At high strain rates a precise high-speed electrooptical camera system was applied. The signals were recorded by a digital oscilloscope, and data processing and analysis were carried out using sequences implemented in FAMOS®.

3 Results and discussion

3.1 Optimization of test set-up for dynamic compression testing

In order to determine the exact trace of yield strength and strengthening behaviour at high strain rates up to 10^3 s^{-1}, a test set-up was designed which operates as a direct impact system like the known drop-weight set-ups. It consists of two bars with the same length made of tungsten heavy alloy.

The sample is carefully positioned in the centre on the bar. For high strength and high hard materials, discs made of high hard tool steel are placed between the bar and the samples.

The upper bar is used as weight. Strain gauges are glued on the lower bar and operate as a load cell. The shape of both bars is design as a cone with 7.28 mm as the smallest and 21.5 mm as the biggest diameter.

In order to ensure a load signal of high quality, i.e. low noise, high amplitude, and shore rise time, numerical simulations using LS-DYNA® were performed to find the best location for the load cell.

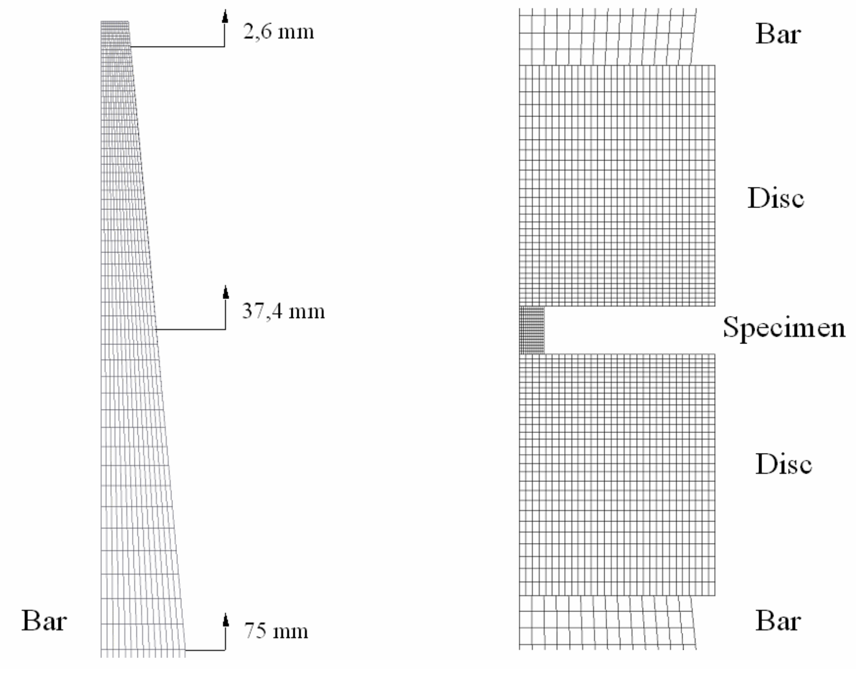

Fig. 1: Location for possible force measurements (left) on the cone shaped bar and close-up of specimen configuration (right).

For our calculations, a difficult to solve combination of low strength material and small specimen size was selected. Therefore, a cylindrical compression sample with 1 mm in diameter and 1 mm in height with the material behaviour of an aluminium alloy with a yield strength of 400 MPa and a tangent modulus of 1500 MPa was chosen to optimise the location for the force measurement. The simulation was performed at a deformation velocity of 1.2 m/s.

In our simulations, locations at different distances from the sample were selected, **Fig. 1** (left) and **Fig. 2**. On the basis of the actual diameter of the bar and the Young's modulus of the tungsten heavy alloy of E=360000 MPa, the calculated strains were converted into forces and further into stresses in the sample.

The calculated contact force, which is the force between the specimen and the disc and at 2.6 mm distance from the tip of the bar reveal a very good correlation between the input material data for yielding and strengthening, **Fig. 2**.

