



Multi-objective finite element simulations of a sheet metal-forming process via a cloud-based platform

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Abstract

The emergence of cloud-based technologies has been transforming manufacturing industries over the last decade; however, their application in process modelling and finite element simulations is still limited. With the development of new hot stamping technologies, comprehensive knowledge of forming process phenomena is essential for their implementation, yet this knowledge is not readily accessible. In this paper, the development of a novel technique known as Knowledge Based Cloud-Finite Element (KBC-FE) simulation is described. KBC-FE is a research-oriented sheet metal-forming simulation technique that operates on an online platform. It was developed to facilitate the computation of advanced predictive models and to provide advanced functionalities to research institutions as well as industry. By making the relevant knowledge accessible, the technique enables multi-objective simulations, comprised of individual advanced functional modules each with their own speciality in the field of hot stamping of sheet metals, for rigorous analyses of different processes and for process optimisation. The capability of multi-objective FE simulations is demonstrated through the case study of a hot-formed U-shaped component, where multiple aspects of a part formed at elevated temperatures were examined. The advanced functional modules ‘Formability’, ‘Tool Maker’, and ‘Tailor’ were used to predict formability, die quenching efficiency, and post-form strength respectively.

Keywords High strength aluminium alloys · Formability · Post-form strength · Hot stamping · KBC-FE · Knowledge Based Cloud-FE Simulation · Multi-objective · Finite element simulation

1 Introduction

The application of cloud computing and the Internet of Things (IoT) in industry has been growing rapidly in recent years. Devices that traditionally operated independently are transforming into wirelessly connected communicating-actuating IoT networks that can be remotely controlled and that can output valuable data for analysis [1]. Cloud-based prognosis services have been developed and implemented in different sectors, such as cloud-based healthcare services [2] and knowledge-based predictive models for identifying extreme weather [3].

With the introduction of Industry 4.0, a growing emphasis has been placed on industrial digitalisation and the creation of advanced cloud-based operating systems [4]. Both single and twin cloud-based system designs have been proposed, establishing stronger links between manufacturing and design and enabling virtual simulations to be conducted throughout the product realisation process [5, 6]. Recent technologies have focused on improving efficiency through advanced tools and collaborative manufacturing systems [7], with IoT technologies being studied to achieve cloud-based monitoring, control, and data communication and collection [8, 9].

In addition to improving manufacturing efficiency, cloud computing can also improve computational efficiency and promote knowledge sharing. A selection of web-based data visualisation services was recently launched by Elsevier to enhance the accessibility of research outcomes [10]. Whilst FE simulations are typically conducted locally, cloud-based applications have been developed that offer numerous advantages over existing applications such as flexible storage and scalable computational power. Autodesk launched Fusion 360™, a cloud-based 3D CAD, CAM, and CAE tool that

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offers a single platform for product design and development [11]. Similar progress has been made in the field of finite element (FE) simulations by ESI Group, a world leader in sheet metal-forming simulation software, which introduced a version of their software that is accessible online [12].

With a greater emphasis on environmentally friendly designs and enhancing efficiencies through the expanded application of lightweight materials in the sheet metal-forming industry, greater requirements have been placed on computational resources that could significantly benefit from cloud-based systems. Aluminium in particular has drawn great interest in the industry due to its unique high strength to weight ratio, especially variants such as 6xxx and 7xxx aluminium alloys [13]. Due to the challenges of applying novel forming techniques such as warm forming and hot stamping to form these alloys [14, 15], FE simulations are used heavily to further our understanding of them and for their optimisation [16, 17]. The functionality of traditional simulation software is currently expanded by running subroutines independently that each incorporates an advanced predictive model. These models could potentially be transformed into functional modules that operate on the cloud simultaneously, thus enabling multi-objective simulations to be run [18].

Advanced mechanism-based predictive models are essential for gaining a comprehensive understanding of different aspects of a sheet metal-forming process, such as the material's formability and post-form strength during hot stamping. Innovative research work was conducted on the aluminium-lithium alloy AA2060, where a Viscoplastic-Hosford-MK model was employed to predict formability under hot stamping conditions featuring non-isothermal and complex loading conditions [19]. Forming limit curves were also determined to predict failure in anisotropic aluminium sheet metal through the implementation of a constitutive model in FE simulation software [20]. The post-form strength of heat-treatable aluminium alloys has also been investigated extensively [21], where it was found that precipitation formation and subsequently the post-form strength are highly sensitive to the cooling rate during hot stamping, and that the alloy content affects the critical cooling rate above which the maximum hardness can be obtained through a subsequent artificial ageing process [22]. Furthermore, to study the interactions between precipitates and dislocations in an ageing process, including pre-existing precipitates and dislocations, advanced mechanism-based models have been developed [21, 23].

Currently, advanced mechanism-based models are operated independently as sophisticated subroutines running on FE simulation software, as was applied to a hot deep drawing process simulated in ABAQUS with a specially designed VUMAT subroutine to predict the evolution of damage [24]. User-defined subroutines are commonly used in conjunction with commercial FE software such as PAM-STAMP to study the material response in a sheet metal-forming process [25].

Although subroutines offer many benefits to conventional simulations, they require extensive knowledge to develop and are tailored to the software being used, making them difficult to adapt and share. Moreover, the development and implementation of multiple subroutines, each covering different forming phenomena, requires excessive multi-disciplinary knowledge and is time-consuming. Subroutines are also typically run in series, and computing a series of these models in FE simulations would therefore be computationally very expensive, particularly with the increasing numbers of simulations being conducted due to the complexity of geometries being studied [26]. Alternatively, the utility of such advanced functions could be enhanced by developing them into FE software agnostic functional modules and subsequently running them simultaneously on a cloud-based platform. This platform would foster a collaborative research and development environment, providing a means for research digitalisation and knowledge sharing, and for exploring manufacturing technologies in more depth and promoting step-changes in scientific research and industrial production. Data interaction and integration within a community would be encouraged, enabling users to gain a comprehensive understanding of various stages of scientific research.

