Design and development of a micro-LDH apparatus to determine formability of sheet metal under hot stamping conditions using Gleeble

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Abstract
In the last few years, demand for hot stamped components has increased in the automotive industry. Determination of formability under hot stamping is challenging due to elevated temperature, fast cooling, and high punch velocity. Although there was various strive for formability determination, but there were limitations with experiments like non-uniform heating of specimen, non-uniform strain, and temperature distribution. Therefore, in this work, an experimental apparatus was developed to determine formability at room temperature, high temperature, hot stamping conditions, and any complex process cycle involving heating and cooling. New specimen was designed to produce different strain paths, uniform, and homogenous temperature distribution with the help of FEM software using thermomechanical and thermoelectrical simulation. A micro hemispherical dome-based experimental apparatus was designed using Solidworks. The designed apparatus was used in conjunction with the thermo-mechanical simulator (Gleeble-3800). Thermomechanical analysis was done in PAM STAMP software to optimize specimen size and shape to get uniform strain distribution and different strain paths. A thermoelectric FEM model was developed using Abaqus 6.14 to optimize the temperature distribution in the specimen. The developed model enables choosing the appropriate polarity of the electrical cable connection to achieve uniform temperature distribution in the specimen. Strain path and temperature profiles for experiment and simulation were compared. Further, a forming limit curve was developed using the designed apparatus to verify the feasibility of the apparatus. For feasibility test of apparatus, hot stamping process was selected. This new design apparatus can be used for a range of temperatures up to 1000 °C, hot stamping conditions, and for different materials (aluminum, magnesium alloys, different grade of steel, etc.). It concludes that the connection of different polarities of electrical cable was critical for homogenous and uniform temperature distribution in specimens.

Keywords 2MnB5 steel · Hot stamping process · Finite element analysis · Gleeble-3800 · Thermo-electrical simulation · Forming limit diagram

1 Introduction
Hot stamping or press hardening is the process of forming metal at elevated temperature and subsequently followed by quenching. 22MnB5 steel is one of the most popular high strength boron alloyed steel used to produce hot stamped components. One of the distinguishing features of this process is that it produces high strength parts at a lesser stamping load with no spring back effect [1]. One of the significant challenges in the hot stamping process is the lack of adequate understanding of the formability behavior at high temperatures (typically between 750 and 930 °C) and higher strain rates (≈ forming velocity is 100 mm/s). It is important to note that the determination of formability is usually done with the help of the Limiting Dome Height (LDH) test at room temperature. However, deformation occurring at high temperature with simultaneous cooling during the hot stamping process is significantly different from the LDH test conducted at room temperature. As a result, it is challenging to determine the formability using the existing approach. Therefore, there is a need for
Formability is defined as the ability of a material to deform plastically without developing any defects such as necking, or failure, etc. Banabic in his book has described the following ways by which formability can be defined and quantified [2]. There are many ways such as (a) thinning and strain distribution, (b) strain non-uniformity index, (c) maximum achievable dome height, (d) stress, and strain-based Forming Limit Diagram (FLD) through which the forming characteristics of sheet metal can be represented. Among such existing approaches, the strain-based forming limit diagram has been extensively used by researchers worldwide to assess the formability of material in the sheet forming process. FLD is a two-dimensional plot between the minor strain (plotted on the x-axis) and the major strain (plotted on the y-axis). Various experimental and simulation methods can be used for determining the formability of materials. However, the use of in-plane and out-of-plane methods has been adopted by multiple researchers for assessing the formability of materials.

