A new Device for Determination of Forming-Limit-Curves under Hot-Forming Conditions

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Abstract. Forming-Limit-Curves (FLCs) are widely used to characterize the forming behaviour of materials. Nevertheless, the determination of FLCs for hot forming processes is a challenging and time-consuming procedure. At the Chair of Automotive Lightweight Design, a new device for the determination of FLCs under hot forming conditions was developed. In a sealed isothermal oven atmosphere, blank holder, die and punch are used for the FLC determination relying on the DIN EN ISO 12004-2. External hydraulic forces actuate the punch and blank holder. To ensure insulation from the thermal load set inside the hot oven atmosphere an innovative cooling system with extensive use of additively manufactured components with integrated cooling channels is used. For the feed of the different deep drawing tests geometries an airlock is installed, which allows keeping the temperatures constant during the testing procedure. Afterward the forming limits for the different geometries are evaluated with optical measurement systems. The developed test rig proved the ability to determine FLCs for isothermal temperatures up to 800° C.

1. Introduction

Hot forming of metal parts is characterized by forming over recrystallisation temperature [1]. For steel press hardening is a popular production technology for creating hardened parts under hot forming conditions. In the conventional press hardening process, the blank is heated above austenitizing temperature and then transferred to the forming tool. The tools are water cooled and therefore ensure a martensitic transformation of the steel material. The most popular alloy is the boron steel 22MnB5, a tensile strength of around 1500 MPa is reached through press hardening processes. The latest body-in-white concepts show a broad range of press hardened parts. The underlying forming methods are aiming to create purpose build components through variations of the press hardening process like tailored-property processes, the use of tailor-welded or tailor-rolled blanks. Moreover, there are several new alloys developed, which aim an increase in the maximum tensile strength of the press hardened parts up to 2000 MPa [2].

Several approaches consider the warm or hot forming of different aluminum and magnesium alloys with heated tool sets [3–6]. While warm forming is characterized by temperatures below the recrystallisation temperature [1]. Especially for high strength aluminum and magnesium alloys these forming processes can provide a solution for forming of parts, which otherwise would fail at cold conditions.
The use of titanium is mostly distributed to aerospace and aircraft. The by far most used alloy is Ti-6Al-4V. As Ti-6Al-4V shows low formability at room temperature, conventional deep drawing is usually not suitable. Therefore, a lot of parts are created with milling operations. As a result, from the high demands for purity in aircraft parts, the created waste cannot be recycled after these milling operations. Another approach is superplastic forming of titanium, which is a complex process with long cycle times at forming temperatures over 800° C [7]. Consequently, there are efforts to develop hot forming processes of Ti-6Al-4V with heated tools. Like at superplastic forming, the temperature for these hot forming processes are over 800° C, to increase the share of the increased formability of the beta-phase of Ti-6Al-4V [8].

As different materials and processes are considered for hot forming the need for the prediction of the multi-axial material behavior under hot forming conditions becomes reasonable. Higher temperatures usually increase the formability of different materials. FLCs are widely used to characterize the forming behavior of materials, while the determination of FLCs for hot forming conditions is a challenging process. Several set-ups were presented in the past, like using tensile testing machines with a heated chamber and Nakajima test assembly [9]. The application of a heat chamber is straightforward as for tensile tests under isothermal conditions it is state of the art, nowadays. Nevertheless, as the temperature in the forming processes increases, the reheating and assembling of the sample geometries becomes a time- and energy-consuming procedure. Moreover, the heating time of the pre-mounted sample geometries can lead to significant influence on the microstructure of the material e.g., grain coarsening which in some cases is not reliable with the considered hot forming process. Other characterization methods are using local heat treatment based on laser or induction heating for designated sample geometries [10,11]. For the consideration of isothermal hot forming processes, these methods need to heat blank-holder, punch and die. To the best of the authors’ knowledge, the current maximum temperatures realized for hot forming FLCs are at 700° C [9,10,12]. As the temperature rise and annealing starts, radiation becomes the significant distributor for heat loss and the need for a sealed atmosphere is useful to ensure a homogenous testing condition.

2. Development of a new device for isothermal FLC determination

2.1. Design

For the determination of isothermal FLCs under hot forming conditions a conventional hardening furnace is modified. Inside the sealed furnace atmosphere blank holder, die and punch are used to determine FLCs based on the norm DIN EN ISO 12004-2 [13]. The enclosed atmosphere leads to heating of the tools, which reach the furnace temperature after a designated heating time. Thermocouples are used to track the temperatures of the tools.

![Figure 1. Design of the developed test rig for isothermal determination of FLCs.](image-url)
A furnace with recirculating air is used for a homogenous temperature distribution. To keep the temperature constant during the testing and avoid reheating the oven, an airlock is installed to feed different sample geometries for the FLC determination. The sample geometries are mounted to the gripper at room temperature and then passed in the furnace atmosphere through the airlock. The punch is actuated with a servo-hydraulic cylinder, which allows control of the forming speed and track the reaction forces with a load cell. Figure 1 shows the design of the new device.