In this work, a novel technique known as 'Knowledge Based Cloud-Finite Element' (KBC-FE) simulation was developed for sheet metal-forming applications. The KBC-FE technique operates on a software agnostic platform dedicated for research and is an efficient and effective method for modelling advanced forming features in conjunction with conventional FE simulations. Advanced models are implemented through the application of functional modules on a cloud computing environment, to guide advanced sheet metal-forming process design. The development of the KBC-FE simulation technique is first described, followed by the application of the technique to the study of a hot-formed U-shaped specimen. Based on an experimentally validated FE simulation, the U-shaped part was evaluated using multiple functional modules: 'Formability', 'Tool Maker', and 'Tailor', from which the formability, the die quenching efficiency, and the post-form hardness respectively were predicted.

2 Methodology

The Knowledge Based Cloud-Finite Element (KBC-FE) simulation technique is a new method being proposed to bridge the gap between scientific models and their implementations via a knowledge sharing platform built on a cloud environment. The aims of developing this technique were to save on computational time, simplify the sheet metal-forming design process, enable the implementation of advanced predictive models, and to increase simulation software flexibility. This section explains the KBC-FE framework, the KBC-FE

simulation technique, and the advanced functional modules that operate on the platform and their characteristics.

2.1 KBC-FE framework

To evolve academic research into practical applications is challenging. Research findings tend to be scattered and difficult to implement, but form a pool of valuable knowledge. Within the sheet metal-forming industry, there is also a pool of users seeking new advanced modelling techniques but lack the knowledge, resources, or network to access them. The reason for this lies in the complexity of implementing academic research, which partly arises due to inadequate access to develop advanced predictive models.

The KBC-FE framework was designed to enable different user groups to share and submit their developed and potentially published work in a unified manner, and to facilitate the optimisation and use of advanced forming technologies. The framework, shown in Fig. 1, operates through active interactions between three groups: knowledge/resource providers, resource users, and the online platform administrators. The resource providers are knowledge contributors who provide knowledge required for the functional modules; resource users are direct beneficiaries of the knowledge and its applications; and the online platform administrators are responsible for maintaining the framework to ensure seamless operations. The framework itself is composed of three core layers: the resource layer, cloud platform layer, and application layer. Resources are collected from various sources and are classified into appropriate categories and constructed into individual modules, and made transferable and accessible. Both resource providers and users are contributors; whilst the resource provider may provide direct inputs such as scientific models, users could also contribute by providing data.

2.1.1 Resource layer

In the KBC-FE simulation framework, the resource layer is also known as the knowledge layer. There are two forms of input to this layer: physical resources and non-physical resources. Physical resources consist of tools that are remotely linked to the platform for completing specific tasks, such as a pilot production line (UNI-Form) [27] developed to mimic a hot stamping production line, or a dedicated test rig (IHTC-Mate) [28] to determine the interactive heat transfer coefficient during hot stamping. Non-physical resources are further classified into simulation resources and knowledge resources. Simulation resources include simulation defining data such as FE simulation-based outputs, forming conditions, material specifications, and other supporting data. Knowledge resources are comprised of advanced models on sheet metal forming and are incorporated through the use of experimentally verified mechanism-based numerical models.

2.1.2 Cloud platform layer

The cloud platform layer is the key computing technology required for the KBC-FE technique to operate. In a KBC-FE simulation, simulation resources are connected to the cloud through data recognition and information processing steps. The platform is compatible with different FE simulation software. Knowledge resources are virtualised through a unified knowledge conversion technique and are made accessible on the cloud environment in the form of functional modules, from which advanced predictive simulations are computed. A key function of this layer is to offer the infrastructure that allows users to manage and access resources on the cloud, including frontier theoretical models and dedicated test rigs. The computation of the functional modules is supported by the facilities provided on the cloud platform layer. Another key function is to provide management support, including management for big data applications, covering all computational data and knowledge as well as keeping track of the data in the module whilst computations are performed. The cloud platform layer acts as the control centre, and is responsible for identifying, connecting, matching, monitoring, and supporting resources.

2.1.3 Application layer

The application layer provides the human-computer user interface, where multi-objective simulations can be achieved through the execution of multiple functional modules simultaneously on the platform. The modules are available on-demand and could be run individually or collectively, providing user-oriented and user-tailored applications. Simulation outputs are stored for each user and are inter-transferrable between different modules. The application layer does not reveal sensitive information as only element data from finite element (FE) simulations are required. Data generated in the application layer may contribute to the resource layer as a simulation resource, further benefiting the cloud database as well as future users.

2.2 KBC-FE simulation technique

The KBC-FE simulation technique integrates traditional FE simulations, advanced mechanism-based functional modules, and cloud computing to transform sheet metal-forming process design, development, and optimisation, as shown in Fig. 2.