In the in-plane method, the deformation occurs in the same plane of the specimen, and no bending occurs in the central region of the specimen, such as in the Marciniak test [3]. The FLD obtained at high temperature has been reported to be highly sensitive to deformation temperature, the microstructure of specimen, phase transformation, strain rate, etc. [4]. Therefore, to better understand these parameters on formability, different researchers have attempted to modify the existing approach. For example, Ghosh et al. [5] used a biaxial warm forming apparatus for aluminum alloys in which the specimen was deformed in the temperature range of 250 to 350 °C. The exact temperature range was also used by Kim et al. [6] for investigating the effect of temperature on the formability of aluminum and manganese alloys. Similarly, Palumbo et al. [7] used induction heating to increase the temperature of specimen; however, the maximum achieved temperature was limited to 300 °C due to oxidation of the specimen and safety of the equipment. Likewise, Lee et al. [8] and Singh et al. [9, 10] utilized Gleeble (thermo-mechanical simulator) for the determination of formability of 22MnB5 steel during hot stamping conditions by modifying the tensile geometry. Although the temperature as high as 930 °C was achieved through this approach, the experiments were only performed at uniaxial strain conditions or the drawing region of Forming Limit Curve (FLC). In a similar line, Shao et al. [11] used Gleeble-3800 to determine the formability of different materials using a designed biaxial deformation setup; however, the applicability of the developed system/setup was limited to low strength material only.

In the out-of-plane method, deformation occurs in two planes, as typically observed in the LDH test or nakazima test [12]. Turetta et al. [13, 14] performed a uniaxial tensile test using a dilatometer to predict the forming behavior of 22MnB5 steel. Bariani et al. [15] conducted experiments using a modified Nakazima test for High Strength Steel (HSS) at a temperature of 600 °C at a punch velocity of 10 mm/s. Pellegrini et al. [16] compared two experimental apparatus to better understand formability at 600 °C with two different velocities (8 mm/s, 10 mm/s) of punch. Li et al. [17, 18] and Shi et al. [19] attempted to determine the forming limit experimentally using a modified LDH setup. However, some of the significant limitations associated with their setup were to (a) maintain precise temperature, (b) maintain appropriate cooling rate, and (c) achieve required velocity of punch during the experimental process.

It is important to note that neither the in-plane nor the out-of-plane apparatus can generate a complete forming limit diagram for hot stamping conditions. These methods are frequently used to determine the formability at room temperature and warm forming conditions; however, heating rate, cooling rate, punch velocity, etc., play an essential role in hot stamping conditions, as discussed earlier. Therefore, a new micro-LDH apparatus is proposed through this research to determine formability at room temperature, high temperature, and under hot stamping conditions.

Based on the dimension and size of equipment, sheet metal forming operations can be divided into three groups: micro, meso, and macro. The equipment in which at least two parts have a dimension in the submillimeter scale is called micro. Similarly, when at least two parts having a size scale of one to 10 mm falls under the category of mesoscale. Likewise, at least two components in macro equipment have a size scale of above 10 mm [20–22]. Based on the classification of forming operation, the proposed apparatus/setup in this research work falls under the category of micro apparatus. Also, based on the deformation process of the specimen, the current experimental setup can be categorized under the out-of-plane method.

The developed micro-LDH apparatus was attached to the thermo-mechanical simulator (Gleeble-3800), in which different specimen geometries were used to generate different strain paths (e.g., uniaxial, plane strain, and biaxial strain). The resistance heating method was used to heat the specimens with different heating rates. Since the formability determination under the hot stamping condition requires a specific cooling rate, a hosepipe was attached to the Gleeble system for cooling purposes. A thermo-electrical simulation model using Abaqus 6.14 was subsequently developed to optimize the temperature distribution in the specimen. An experiment was further performed to validate the predicted temperature profile of the specimen. Finally, a forming limit curve was developed using the micro-LDH apparatus to verify its feasibility.
2 Experimental apparatus design