The movement of the blank holder is realized through eight shafts, which are going through the front door of the furnace. The upper three shafts can be loosened from the blank holder through a bayonet mount, to ensure the feed of the testing samples. The lower five shafts are permanently connected with the blank holder. After passing the specimen inside the heated chamber, the upper three shafts are reconnected to the blank holder. The blank holder force is applied through radial hydraulic cylinders, which are tighten the blank holder shafts outside the heated chamber. Following the positioning of the sample inside the furnace atmosphere, the airlock is closed and after a holding time, the punch movement is started. Figure 2 shows the concept of moving the sample geometries inside the furnace atmosphere.

![Figure 2. Feed of the sample geometries inside the heated furnace atmosphere:](image)

(a) Blank holder open and sample positioned at gripper; (b) Blank holder closed and sample fixed inside furnace.

2.2. Cooling system

To encounter the temperature loads over 700° C, the materials inside the furnace atmosphere are made of the aerospace nickel-based alloy Inconel 718, which has a yield strength of over 600 MPa at 800° C [12]. The punch is additively manufactured through selective laser melting out of Inconel 718 with a hollow design to reduce the effective mass and heating duration. The connection to the driving shaft of the hydraulic cylinder is realized through the front door of the furnace. Based on the DIN EN ISO 12004-2, a Nakajima punch geometry with a diameter of 100 mm is chosen.

Thermal insulation needs to be carried out between the parts inside the hot furnace atmosphere and outside where the blank holder and punch forces act. The cooling is realized with a water-cooling system. The cooling of the blank holder and punch shafts is ensured with radial cooling cylinders. For the radial cooling cylinders of the blank holder shafts additive manufacturing is employed. Therefore, the cooling channels inside the cylinders can be directly created without any post-treatment. The cooling cylinders are made of stainless steel 316L. A flow simulation is used to design the cooling elements. Heat insulation made of calcium silicate is used for the radiant heat inside the furnace. Figure 3 shows the cooling concept for the high-temperature deep drawing test device.
2.3. Sample geometries

As shown in figure 2, the sample geometries are supplied through the airlock via a gripper system. To secure that the samples are symmetrically tensed and fractured samples remain conjoined, the FLC sample geometry based on Hasek [14] is modified. Moreover, three holes are added to let the moveable shafts of the blank holder pass. For the evaluation of the tested samples, they are marked before testing. The investigation is carried out with the a posteriori optical measurement system GOM Argus. A marking laser is used to create a regular pattern on the sample geometries with a circle diameter of 1 mm and 2 mm distance between the circles. Depending on the underlying tested material, the parameters for the marking laser need to be estimated before experiments to ensure a high contrast between the material surface and the laser pattern after heat treatment.

To reduce friction, high-temperature lubricants boron nitride or graphite can be used. The Nakajima punch inside the heated chamber is polished to a surface roughness of 0.2 µm to reduce friction between the punch and sample. Moreover, the lasered pattern can be secured with a protective layer to avoid scaling. Figure 4 shows the developed sample geometries for the FLC determination.

3. Experimental procedure

3.1. Material

A conventional press hardening steel 22MnB5 with aluminium-silicon coating is considered to validate the isothermal FLC determination. The sheet thickness is 1.50 mm. Table 1 shows the chemical composition of the material. Moreover, boron nitride is used as a lubricant layer between sample and punch.
Table 1. Chemical composition of the tested 22MnB5 material with aluminium-silicon coating.

|   | C   | Mn  | Si  | Cr  | Al  | B  |
|---|-----|-----|-----|-----|-----|----|
|   | 0.22| 1.26| 0.29| 0.15| 0.05| 0.0037 |

3.2. Testing

Before experiments, the samples are cleaned and marked with the regular laser pattern. The marking is done with a Keyence MD-X1520C laser marking unit. Table 2 shows the parameters that are applied for the laser marking of the Argus pattern.

Table 2. Parameter set for the marking of the Argus pattern before testing of the samples.

| Laser output | Scan speed | Pulse frequency | Wavelength |
|--------------|------------|-----------------|------------|
| 25 W         | 50 mm/s    | 70 kHz          | 1064 nm    |

The samples are mounted to the gripper outside the furnace at room temperature. Afterward, the airlock is opened, and the sample is moved inside the heated chamber. The blank holder is fixing the sample and after a designated holding temperature, the punch movement is started. Validation tests with thermocouples were done beforehand to determine the necessary holding time till the sample reaches the furnace respectively tool temperature. For the 22MnB5 material, a holding time for 10 minutes at 800° C is chosen. It must be stated, that this austenitization temperature and time only leads to austenite volume fractions of 0.7 for the specimens [15]. However, for the validation of the isothermal experimental procedure this is accepted. For fully characterizing non-isothermal processes like press hardening an external heating could be added in the future to the test rig e.g., through resistance heating at the gripper location.