Conventional FE models are built and run offline on a local computer using simulation software such as PAM-STAMP. The required outputs from these simulations are then uploaded to the online multi-objective platform and processed within selected functional modules. Functional modules are

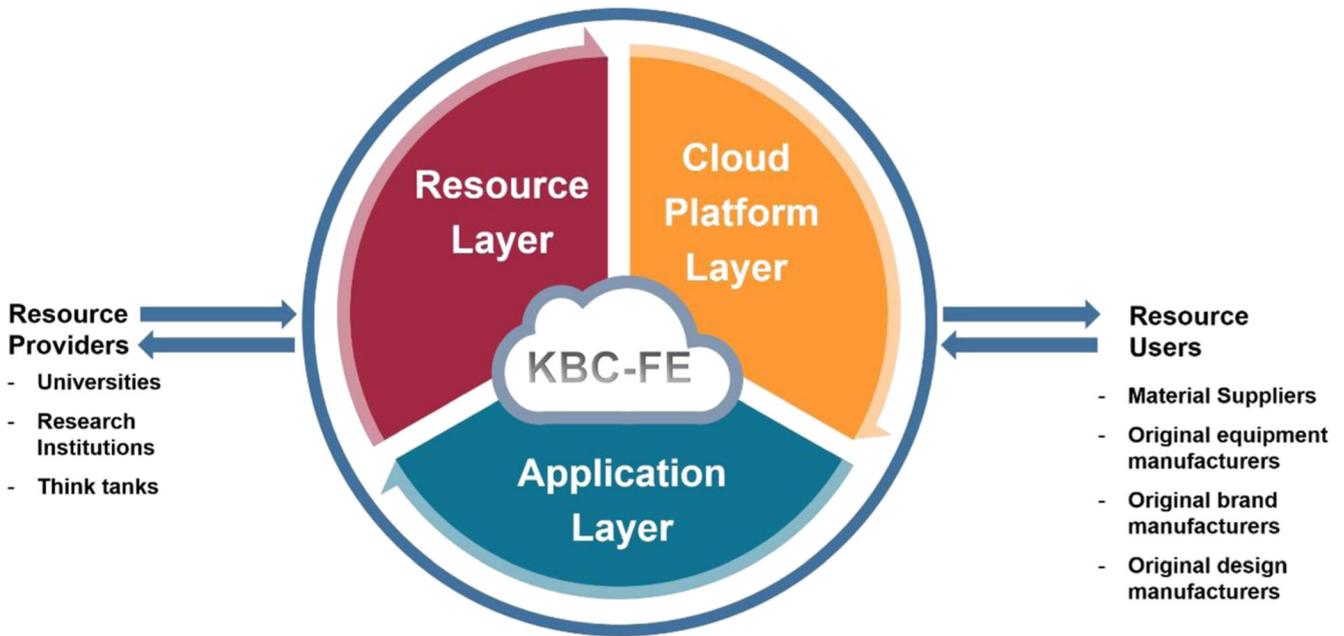


Fig. 1 The KBC-FE framework

developed based on predictive models, and each has their own speciality, offering cross-disciplinary knowledge on sheet metal forming. Predictive models studied in this paper are all physical based. Advanced predictions are computed within the modules on a cloud-based environment where computed data can then be downloaded and results visualised in the original FE simulation software.

As the predictive models are developed as modules operating on a cloud-based environment instead of as subroutines running locally within FE software, the platform is FE software agnostic and also enables multi-objective simulations. Additionally, the database within the framework evolves over

time with increasing volumes of data, which can offer powerful strategic guidance on future research and application developments.

For a FE simulation to effectively capture the features of a real forming process, it should accurately model the setup, forming process, and forming behaviour. To achieve this requires several steps: well-defined inputs, a verified FE model, and powerful predictive models. The functional modules offer guidance on the required inputs as well as descriptions of the advanced predictive models within them, whilst conventional FE and CAD software are used for the FE model setup and computation.

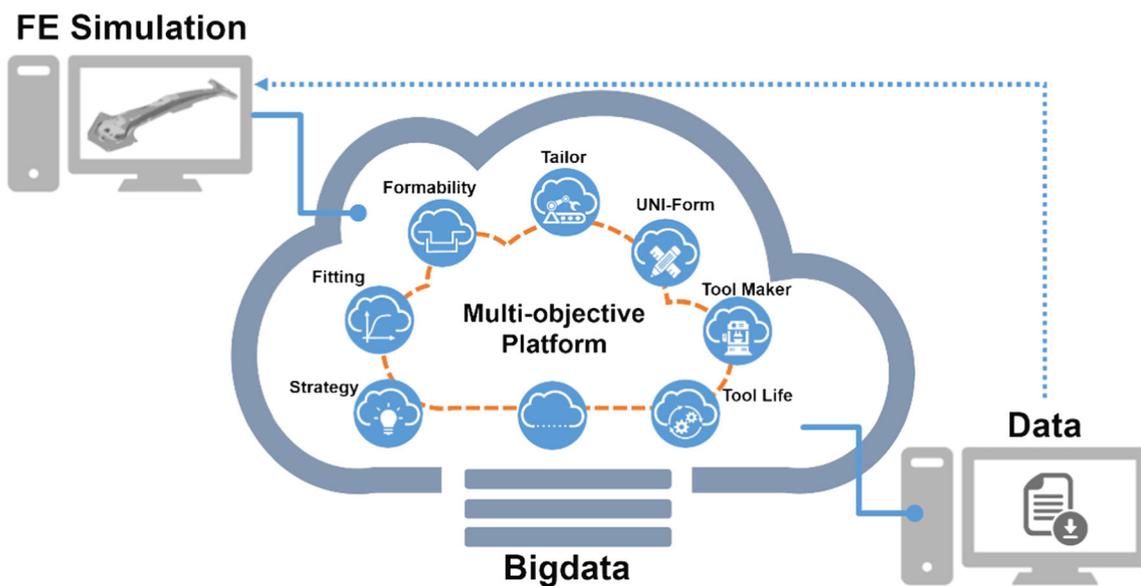


Fig. 2 The KBC-FE simulation technique

2.3 Advanced functional modules

The modules are classified into two major categories: pre- and post-FE simulation modules. Pre-FE focuses on modules that facilitate the FE model development prior to computation, whilst post-FE modules focus on the application of advanced predictive models. Pre-FE modules offer tools that facilitate the input selection process of a FE simulation, such as proposing material testing guidelines that identify the uniaxial tensile test conditions for hot stamping applications [29]. The post-FE subgroup consists of mechanism-based modules that predict post-form properties, such as necking and post-form strength.