The design of the micro-LDH apparatus contains mechanical, thermal, and electrical aspects. A detailed design process flow chart of the apparatus in Gleeble-3800 (thermomechanical simulator) is shown in Fig. 1. The mechanical component consists of a die, punch, blank holder (ring), and nut. These mechanical parts were modeled and designed using Computer Aided Design (CAD) software (SolidWorks). The design of the mechanical part was followed by the design of the heating system. Lechler et al. [23] demonstrated that the heating process adopted for the specimen influences the properties of the final product and the overall process time. Therefore, the main challenge for the heating systems was to maintain a uniform temperature in the specimen with optimum process time. The elevated temperature forming process specimen can be heated using different heating methods like resistance heating, induction heating, etc., which follows different heat transfer mechanisms such as conduction, convection, and radiation in a furnace. In the present work, the resistance heating process was used. A thermo-electric model was developed using Abaqus 6.14 to optimize the temperature distribution in the blank. In the resistance heating process, electrical polarity connection has a significant effect [24, 25]. Therefore, for optimal temperature distribution in the specimen, the effect of electrical polarity was also analyzed. After designing parts of the apparatus, different components were manufactured using a Computer Numerical Control (CNC) machine and Electrical Discharge Machining (EDM) equipment. A room temperature LDH test was subsequently performed to verify all mechanical system movement and clearance between the punch and the die. Once all combinations of the possible experiments at room temperature were completed, the heating arrangement was attached to the apparatus and Gleeble to perform the experimental work under the high temperature conditions. Teflon shielded copper wire was connected between the apparatus and Gleeble machine to heat the blank to a specified temperature using resistance heating. Before starting the experiment with a heating arrangement, it was again significant to check the mechanical movement of different components under the room temperature condition. In the proposed apparatus,

![Flow chart for micro-LDH apparatus design for formability analysis](image-url)
experiments were performed under low to high strain rates. To attain the constant strain rate, the punch velocity needs to be adjusted with time. In Gleeble, the punch velocity can be controlled by controlling the movement of the jaw. Two types of movement control modes (velocity mode and strain rate mode) are possible in Gleeble for the deformation of the blank. In the velocity mode, a constant velocity of jaw needs to be provided, whereas, in the strain rate mode, the velocity of punch needs to be programmed so that it adjusts itself with time to maintain a constant strain rate. In the present study, the experiments were performed in the strain rate mode.

In the conventional LDH test, the strain can be measured using different techniques like Digital Image Correlation (DIC), grid marking method, etc. [2]. Generally, the DIC technique uses various software like ARGUS, ARAMIS, etc., for analysis of the image. Different inks are used in the ARGUS method for printing the grid on the specimen. The printed grid can be further analyzed using a digital camera. In the ARAMIS method, speckle patterns are made using paint to measure strain. Although these methods hold many merits, they are not applicable for elevated temperatures because the ink and paint cannot sustain high temperature conditions (≈ 1000 °C). Therefore, in this research, the laser engraving technique was used to make the grid which was further analyzed using a special design camera provided by CosCam.

### 2.1 Micro-LDH apparatus components

The dimension of the micro-LDH apparatus was decided based on (a) the optimum utilization of the available space in the Gleeble and (b) the miniaturization effect of the geometry of different components in the apparatus. The upper dimensional limit was decided based on the space available in Gleeble testing chamber. The lower limit of apparatus was finalized after considering the available fabrication facility, the accuracy of fabrication, and the miniaturization effect [21, 26, 27].

The diameter of hemispherical punch was decided based on ISO 12004 specification [28]. As per this standard, fracture to the specimen should occur at a tolerance level of 15% of punch diameter from the vertex of the hemisphere. It is important to note that room temperature forming operation was considered in ISO 12004. However, the same method was used in this research work for the design of punch.

It is to be noted that the load carrying capacity of different components of this setup is different; therefore, the final load carrying capacity will be governed by the weakest part. Accordingly, the overall load-bearing capacity of the designed apparatus was calculated [29], and it was found to be 100 kN under extreme conditions, which are suitable for almost all the materials used extensively in forming operations like magnesium alloy, different grades of steel, aluminum alloy, etc. with thickness up to 2 mm. The thickness of the sheet was decided based on the clearance between the die and the punch. As shown in Fig. 2a, the punch is connected to a movable Gleeble jaw. Similarly, the die was attached to the fixed Gleeble jaw. Likewise, the sheet is sandwiched between the blank holder and die with the help of a nut. Once the assembly of all parts had been done, the experiment was performed according to the requirement. Dimensional details of different components are shown in Fig. 2b.
2.2 Design and development of specimen geometry

The design of specimen geometry is critical to determine formability because for LDH type test, different sizes and shapes of geometry are used. Therefore, in the subsequent section, a more detailed design of specimen geometry is discussed. In addition to this, heating and cooling system are involved for hot stamping tests, and therefore design of heating and cooling arrangement is also discussed in subsequent sections.