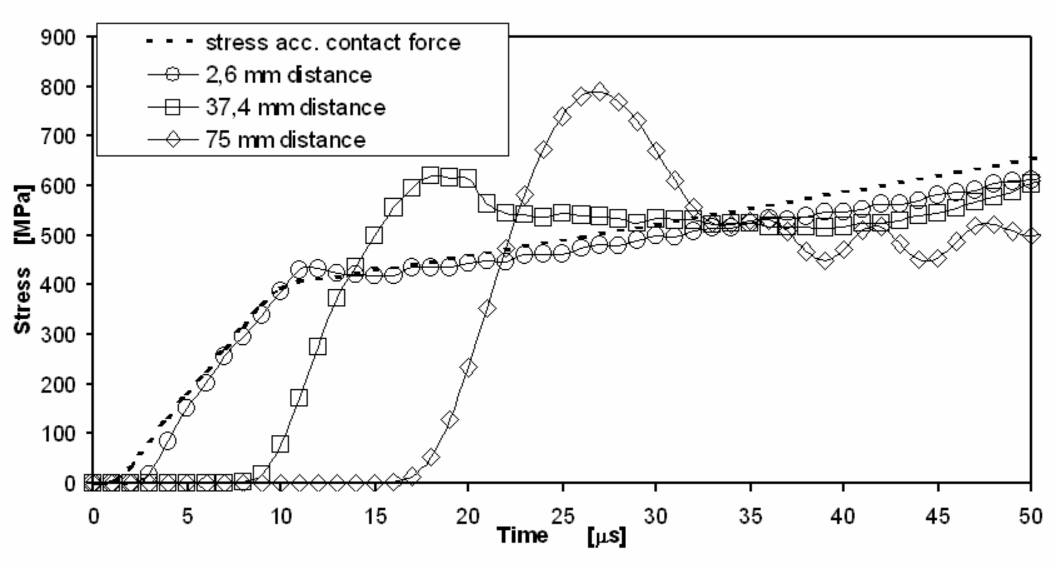

Fig. 2: Calculated stress-time response at different measurement points at outer circle from lower bar.

Furthermore, the results of our calculations clearly show that there are distinct differences in the stress signal calculated from the force between the location close to the specimen and further away.

An important practical consequence of such differences is to fix the strain gauge at the bar as close as possible to the specimen to minimize dispersion effects in the bar and get a signal with high strain amplitude which corresponds to the force / stress.

3.2 Influence of residual stresses on flow stress behaviour

It is well known that manufacturing can generate residual stresses. This might influence the flow behaviour if specimen with reduced sizes are tested. Usually, the specimen size is above 6 mm. However, if scaling effects are under investigation and/or high strain rates are desired, much smaller specimens are used.

Therefore, a preliminary assumption of the effect of residual stresses on the volume of a cylindrical compression sample with a height to diameter-ratio of 1 was performed and is shown in **Fig. 3**.

In this simplified estimation, for the residual stresses, three different depth of 30, 60, and 90 µm were selected. For the smallest specimen geometry in our tests, roughly 30 % of the total volume are effected, if an depth of induced residual stresses of 60 µm is assumed.

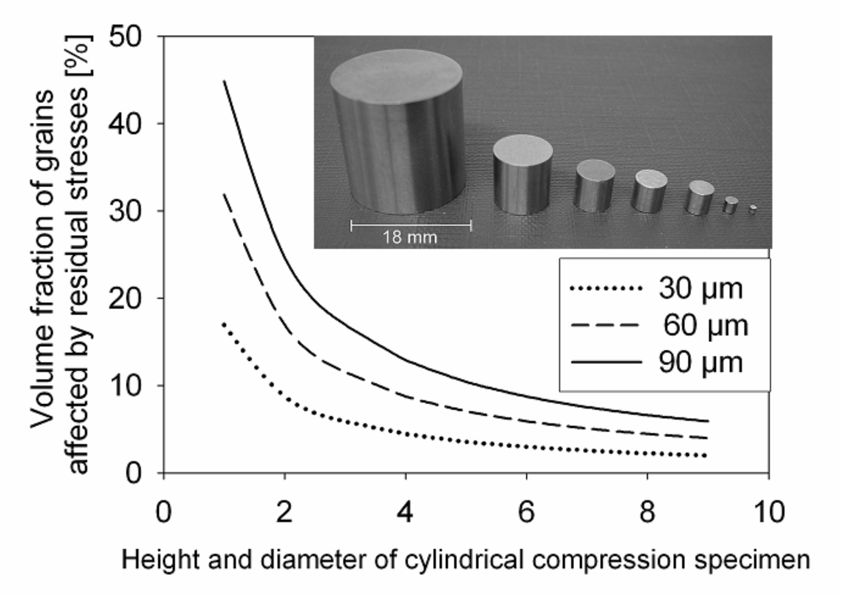

Fig. 3: Estimation of specimen volume effected by residual stresses.

For specimens with 9 and 1 mm in diameter in the grinded and grinded plus additionally annealed condition, residual stress measurements by X-ray were performed by Prof. Dr.-Ing. Löhe, Karlsruhe. The results are given in **Tab. 1**. There are large compressive residual stresses of up to 400 MPa in the near surface regions of both sample geometries.