The temperature of the punch, die and blank holder is tracked by thermocouples during testing and showed homogeneity of ± 5° C for the aimed temperature of 800° C. The force and displacement are tracked at the hydraulic cylinder of the punch. In addition, the force of the blank holder can be adjusted via the hydraulic pressure in the radial hydraulic cylinders. A criterion of 20 percent force drop is utilized to stop the punch movement and characterizing the failure of the specimen. After failure, the blank holder is loosened, and the sample is released through the airlock.

Figure 5. Force-displacement curves for the Nakajima tests of 22MnB5 at 800° C.
Based on the DIN EN ISO 12004-2 a punch velocity of 2 mm/s is used. A set of 3 samples per geometry is investigated. The sample geometries full equibiaxial, 100 mm, 65 mm and 40 mm specimen width are considered, see figure 4. Figure 5 shows the force-displacement curves for the different sample geometries, which are suitable for validation of simulation results. The force-displacement results emphasize the temperature homogeneity of the test rig.

3.3. Evaluation
To evaluate the forming limits for the different sample geometries, the optical measurement GOM Argus is used. Relying on the DIN EN ISO 12004-2, major and minor strains are determined for the specimens after the isothermal forming process. The deformed laser pattern is optical scanned to calculate strains. The major and minor strains of the samples are determined with the cross-section method [13]. Figure 6 shows the laser pattern and resulting major and minor strain for the specimen 1 with a width of 100 mm.

![Figure 6](image-url)

Figure 6. Left: Fractured specimen with laser pattern. Middle and right: Major and minor strain distribution for the optical a posteriori measurement.

The formation of the double dome strain concentration can be clearly seen, which is due to the friction between punch and sample. The norm DIN EN ISO 12004-2 demands fracture at the dome apex with a maximum deviation of 15 percent, which could not be satisfied for the 22MnB5 material for 65 mm, 100 mm and full equibiaxial specimens. The coefficient of friction for 22MnB5 at hot stamping conditions is about 0.55 at dry condition and can be lowered with the application of lubricants to about 0.4 [16]. In [17] researchers analyzed the correlation between the coefficient of friction and different sample geometries of the FLC and concluded that a coefficient of friction lower than 0.10 should be accomplished to reduce the effect on non-centric failure of specimens. These failure mechanisms were also observed by other researchers, who identified FLCs at hot forming conditions [4,10,18,19]. Figure 7 shows the FLC for the 22MnB5 material at a forming temperature of 800 °C. Moreover, a comparison to a FLC determined at 600° C for 22MnB5 is taken from [18]. As seen in the figure, the fracture occurrence is obvious. As described, the results are influenced by the coefficient of friction. The current research activities focus on the improvement of the friction system for the developed test rig. For temperatures around 600 °C, where radiation is less distinct, fracture is reached as demanded by the DIN EN ISO 12004-2.

4. Conclusions and Outlook
The development of hot forming processes considers new alloys and manufacturing methods. The need for formability evaluation of these developments can be conquered by determination of isothermal FLCs. However, as the temperatures rise and annealing of materials start, these experiments are challenging. Therefore, a new device for the determination of FLCs under hot forming conditions was presented, where temperatures over 700° C can be established. In a sealed atmosphere, which can be accessed by an airlock, the whole experimental procedure takes place. While the device
showed its ability to characterize the material under isothermal forming conditions, there are several further topics, which will be addressed within the new test rig:

- The fracture of the sample geometries is not in the dome height, due to the friction between punch and blank. To reach a coefficient of friction lower than 0.10 at high-temperature deep drawing tests conventional lubricants fail and research for the tribology system can be conducted. Moreover, the test rig provides a solution, where different lubricant-material pairing can be directly tested and evaluated for the minimization of the friction in hot stamping operations. Nevertheless, the tribology system becomes more important as temperatures rise and the DIN EN ISO 12004-2 [13] should be extended for FLC determination at different temperature levels.

- The proposed evaluation method considers the fractured samples with the cross-section method. Another possibility is the use of the time-dependent forming limit evaluation [20]. For this method, the deformation would be necessary to be measured in-line e.g., with an optical measurement system. An in-line optical measurement would also decrease the current effort, as the a posteriori evaluation is the by far most time-consuming part.

- For a non-isothermal forming process like press hardening the temperature evolution needs to be included for the determination of FLCs and this includes the austenitization followed by a forming process. External heating could be applied for the austenitization e.g., through resistance or inductive heating at the gripper location, which is followed by an isothermal forming process inside the furnace atmosphere. To evaluate the whole non-isothermal process a set of FLCs need to be determined for the characteristic different forming temperatures.

**Figure 7.** Left: FLC for 22MnB5 at 800 °C and comparison to a FLC at 600 °C [18]. Right: Fractured specimens for different geometries.

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