2.2.1 Specimen dimensions

Specimens were machined to the specified dimension (refer to Fig. 3) using wire EDM. Due to space constraints, the samples were scaled down from the standard geometry provided by Ozturk et al. for the LDH test [28].

Optimization of specimen dimension was done with the help of simulation that was performed in commercially available software PAM STAMP-2G. These simulations were performed to optimize strain paths for different sizes of geometries. A thermo-mechanical simulation model was developed to optimize these geometries. The initial temperature of specimen was 850 °C that undergoes isothermal deformation up to necking. Various temperature-dependent properties list used in the simulation are given in Tables 1 and 2. The actual magnitude of these properties at different temperatures is taken from the literature [29, 31].

Tensile tests were performed at different temperatures and strain rates to obtain the flow behavior of the material. Tabulated true stress and true strain value were used for the constitutive behavior of material. Hill-48 with isotropic hardening was used as the material model. Determination of necking was done with the help of thickness gradient-based necking criterion [30]. It was found that the strain path of geometries follows nearly linear path in different regions of the FLC. Whereas smallest geometry (15 × 55) lies in the drawing region, and as width of the specimen increases, it shifts toward stretching region. The medium size specimen (25 × 55) was found to be near plain strain condition, whereas the largest size specimen (55 × 55) generated biaxial strain path. Predicted strain paths of different specimens are shown in Fig. 4.

2.2.2 Thermal analysis

A process model for thermo-electrical simulation consists of (a) Joule heating and (b) heat transfer phenomenon. According to Joule’s first law, when electrical current passes through a conductive material, electrical energy is converted into heat energy due to the material’s resistance. The heat

![Fig. 3 Specimen dimensions (all dimensions in mm) for micro-LDH test](image-url)
generated in the material is directly proportional to the square of current supplied and resistance of the material, as described by Eq. (1).

\[ P = I^2 \times R(T) \]  

(1)

Resistance as a function of temperature,

\[ R(T) = \frac{l}{A} \times \rho(T) \]  

(2)

Resistivity of materials

\[ \rho(T) = \rho_0(1 + \alpha \times dT) \]  

(3)

where \( \rho_0 \) is the material’s resistivity at room temperature, \( \alpha \) is temperature coefficient, \( P \) is the thermal power generated from electrical energy, \( I \) is current supplied through materials, and \( R \) is the material’s resistance. The transient state heat transfer during joule heating is described by Eq. (4).

\[ K(T) \times \nabla^2 T + \frac{I^2 \times R(T)}{V} = \frac{\partial T}{\partial t} \]  

(4)

where \( K \) is the thermal conductivity of the specimen (assume constant throughout the specimen), \( V \) is the specimen volume, \( T \) indicates temperature, \( t \) is time. However, thermal conductivity, resistance of material is function of temperature; therefore, for thermal analysis, these variations are considered as given below.

Specific heat of advanced high strength steel (AHSS) [J/Kg-K] [31]

\[ C_p = 648 + 0.3 \times T - 2.6 \times 10^{-4} \times T^2 + 1.24 \times 10^{-7} \times T^3 \]  

(5)

Thermal conductivity of AHSS [W/m–K] [30]

\[ K = 32 + 1.2 \times 10^{-2} \times T \]  

(6)

\( R \) is the resistance of a material, \( \rho \) is the resistivity of the material, \( l \) length of specimen, and \( A \) is the area of specimen’s cross section, \( T \) is temperature.

2.2.3 Electrical connection between specimen and Gleeble

In Gleeble, two copper blocks are used for the supply of current for heating the specimen. In the existing arrangement, the specimen remains in direct contact with the copper block. However, since the specimen is placed between punch and die, this arrangement cannot be used to heat the specimen in the micro-LDH apparatus. Therefore, two copper plates having the same dimension were used to connect Gleeble and specimen in Micro-LDH. A copper plate with dimensions 25 mm x 10 mm x 3 mm was sandwiched between jaw and punch, while another copper plate with the same dimension was kept between the second jaw and die. In each copper plate, two holes with thread were used for cable connection (made with the help of nuts and lugs) to connect the copper plate with the specimen. In this arrangement, the copper plate used in the punch side acted as positive polarity, and the die side copper plate behaved as negative polarity.