Every post-FE functional module is a mechanism-based predictive model derived from fundamental research. Mechanism-based modules are constructed by incorporating novel scientific models into executable applications, as shown in Fig. 3. Research is conducted locally by experts in their specialised field. Core knowledge from these outcomes is then extracted, which consists of a set of equations that are formatted to be compatible with FE simulation outputs. The advanced predictive models are then built as explicit time-based solvers into a functional module through a computer-based algorithm. Once constructed, the module is made available on the cloud-based simulation platform, and is compatible with different conventional FE simulation software.

Each module forms a dedicated piece of research that is digitalised for use with FE simulations. A material database tailored to the module is also created as forming behaviour is material dependent. The user can simply utilise the model through the functional module whilst the concept and basic understanding of the model can be obtained through its corresponding available research articles. This saves considerable time and effort for users to implement models created by other researchers.

With the KBC-FE technique, users can design their part with a mindset of the entire design process. The user, with a validated basic conventional FE simulation, can assess different post-form characteristics of the part through multi-objective simulations, allowing design engineers to better predict the performance of the formed part. Functional modules offer users the flexibility to choose the ones that are most appropriate for their application and thus customising their simulations, as shown in Fig. 4. In general, the multi-objective simulation environment that KBC-FE offers allows users to carry out various feasibility studies to optimise their product design, especially in hot stamping where it is essential to incorporate frontier knowledge.

2.4 Characteristics of the KBC-FE simulation technique

The KBC-FE framework is designed to enable researchers to share their models, testing facilities, and data through functional modules. The resource layer is dynamic, with flexible

inputs that are designed to fulfil the needs of design challenges, whilst the application layer offers tailored functional modules for computation; both rely on the underlying cloud platform layer, which efficiently carries out the computations and processes the data inputs and outputs, whilst linking all the users of the framework together.

KBC-FE offers various unique functional modules that enable multi-objective simulations of metal-forming processes, allowing streamlined predictions of post-form characteristics. It provides the capability to monitor all stages of process design, creating a virtual environment for the design to be analysed under a variety of metal-forming techniques and conditions, whilst avoiding traditional lengthy trial and error processes. The KBC-FE simulation technique initiates a research and data-based value chain, as shown in Fig. 5. The value chain comprises of primary and supportive activities to deliver value. Primary activities consist of actions required to convert research and data into applications that facilitate forming process design. Support activities consist of resource, cloud platform, and applications layers that provide support for the cloud-based simulation realisation. KBC-FE connects research and FE simulations through predictive functional modules to continually improve forming process designs, whilst creating a collaborative research environment for the exploration of new technologies/features.

Operating on a cloud environment brings the benefit of saving on local computational and storage resources, particularly if a user is intending on running multiple models simultaneously. The modules used in this study are also constructed from advanced physical-based models, using knowledge gathered from different specialists in the metal-forming industry. This enhances access to expertise knowledge that is otherwise very time-consuming to implement. Whilst existing user-defined subroutines are available that can be run locally offline and do not necessitate an internet connection, KBC-FE offers equally powerful advanced predictive models but with much more operational flexibility. Currently, the number of available functional modules is limited; the platform will facilitate their expansion by providing a streamlined method for sharing knowledge. For the KBC-FE simulation technique, knowledge is the core element and evolves dynamically with ongoing research. As a knowledge centre, it will support simulation-based design, and allow advanced knowledge to be centralised and to reach both industry and academia in a more efficient manner.

3 A case study: KBC-FE simulation of a hot stamping process featuring complex thermo-mechanical loadings

Hot stamping of aluminium alloys possesses several unique features. During hot stamping, the blank experiences non-linear loading, cold die quenching, and temperature- and strain

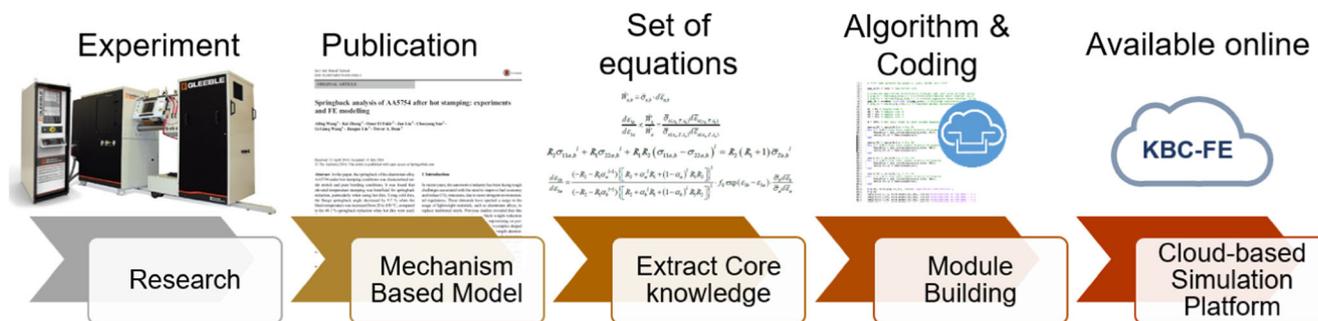


Fig. 3 Mechanism-based module development

rate-sensitive deformation. The temperature change is modelled by contact pressure-dependent interfacial heat transfer coefficients, where pressure is forming process and tool design dependent. The post-form strength is affected by pre-existing dislocations, quenching rate, as well as the level of strains and precipitation formation. However, these advanced features cannot be modelled by conventional FE simulation software and require advanced predictive models introduced through functional modules.

