Crack formation on metal foils during high dynamic and quasi-static bulge test

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Abstract. Resource efficiency combined with high-strength materials is the key to enable intelligent lightweight design. Forming processes, such as high speed forming processes, have a high degree of material utilization compared to other manufacturing processes. In the micro range, processes based on laser induced shockwaves are promising for high speed forming operations. High speed forming offers the possibility to achieve high strain rates and accordingly the forming limit of thin metallic foils can be increased compared to conventional forming operation. However, the effect of the increased forming limit is not completely understood. Therefore, in this work the position of the crack initiation is investigated for quasi-static and dynamic bulge tests. The investigated material is Al99.5 and CU-ETP1 in the thicknesses of 20 µm and 50 µm. It is found, that the crack formation for quasi-static forming is showing a stochastic distribution over the formed area, while the crack initiation for the dynamic forming process is in the centre. This behaviour is explained by an increase in material temperature during the laser shock forming process, which is decreasing the flow stress in the centre of the forming area, thus the crack initiation is located in this area.

1. Introduction

Resource efficiency combined with high-strength materials is the key to enable intelligent lightweight design. Forming processes, such as high speed forming processes, have a high degree of material utilization compared to other manufacturing processes. In the micro range, processes based on laser induced shockwaves are promising for high speed forming operations [1]. Laser shock forming is a medium based process, without the use of a punch, which reduces the overall friction of the process [2]. Due to laser treatment free electrons are generated by thermo emission out of the surface [3]. The number of free electrons depends on focus size, laser pulse intensity and surface material [3]. These free electrons absorb energy by inverse bremsstrahlung absorption and can produce further ions and electrons by impact processes until an optical breakdown and thus a plasma formation is achieved [4]. The inverse bremsstrahlung increases with the square of the wavelength accomplishing a nearly complete absorption of the longer wavelength of CO₂-laser light by the plasma. If the energy density of the laser pulse exceeds a certain threshold, the fast expansion of the plasma forms a shock wave [5], which is initiated ~8 mm above surface [6]. This shock wave moves spherically [7]. The shock wave pressure, which is in the range of some MPa [8], leads to a forming of the surface [9]. Laser induced shock waves can substitute mechanical forming and cutting processes in the micro range. Complex three-dimensional micro parts can be produced by laser shock forming. One
further process, which uses laser induced shock waves, is a mechanical joining process based and laser shock forming [9].

In the micro range so called size-effects occur, which reduce the formability of the material [10]. The forming behaviour of metallic materials depends on the strain rate, the temperature, the strain itself and especially for the micro range the material structure. For Aluminium and Copper with a material thickness below 50 μm the amount of grains in thickness direction of the material is lower compared to thicker materials with same grain size. Accordingly, the material does have only one grain in thickness direction for thin materials, the so called tiffany structure [10]. This leads to different forming behaviour of thin materials. The influence of individual grains on the flow stress increases, which results in reduced formability. For a bulge test in the macro range, the maximum strain in the centre of the forming area and the strain values decrease concentrically around this point. In the micro-range, different behaviour occurs. The maximum strains are located stochastically on the forming area [10]. The material behaviour cannot be seen as a continuum as it can be observed for the polycrystalline materials. Respectively, the orientation of a single grain is decisive for the formability of the material [10].

Under these conditions, high speed forming offers the possibility to achieve high strain rates and an increased forming limit of thin metallic foils [11]. It is assumed that at high strain rates viscous damping restricts the dislocation movement [12]. This increases the sensitivity at high strain rates and changes the deformation behaviour. In the case of a high speed forming process, the temperature in a workpiece can be increased by adiabatic heating [13]. It has been observed, that on one hand an increase in temperature leads to an increase of the strain rate sensitivity. On the other hand the flow stress is reduced. This behaviour leads to a better formability of the material.

Balanethiram and Daehn [14] use another theory to describe the increased formability at high strain rates. They assume that the forming is uniformly distributed over the forming area. When necking starts, the forming is not uniform, which leads to different strain rates over the specimen. Due to inertia effects, the strain in the forming area is increased, which leads to higher forming degree, while necking is delayed [14].

Compared to pneumatic forming processes, the pressure of a shockwave does not have a uniform pressure distribution [13]. The centre of the laser-induced shockwave out of aluminium with a pulse energy of 5.6 J is located 8 mm above the surface [9]. The pressure distribution and impact angle shows an effect on the strain distribution in the forming area. Using shock waves for the deformation of sheet metal, different geometries can be observed. Due to the short pressure rise time the shape of the cup is cone-shaped [13]. With the use of multiple shock waves an elliptical cup is formed.

However, the effect of the increased forming limit for high strain rates in the micro range is not completely understood. Therefore, in this work the position of the crack initiation is investigated for quasi-static and dynamic bulge tests and compared to laser shock forming.

2. Method of Investigation

2.1. Experimental setup

For the investigation of the crack formation during laser shock bulge test and pneumatic bulge test, two different experimental setups are used, which are shown in Fig. 1. The pneumatic (quasi-static) bulge tests are performed in a pressure chamber. The pressure is adjusted by a regulating valve and measured by a pressure gauge. During the process, the pressure is increased linearly until the crack formation takes place. For the laser shock (high dynamic) bulge test, the pressure chamber was removed, thus the laser can irradiate directly onto the surface. For the laser induced shockwaves, a TEA-CO₂-laser with a pulse energy of 4.75 J and a repetition rate of 20 Hz is used. The laser irradiates directly on the surface of the specimen and a plasma is created on top. Several shock waves are used until the material breaks. The focal distance was set to 200 mm with a focal area of 2 x 2 mm².
The crack initiation is observed with the high-speed camera Phantom v5.1 from Vision Research. A frame rate of 13 kHz with a resolution of 256 x 256 pixels is used. For the increase of the contrast, the material is coated with white paint, thus the crack initiation can be observed in a better way. Strain rate determination was done using a measurement system based on the shadow effect. The procedure is described in [2]. This system is integrated into the drawing die. When the specimen is deformed, the amount of light irradiating on the sensor is reduced, thus the speed of the forming can be determined [2].