2.2.4 Material of electrical cable

The selection of material for a cable connection between specimen and copper plate was done in such a way that resistance of the cable is less than specimen so that the heat generation in the cable could be minimized. The resistance of a material is directly proportional to the resistivity of the material, length of the cable, and inversely proportional to the area of cross section of cable (Eq. 2). Based on Eq. (2), copper wire cable having the optimum size and cross-sectional area of 8 mm² (due to space restriction) was considered. Teflon-coated wire was used to sustain high temperatures.

2.2.5 Process model for heat transfer

To achieve uniform temperature in the specimen of the proposed micro-LDH setup, it was required to develop a configuration that can provide consistent heating and temperature. Various factors such as (a) voltage and supplied current, (b) point or area of contact between different components, (c) type of connection between the component (e.g., series or parallel connection), and (d) properties of materials (density, resistivity, conductivity, etc.) play a vital role in temperature distribution in the specimen. Therefore, considering these factors as mentioned above, thermo-electric simulation was
performed. Accordingly, the optimized configuration and properties (current and voltage) obtained from the simulation were further used for experimental purposes. Joule heating, as well as the heat transfer phenomenon, was considered during the heating and soaking stages. However, in the case of cooling, only the heat transfer phenomenon was considered, as shown in Fig. 5a. The heat transfer phenomenon consists of conduction, convection, and radiation. Conduction was considered for physical contact between different parts like die to blank, blank to punch, etc., whereas convection was considered with the cooling medium like air and water. Similarly, radiation was considered for heat transfer during the entire process to the outer environment. It is important to note that the conduction, convection, and radiation is a temperature-dependent phenomenon; therefore, material properties were taken as temperature dependent in this work.

2.2.6 Cooling method

Cooling in the proposed setup was done with the help of high-pressured compressed air supplied from the hose pipe. One end of the pipe was attached to the compressor, and another end was kept open in the direction of the fixture where the specimen was fixed. One of the advantages of this arrangement is that one can use various mediums for cooling, such as water, air, different gases, etc. Another factor influencing uniform cooling is the small size of the specimen. The cooling rate was controlled by adjusting the flow rate of the cooling medium. The flow of the cooling medium was controlled by flow pressure in the hosepipe through the compressor.

2.2.7 Thermo-electrical simulation

The hot stamping process consists of a complex process cycle in which specimen (blank) is heated up to austenitization temperature and kept for some time for uniform heating, then formed and cooled simultaneously. This indicates that hot stamping process is a non-isothermal deformation process, as shown in Fig. 5b. Hot stamping process was used to demonstrate the feasibility of micro-LDH apparatus. In this work, isothermal deformation was considered where temperature is constant during deformation after deformation sample was cooled down to room temperature using compressed air.

One of the most important tasks in process modeling is to decide the appropriate input parameters. A small error in the input parameter can make the whole process model redundant. The input can be selected in three major categories: geometry, process parameters, and material properties. The various input parameters are given in Table 1. During the process modeling, mesh control has to be done precisely. In the thermo-electrical process, 6-node linear coupled thermal-electrical triangular prism (DC3D6E) mesh with Arbitrary Lagrangian–Eulerian (ALE) adaptive meshing was used to control the mesh distortion and accuracy. This method combines the advantage of both Lagrangian and Eulerian techniques. Because of ALE adaptive meshing, the high-quality mesh was maintained throughout the forming analysis by allowing the mesh to move independently of the material. Once the simulation is completed, the output needs to be validated against experimental results. The validation was done in terms of post temperature distribution comparison with the lab-scale experimental setup. Once the output is validated, the contours of state variable temperature at any moment during the thermo-electrical process can be generated. The validated FE model was further used for simulating the temperature distribution of the component under different process conditions.