In the present research, the capability of KBC-FE enabled multi-objective simulations is demonstrated through the study of an aluminium alloy AA6082 U-shaped component produced under hot stamping conditions, where the advanced predictive functional modules ‘Formability’, ‘Tool Maker’, and ‘Tailor’ are demonstrated. The U-shape geometry was selected to demonstrate the functionality and benefits of a multi-objective simulation; however, more complex-shaped components were used for the development of the individual modules. ‘Formability’ inspects the formed part for the occurrence of necking [29, 30]; ‘Tool Maker’ assesses the quenching efficiency of the tools, which has a direct impact on the post-form strength [31]; and ‘Tailor’ predicts the artificial ageing process required to achieve the desired post-formed strength of a formed part for a given set of stamping conditions [23]. The multi-objective simulation was achieved by carrying out parallel computations of several modules on

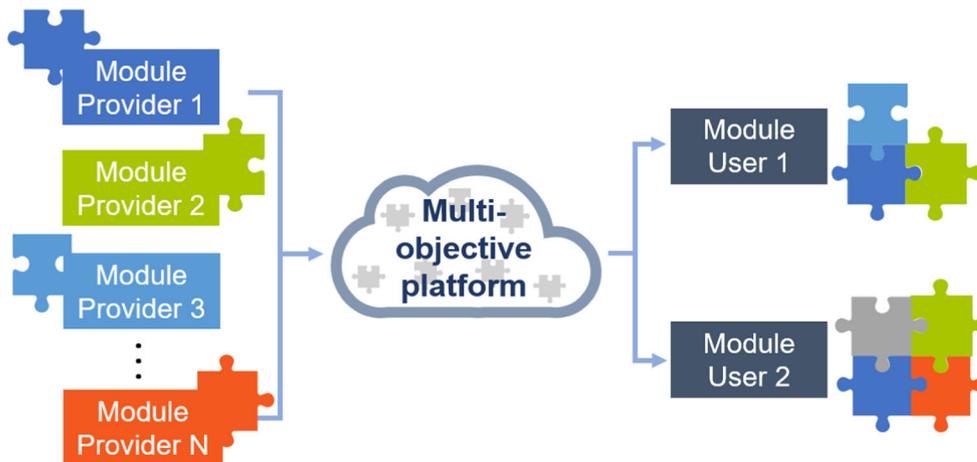
the KBC-FE platform. This analysis was not possible using the conventional simulation of the forming process alone.

The KBC-FE simulation technique requires the use of conventional FE simulations in conjunction with advanced functional modules on the platform. The conventional FE simulation is conducted locally using FE simulation software such as PAM-STAMP. With an experimentally validated FE model, basic simulation outputs required by the functional modules of interest are uploaded onto the online platform, via www.smartforming.com. Once uploaded, the input files are processed and every element’s thermo-mechanical deformation history is recognised and stored with a unique and anonymous identifier for subsequent computation. Functional modules are then selected depending on the features of a forming process the user intends to capture. The computation is then carried out on an element by element basis remotely. Once completed, the system writes the computed results into a format that can be imported back into the original FE simulation to visualise the results on the simulated part; the procedure is shown in Fig. 6.

3.1 Conventional FE simulation setup and FE model validation

To obtain the experimental data for this work, a U-shaped part was hot formed from 1.5-mm-thick AA6082 material. The

Fig. 4 Module-based tailored design process for a given simulated part



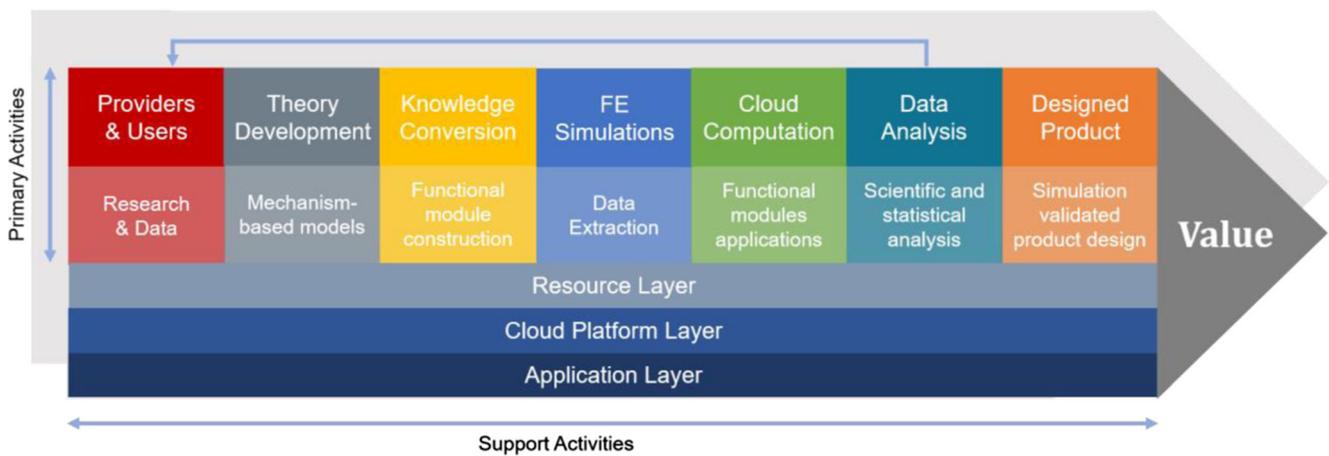


Fig. 5 The KBC-FE value chain

blank was first heated in a furnace, transferred to the forming tools, and formed at an initial temperature of 490 °C, followed by in-die quenching. The FE model was set up accordingly where only half of the U-shape was simulated by utilising a symmetry condition, as shown in Fig. 7. The simulation process parameters are listed in Table 1 and represent the real forming conditions. The locally conducted FE simulation in PAM-STAMP forms the basis for the advanced multi-objective simulations on the KBC-FE platform that follow.