The investigated material is Al99.5 and CU-ETP1 in the thicknesses of 20 µm and 50 µm. The average grain sizes of the material are for the CU-ETP1 11.65 µm and for Al99.5 24.35 µm.

![Experimental setup for pneumatic forming (left) and laser shock forming (right)](image)

Figure 1: Experimental setup for pneumatic forming (left) and laser shock forming (right)

The temperature measurement is performed for the high dynamic bulge test. For better measurement conditions, the sample is coated with graphite. The measurement was done using Vario Thermo Cam with a maximum frame rate of 50 Hz and a lateral resolution of 100 µm.

3. Results

3.1. Pneumatic bulge test
In Fig. 2 the crack formation of Al99.5 with a thickness of 50 µm and CU-ETP1 with a thickness of 20 µm can be seen.

![Figure 2: Pneumatic bulge test for Al99.5 and CU-ETP1](image)

The number of 50 measurements per material are performed. 45 experiments could be evaluated for Al99.5 and 49 experiments for CU-ETP1. The crack formation is shown as coordinate in a Cartesian
coordinate system. The centre of the forming area is the zero position. It can be seen, that the crack initiation is distributed stochastically over the surface. Every point of material failure is in the range of 2 mm from the centre of the forming area. The average strain rate for the pneumatic forming was measured to 0.93 s\(^{-1}\).

3.2. Laser shock bulge test

For the high dynamic bulge test, the evaluable specimens are less than for the quasi static process. It can be seen, that the position of crack initiation is more located in the centre region. Nearly every crack initiation point is located in the range of 1 mm from the centre of the formed cup.

Figure 3: Laser shock bulge test for Al99.5 and CU-ETP1

Compared to the quasi static forming, the average strain rate for the high dynamic forming was measured to 520 s\(^{-1}\).

In Fig. 4 the distribution of the crack formation for pneumatic and laser shock bulge tests are shown for all experiments. It can be found, that for the high dynamic forming, the crack initiation has less standard deviation from the centre compared to the quasi-static forming.

In Fig. 5 the fracture behaviour of the material is shown for laser shock bulge tests. For Aluminium the crack starts in the centre of the specimen. It can be observed, that in case of further irradiation with the laser, these cracks progress to angular edges. In the right picture CU-ETP1 is used as material for
the investigation of the material heating. On the laser irradiation point, an oxide layer is visible after more than 300 laser pulses, while for the aluminium no change in the surface can be seen.

Due to the experimental setup for the temperature measurement, only the first laser pulse can be measured. For the quasi-static forming, the temperature is not increasing, while the temperature for Al99.5 with a thickness of 50 µm shows an increase by 30 °K for one laser pulse on the bottom side of the metal sheet. The temperature is decreasing in 0.5 s to room temperature.

![Figure 5: Breaking behaviour of the material](image)

4. Discussion

These results would seem to suggest that high strain rates decrease the standard deviation for the position of crack initiation as shown in Fig. 4. This findings seem to be consistent with the work of Balanethiram and Daehn [14] which found that inertia effects are leading to higher formability of the material. When necking occurs locally, the strain rates are higher in the necking than in the rest of the forming area. Since the flow limit increases with increasing strain rate, inertia effects lead to an ongoing forming in the rest of the specimen. The strain rate sensitivity of aluminium and copper is low at room temperature [15]. Therefore, the pneumatic forming does not show this effect. For high strain rates the flow stress can rise significantly, whereas a material failure is delayed and the shape change becomes more uniform. However, after several pulses, the strain rate decreases because of strain hardening of the material. For this reason, this effect is decreasing with continuous laser pulses for the forming. Furthermore, this effect does not influence the location of the material failure. A change in position where a crack occurs cannot be explained by this effect.

The surface of the material is heated for the emission of free electrons, which are needed for the plasma generation. For the determination of the absolute temperature of the surface all process parameters, such as the absorption of laser radiation by the plasma need to be considered. While the sheet thickness is only 50 µm, for the Al99.5 the measurement of the lower side of the material can be used as an estimation of the temperature of the material. The temperature can contribute to the material failure since the flow stress decreases with increasing temperatures. This could cause the material in the heat affected zone to reduce the flow stress, which causes the cracks formation in this region. Wielage has already investigated the influence of temperature on laser radiation in consideration of the surface and structure [1]. After 300 laser pulses on a copper sheet no melting could be observed and the rolling ridges were still visible. In the case of laser irradiation on aluminium sheets, no change in the surface could be observed. It can be concluded, that the maximum temperature of the aluminium and copper are below the melting temperatures. The temperature rise of the specimen is 30 °K for one laser pulse. The cooling of the specimen needs 0.5 s back to room temperature. While the experiments were conducted with a pulse repetition rate of 20 Hz the heating of the material is adding up, thus the flow stress of the material is decreased significantly. By the heating of the samples with the laser radiation, the flow limit of material is reduced locally in the centre of the specimen, which is leading to a change of position for the material failure.
5. Conclusion
From the reported work, it can be concluded:
- The workpiece temperature during high dynamic forming is increasing due to the laser irradiation
- Crack formation appears in the centre of the forming area during laser shock forming due to the temperature rise by the laser irradiation

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