In the developed apparatus, specimens were heated with the help of resistance heating with a feedback control loop.
Current was supplied with the use of Teflon cable to the specimen. Various shapes and sizes of the specimen, as shown in Fig. 3, were available for thermo-electric simulation. For different polarity arrangements, simulations were performed on the smallest or uniaxial (15 mm × 55 mm) and largest or biaxial (55 mm × 55 mm) specimens. One end of the cable was attached to the Gleeble, and another end was connected to the specimen. It may be noted that there are various possible arrangements to connect the positive and negative ends of the cable to the specimen. The positive sign (+ ve) indicates the positive polarity of the cable, and the negative sign indicates the negative polarity (− ve) of the cable.

All possible arrangements of electrical heating for different polarity connections are described in Table 3 and shown in Fig. 6. For example, Type I cable connection has positive ends connected to the opposite corner of the specimen. Similarly, Type II cable connection has positive ends connected to the same corner of the specimen. Likewise, Type III cable connection has positive ends connected to the same corner of the specimen with one positive end at the center (corresponds to the upper surface of the die). Finally, Type IV cable connection has positive ends connected to the opposite corner of the specimen with one positive end at the center.

Initially, a thermo-electrical simulation was performed on the smallest size specimen with all possible arrangements. It was found that the opposite polarity on diagonal results in higher temperature at the outer edge of the specimen, as shown in Fig. 7a. Similarly, the same polarity on the same side results in a higher degree of heating uniformity in the central region of the specimen as shown in Fig. 7b, because in case of opposite polarity on same side, current density distribution is higher on outer edge of specimen, whereas in case of same polarity on the same side there is more current density distribution in central and throughout the specimen as indicated in arrow in Fig. 7. In the micro-LDH test, deformation occurs in the central region of the specimen; therefore, a higher temperature is required in the central region of the specimen. As a result, the Type II cable connection arrangement was suitable for the smallest or uniaxial type of geometry. However, it was observed that Type II, Type III, and Type IV had similar results; therefore, one of them (Type II) is discussed. Temperature vs distance from outer to inner (toward center) point in the specimen is shown in Fig. 8, which indicates the presence of temperature gradient in the specimen. Also, the maximum temperature difference in Type I and Type II can be observed to be less than 15 °C and 3 °C, respectively, which is a reasonably low value and can be accepted.

It was observed in the simulation of smallest geometry of specimen different types of polarity having different temperature distribution, but in case of type II, type III, and type IV having similar results; therefore, these results are not reported in this paper. However, in the case of the largest specimen, deviation in temperature distribution in all possible conditions was observed. For the largest specimen, among all four types of polarity connections, the highest temperature uniformity in the specimen was observed for Type IV cable connection, as shown in Fig. 9. Therefore, for heating purpose, Type IV was used in the experimental setup for this study.

Temperature distribution vs distance (from one end of corner to center) of specimen for different locations in thermo-electrical simulation for type IV arrangement is

| Table 3 Different cable connections possible for thermo-electrical simulation |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Upper right corner of specimen | Upper left corner of specimen | Lower right corner of specimen | Lower left corner of specimen | Center of specimen |
| Type I | − ve | + ve | + ve | − ve | None |
| Type II | + ve | + ve | − ve | − ve | None |
| Type III | + ve | + ve | − ve | − ve | + ve |
| Type IV | + ve | − ve | − ve | + ve | + ve |

Fig. 6 Different possible combinations of cable connection arrangement for thermo-electrical simulation
shown in Fig. 10. It was found that temperature distribution across three directions was uniform throughout the specimen. Additionally, the maximum temperature was found to be in the center region of the specimen that undergoes deformation during test. As the distance from the center increased, maximum temperature variation can be seen to be 15 °C.

However, when the size of specimen increases, diagonal connection gives uniform heating; therefore, apart from uniaxial specimen all other specimens are connected through Type IV arrangement (same polarity on diagonal).