The simulation results were first experimentally validated to ensure that the subsequent computations by the functional modules were reliable. This was done by comparing the temperature evolution and thickness distribution between the experiments and simulations. Figure 8a shows the temperature evolution comparison measured at two locations on the specimen by thermocouples embedded mid-thickness of the specimen over the duration of the stamping process; Fig. 8b shows the central cross-sectional thickness distribution comparison between the experiment and simulation along the curvilinear distance of the formed part. Very good agreements were obtained for both the temperature and thickness comparisons, verifying that the FE simulation was conducted accurately and was suitable for further computation using the advanced functional modules.

3.2 Cloud-based multi-objective simulation

With the FE simulation verified, the online KBC-FE platform was accessed to select the desired functional modules. These modules were built independently from theoretical models to simulate a given phenomenon. Each module specifies their own required inputs in two forms: the simulation process parameters and the simulation data outputs. The simulation process parameters consist of details such as the material used, forming stroke, and forming speed. The conventional simulation data outputs are computed by the FE software, and include temperature, major strain, and minor strain histories.

The required inputs were uploaded to the functional modules for computation, as shown in Fig. 9. The advanced functional modules chosen in this case study were ‘Formability’, ‘Tool Maker’, and ‘Tailor’.

Once the forming process conditions were specified, the required simulation data outputs from each element of the model were exported from the conventional simulation and uploaded onto the online platform.

For the ‘Formability’ module, the simulation outputs required are the temperature, major strain, and minor strain of each element from every simulation stage, whilst the forming process conditions required are the material, stamping speed, and stroke. For the ‘Tool Maker’ module, the simulation outputs required are the temperature and contact pressure of each element for every simulation stage, whilst the forming process conditions required are the material, stamping speed, stroke, and quenching time. Finally, for the ‘Tailor’ module, the simulation outputs required are the temperature, major strain, and minor strain of each element for every simulation stage, whilst the forming process conditions required are the material, stamping speed, stroke and artificial ageing time, and temperature. Selective computation is available if desired, where a filter is applied such that only regions of potential risk are computed, thus reducing computational cost, e.g. the ‘Formability’ module is only applied to moderately and heavily stretched elements. During computation, the module evaluates the elements against the module-specific criteria. The computation results were subsequently downloaded and imported back to the FE software to be visualised.

3.2.1 Module: Formability

During hot forming, the blank material undergoes complicated temperature, strain rate, and strain path changes that affect its formability, but are not captured by traditional constant temperature forming limit diagrams. The ‘Formability’ module predicts failure by incorporating an advanced Viscoplastic-

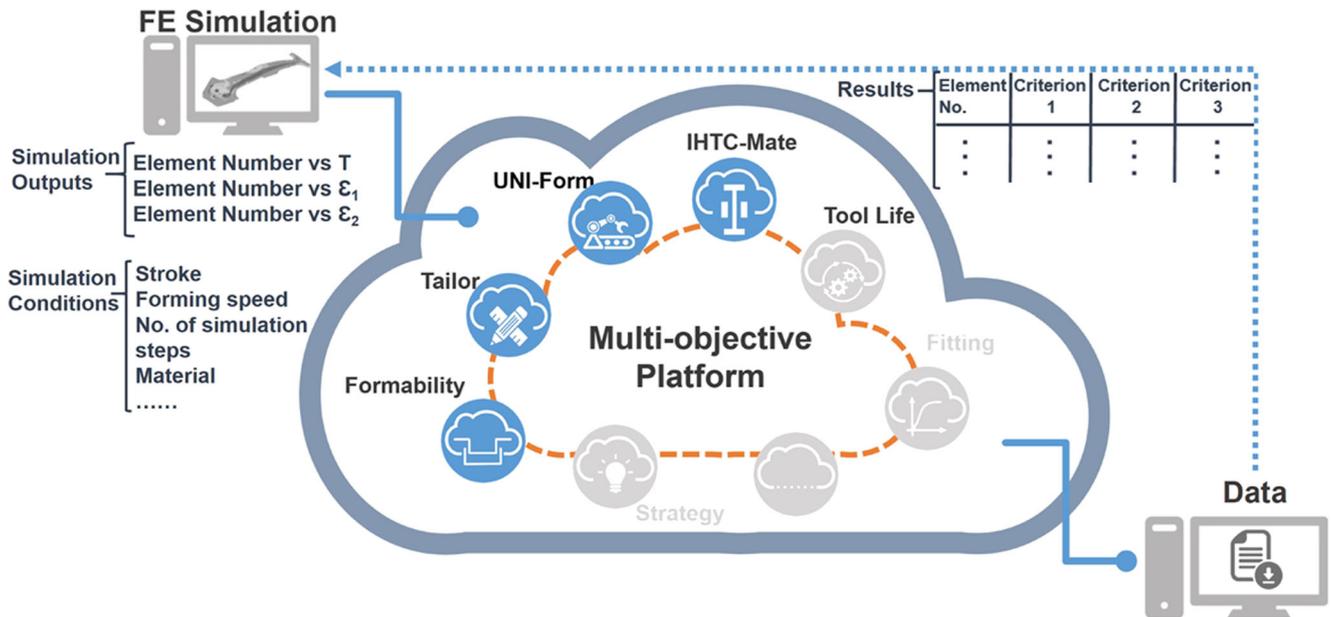


Fig. 6 The KBC-FE procedure used in the present case study

Hosford-M-K model calibrated for AA6082 that accounts for the effect of the complicated thermo-mechanical changes occurring during each time step of the deformation process. Failure is defined as when localised necking occurs, and is characterised by the evolution of specified failure criteria, Eq. (1) [30].

$$\frac{d\varepsilon_{1B}}{d\varepsilon_{1A}} \geq 10, \text{ or } \frac{d\varepsilon_{3B}}{d\varepsilon_{3A}} \geq 10 \tag{1}$$

A failure criterion larger than 10 indicates localised necking; elements with values lower than 10 are defined as safe. ‘Formability’ predicted that the U-shaped part could be

successfully formed without necking, with the failure criterion reaching a maximum value of 1.2 in the sidewall region, as shown in Fig. 10. This was confirmed by the experimentally formed component, which had no visible necking. In addition to the incidence of necking, the ‘Formability’ module can also provide the evolution of various parameters for each element of the model, including the individual stress and strain components, for further analysis.