After annealing, the compressive residual stresses are reduced but still exist.

Tab. 1: Residual stresses and integral with of 40 CrMnMo 7 on the surface.

specimen size	condition	residual stress [MPa]	Integral with [°]
∅ 9 mm	grinded	-335	3.6
∅ 9 mm	grinded and annealed	-32	2.4
∅ 1 mm	grinded	-409	3.1

∅ 1 mm	grinded and annealed	-101	2.5

Deformation experiments at strain rates of $10^{-3}\ \mathrm{s}^{-1}$ reveal no measurable effect of residual stresses if specimens of 9 mm are tested, **Fig. 4**. However, if smaller specimen geometries are tested, a different flow behaviour was measured. Samples with 1 mm in diameter without additional annealing showed a slightly higher flow stress due to residual stresses of 50 MPa compared to the 9 mm specimen. On the other hand, after additional annealing a smaller flow stress, but similar work hardening was observed. In this case, the flow stress is 50 MPa or 4 – 5 % less than the base of the 9 mm specimen.

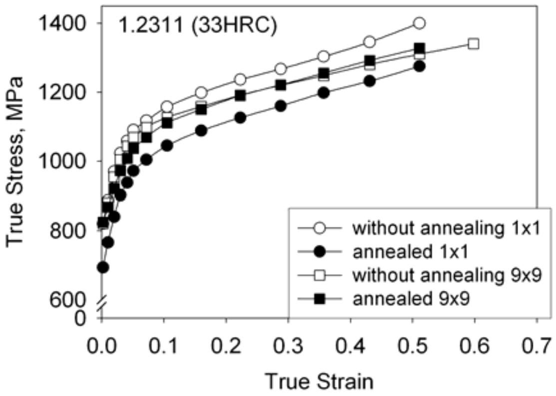

Fig. 4: Flow stress behavior under quasistatic compression loading of $10^{-3}\ \mathrm{s}^{-1}$ and influence of residual stresses and specimen size.

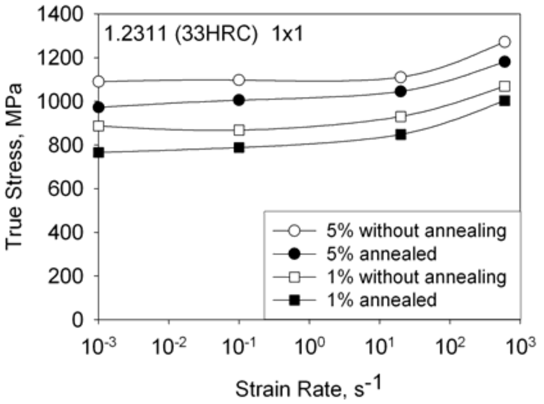

Fig. 5: Effect of residual stresses on rate sensitivity of 1 % and 5 % flow stress of cylindrical specimen with ∅ 1 mm and 1 mm in length.

For this remarkable result, several explanations are possible. If smaller specimens are deformed, the ratio of surface which is effected by friction relative to the volume is much larger. Therefore, with decreasing sample size friction forces in radial direction occur more pronounced and may lead to the measured enhancement in the axial load and calculated stresses.

Other reasons could be the effect of texture, which is more effective in the smaller sample sizes. The most probably explanation is an enhancement of the yielding by the higher volume fraction of strain hardened grinded surface layer. Also the reduction of flow stress is in a accordance with the model of grain relaxation by annealing. Only the amount of "overshooting" beyond the "9 mm" – level needs a further explanation. Finally, decarburisation and possible changes in the amount of residual stresses and stress distribution might have an strong effect on the flow properties.

In **Fig. 5**, the 1 %- and 5 %- flow stresses in the non-annealed conditions measured versus strain rate, presents an athermal range up to $\dot{\varepsilon} = 10\ \mathrm{s}^{-1}$. At higher rates a thermal activated rate sensitivity exists. In the annealed material status the flow stress is reduced for 70 to 100 MPa, and even a small rate sensitivity occurs. Both events meet the model, that released mobile dislocations are set free by the annealing process, which in turn is necessary to explain the noticed strain rate sensitivity.

Further investigations are necessary to identify the reasons for the measured material behaviour of small specimen sizes. These measurements are of high importance, especially if scaling and size effect have to be determined.

4 Conclusions

Material testing of small specimen sizes requires special attention starting with sample manufacturing up to testing. Residual stresses and other factors can have a strong influence on the measured flow behaviour. Optimised test set-ups and defined microstructures are necessary to measure high strain rate properties.

5 References

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