2.2.8 Validation of thermo-electrical simulation

The hot stamping process cycle was followed for the validation of simulation. An optimized configuration of the electrical arrangement was used for the experimental analysis. To determine the temperature of the specimen at three different locations, three thermocouples (T1, T2, T3) were welded to the specimen, as shown in Fig. 11a. A comparison of the simulated and experimental temperature profiles at these different locations with respect to time is shown in Fig. 11b.
Electrode flow direction in specimen and FEM simulation of electrical heating arrangement. (a) Type I positive ends are connected to opposite corner of specimen. (b) Type II positive ends are connected to the same side corner of specimen. (c) Type III positive ends are connected to same corner of specimen with one positive end at center. (d) Type IV positive ends are connected to opposite corner of specimen with one positive end at center.

Fig. 10  Temperature vs distance across L1, L2, L3 lines from outer region toward center region of the specimen at the end of the heating state obtained from simulation for Type IV cable connection arrangement.
2.3 Assembly of apparatus

The electrical circuit design of a micro-LDH apparatus was carried out as per the predicted results obtained for thermo-electric simulations, as discussed in the previous section. Different components (die, punch, blank holder, heating cable, cooling pipe, and the blank) were assembled in a proper sequence as shown in Fig. 12 to perform the experiments. The step-by-step assembling of the components is described below:

- **Step 1**: Two copper plate was used for the wire connection. One copper plate was sandwiched between the die and fixed jaw (stroke), while another copper plate was sandwiched between the punch and a movable jaw (wedge). The cable was attached with the help of a screw and electrical lugs.
- **Step 2**: Die was fixed in the stroke side (fixed jaw), and punch was attached to another end of movable jaw. These two ends were connected to Gleeble (thermo-mechanical simulator), as shown in Fig. 2.
- **Step 3**: Thermocouple was welded in the blank. Blank was fitted in the die with the help of a blank-holder ring and screw.
- **Step 4**: Four Teflon cables were attached in the blank with the help of bolt and nut. Cables were connected as per the optimized polarity, as mentioned in the previous section.
- **Step 5**: An experimental program was written using QuikSim2 software (user interface between the Gleeble embedded control system) for various experiment steps.
A preliminary test was performed for validation of the apparatus using 22MnB5 steel. The chemical composition and the mechanical properties of as received uncoated 22MnB5 steel from JSW Steel Ltd. with a sheet thickness of 1.8 mm are provided in Tables 4 and 5, respectively.

To assess the formability of 22MnB5 steel during the hot stamping process, forming limit diagram was obtained by performing the LDH test (on the specimen of different geometries as mentioned in Fig. 3) on the micro-LDH apparatus with different experimental parameters as provided in Table 6.

### Table 4 Chemical composition of uncoated 22MnB5 steel in as received condition (wt. %)

| Element | Composition |
|---------|-------------|
| Al      | 0.108       |
| B       | 0.003       |
| Cr      | 0.163       |
| Cu      | 0.063       |
| Mn      | 1.17        |
| Ni      | 0.0055      |
| Si      | 0.23        |
| P       | 0.013       |
| Ti      | 0.018       |

### Table 5 Mechanical properties of uncoated 22MnB5 steel in as received condition

| Property     | Value   |
|--------------|---------|
| Yield stress | 352 MPa |
| Tensile stress | 530 MPa |
| Total elongation | 24.25% |

### Table 6 Experimental parameters for 22MnB5 steel

| Property                      | Value                  |
|-------------------------------|------------------------|
| Thickness of sheet            | 1.8 mm                 |
| Temperature at start and end of deformation | 850 °C |
| Temperature at the end of the experiment | Room temp |
| Heating and cooling rate      | 1 °C/s and 40 °C/s     |
| Soaking time                  | 3 min                  |
| Austenite soaking temperature | 930 °C                 |
| Punch velocity                | Variable (programmed)  |

### 3 Material used

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### 4 Forming limit test

To determine the forming limit curve using the above experimental setup, different parts of the apparatus were assembled, as described earlier. Specimens of different shapes and sizes were heated through resistance heating using Type IV configuration of electrical arrangement for the biaxial specimen (55 mm × 55 mm), and Type II for the uniaxial specimen (15 mm × 55 mm) to have precise control of temperature thermocouple welded over the specimen. Once the specimen was heated up to the austenitization temperature, it was held for 3 min for attaining uniform temperature. The specimens were further cooled to the required deformation temperature (850 °C) using compressed air coming from nozzle and deformed till fracture. The fractured specimen was subsequently cooled down to room temperature using compressed air. To accurately measure fracture strains, it was imperative to have rupture in the center of the tested sheet metal. Therefore, lubricant was used in between the punch and specimen.