3.2.2 Module: Tool Maker

Tool design is a crucial factor in the forming of a component to ensure that it fully meets the desired design specifications. In the hot forming of a heat-treatable aluminium alloy, an accurate design as well as optimised process parameters is required to ensure that the critical quenching rate is achieved during forming, thus obtaining the optimal strength in a subsequent artificial ageing process. The ‘Tool Maker’ module evaluates the tool/blank quenching efficiency during the hot stamping process by assessing the temperature evolution during forming.

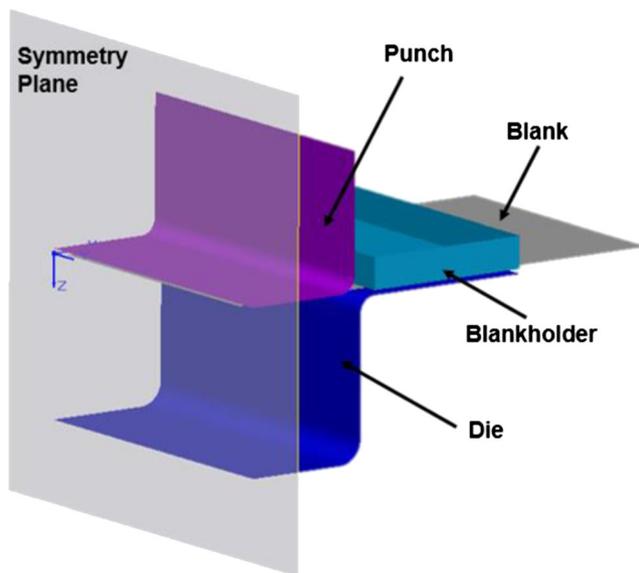


Fig. 7 U-shape half model used in the FE simulation

Table 1 Main process and simulation parameters

Initial workpiece temperature (°C)	490
Initial tooling temperature (°C)	20
Punch speed (mm/s)	250
Blankholding force (kN)	5
Die closing force (kN)	50
Friction coefficient	0.15
Interfacial heat transfer coefficient	Function of pressure/gap [30]

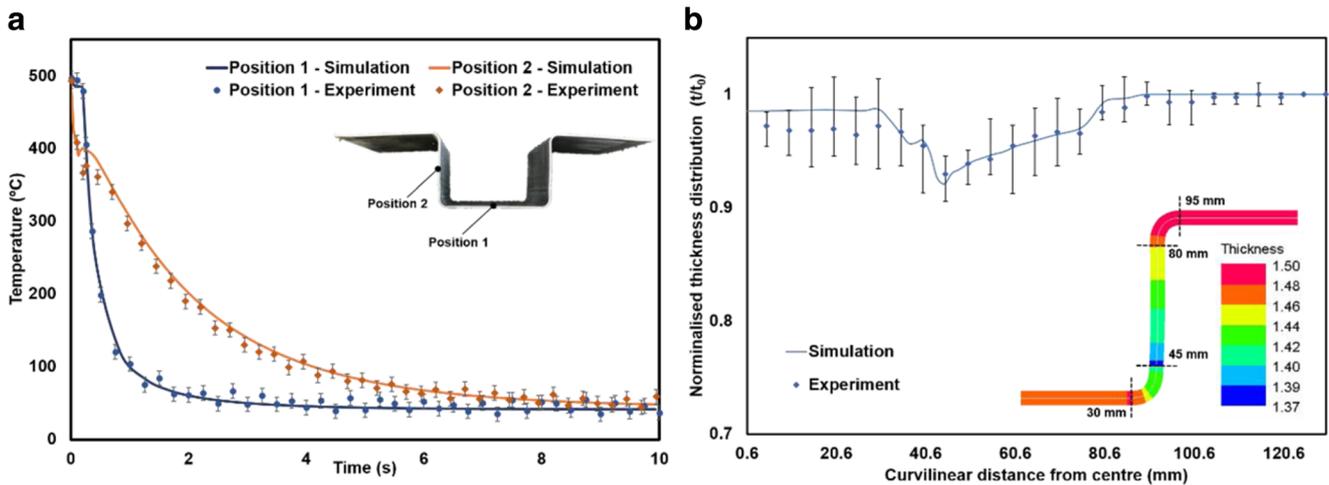


Fig. 8 a Temperature evolution comparison between the experiment and simulation. b Central cross-sectional thickness distribution comparison between the experiment and simulation along the curvilinear distance of the formed part

The temperature history of each element and the corresponding cooling rate during forming is assessed and evaluated against the material-specific CCP diagram, to compute the quenching rate of each element and determine whether it has met the critical cooling rate. Figure 11a shows the cooling rate and the pressure encountered during stamping and quenching, accompanied with a temperature contour of the component 1 s into the in-die quenching process, from which the variation in the blank temperature can be observed; Fig. 11b shows the temperature profiles for the elements selected in Fig. 11a during forming, and the CCP diagram for AA6082. If the region of interest does not meet this requirement, this would indicate that the forming process design needs to be modified, e.g. by adjusting parameters such as die design, die closing force, cooling channel design, and forming speed.