There are various lubricants available for room temperature forming operation; however, there is a high chance of catching fire in the specimen due to their relatively lower ignition point of those lubricants. Therefore, those lubricants are not suitable for high temperature experiments. Finally, based on multiple trials on different lubricants, graphite foil with nickel paste was used as a lubricant between punch and sheet in this research work as it can sustain temperature up to 1000 °C. However, it was observed that in the specimens failure occurs in between center and clamp region due to friction between punch and specimen.

The movement of jaws in Gleeble was controlled by a closed feedback loop system for the standard test. However, for the present research work, a minor modification was made to the apparatus so that a constant strain rate could be achieved. A tabulated program was created using QuikSim2 software (user interface between the Gleeble embedded control system) in which displacement of the jaw was adjusted based on a specific strain rate with time. In this experiment, 0.01/s strain rate was used for demonstration.

Different type of technique was used to measure the strain during forming operation. Generally, paint or grids are made on the surface of sheet specimen; however, at elevated temperatures, these grids get deteriorated. Therefore, the circular laser grids were engraved with few micron depths on the specimen so that it could not get affected due to elevated temperature conditions.

Specimens were laser marked with a circular grid to measure the strains. After deformation, the circular grids change their shape to ellipse. The deformed specimen was analyzed using a specially designed camera by the CosCam. Initial (or grid marked sample before deformation) and final images (or sample after deformation) were taken with scale using the CosCam camera to calculate strain values. The images were subsequently analyzed with the help of ImageJ software. Measuring distances between two extreme points on the grid provided maximum and minimum distance between two points. Further, using the standard formula for true strain, major and minor strains were calculated for the
deformed samples. Figure 13 shows the plot between minor and major strain, and it was found at plane strain conditions minimum value of limit strain. Other advantages associated with this novel apparatus can be heating specimens up to temperature 1000 °C. Due to the higher load carrying capacity of equipment, it can be used for other high strength materials.

5 Conclusion

A micro-LDH apparatus was designed to determine the formability of sheet metals at room temperature and high temperature with a constant strain rate. Design of this apparatus consists of mechanical, electrical, and thermal aspects. Design of mechanical components was done with the help of SolidWorks. To design the heating cycle, several thermo-electric simulations were performed with the help of Abaqus 6.14 FEM software. In thermo-electric simulation, two extreme geometries of specimens were taken for optimization of polarity connection. It was found that when the electrical cable having the same polarity was connected on the same side of the two adjacent corners of the specimen, it produced uniform temperature for the uniaxial specimen. However, for biaxial specimens, the connection across the diagonal of the specimen generated uniform temperature. It was found that when the size of specimen increases, diagonal connection gives uniform heating; therefore, apart from uniaxial specimen, all other specimens are connected through type IV arrangement (same polarity on diagonal). Therefore, these configurations were used for conducting experiments. Experiments were further performed to validate the apparatus under hot stamping conditions at the heating rate of 1 °C/s up to austenitization temperature (930 °C) and soak for 3 min. It was subsequently followed by cooling the specimen at the cooling rate of 40 °C/s using compressed air. There were three thermocouple welds in specimen at different locations to compare experimental and simulated results, and good agreement was found between them. Once heating arrangement validation was completed, formability test is performed to determine FLC using the proposed apparatus. To determine the formability of 22MnB5 steel for different possible strain states, different sizes and shapes of geometry were used with hot stamping process cycle. Under hot stamping conditions, the forming limit diagram was experimentally measured using the novel setup developed in the present work.

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Author contribution AKS: software, investigation, validation, methodology, writing—original draft. KN: supervision, funding acquisition, reviewing and editing.

Data availability The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval The article follows the guidelines of the Committee on Publication Ethics (COPE) and involves no studies on human or animal subjects.

Conflict of interest The authors declare no competing interests.

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