For the U-shape component analysed using ‘Tool Maker’, element 1 had a low initial pressure as direct contact with the punch was not established, resulting in a low cooling rate. However, pressure increased as deformation progressed and when the die closing force was applied, up to the constant pressure used during quenching, leading to a higher cooling rate. On the other hand, element 2 had a higher initial cooling rate and moderate pressure as the element was in contact with the blankholder. The pressure then decreased as the material flowed from the blankholder region to the side wall region. Element 3 was free hanging and thus had zero pressure acting on it. Its cooling rate eventually increased due to heat transfer with adjacent elements, which were rapidly cooled under the blankholder region. The results from ‘Tool Maker’ showed that the majority of the part had achieved the critical quenching rate.

Fig. 9 The advanced functional modules and their required inputs for the KBC-FE enabled multi-objective simulations

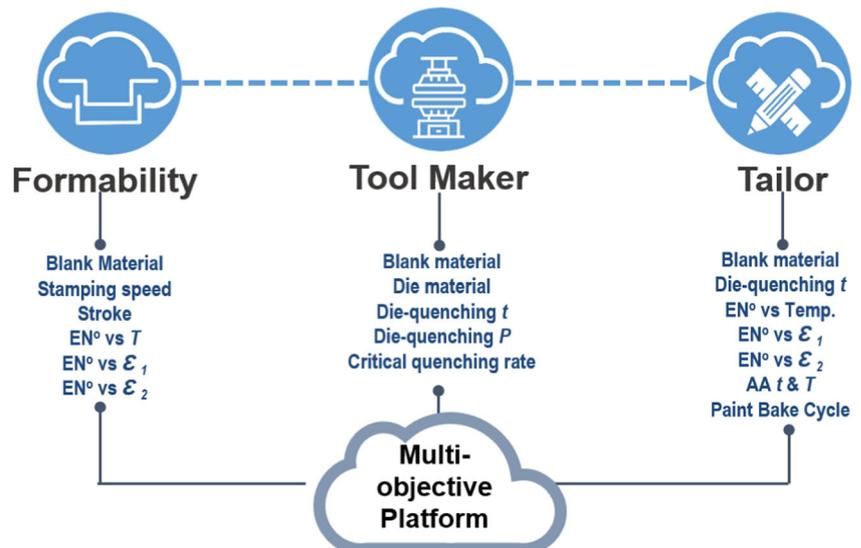
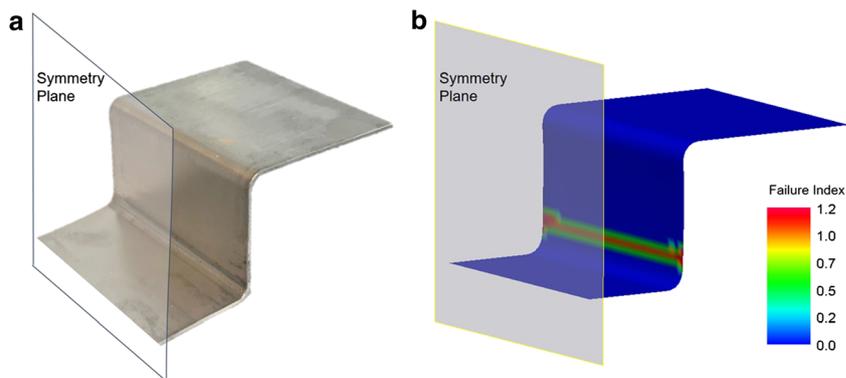


Fig. 10 Formability of the U-shaped formed part. **a** Half U-shape formed specimen. **b** ‘Formability’ module failure prediction



3.2.3 Module: Tailor

Post-form strength prediction for hot forming of the heat-treatable aluminium alloy AA6082 is challenging due to the combined effects of heating, pre-straining during stamping, and multi-stage artificial ageing. The precise details of the artificial ageing process are highly dependent on the temperature and strain evolution that the blank material undergoes. Determining the optimal artificial ageing condition is crucial for strengthening the material to its peak condition, whilst avoiding undesirable under or over-ageing. The functional module ‘Tailor’ incorporates an advanced post-form strength (PFS) prediction model developed by Zhang et al. that accounts for pre-existing precipitates and dislocations during hot stamping, and multi-stage post-form heat treatments [21]. The model was calibrated for AA6082 through a series of high temperature tensile tests carried out at different strain levels and strain rates, and artificial ageing tests at different temperatures and time periods. The model consists of two sub-models. The first sub-model consists of viscoplastic constitutive equations that were used to capture the stress-strain

evolution of the material, same as that used in the ‘Formability’ module. The normalised dislocation density, $\bar{\rho}$, from the first sub-model was used to calculate the dislocation density rate, $\dot{\bar{\rho}}$, Eq. (2), which was used as an input to the second sub-model. The first term represents dislocations generated due to plastic deformation, the second term represents the dynamic recovery of dislocations, and the third term represents static recovery [32].

$$\dot{\bar{\rho}} = A_0 \dot{\epsilon}_p - A_0 \bar{\rho} \dot{\epsilon}_p - C_{aging} \bar{\rho}^{n_2} \tag{2}$$

where A_0 , C_{aging} , and n^2 are calibrated material constants, and $\dot{\epsilon}_p$ denotes the plastic strain rate.

The second sub-model consists of age hardening equations to predict the precipitation hardening responses of AA6082 during artificial ageing. The yield stress, σ_y , was defined as a function of the stress due to dislocations, σ_{dis} , the solid solution stress, σ_{ss} , the intrinsic strength, σ_i , and the precipitation strength, σ_{ppt} , as shown in Eq. (3), where the latter is in itself a function of the precipitation shearing stress, σ_{sh} , and the precipitate bypassing stress, σ_{by} . Dislocation hardening strength

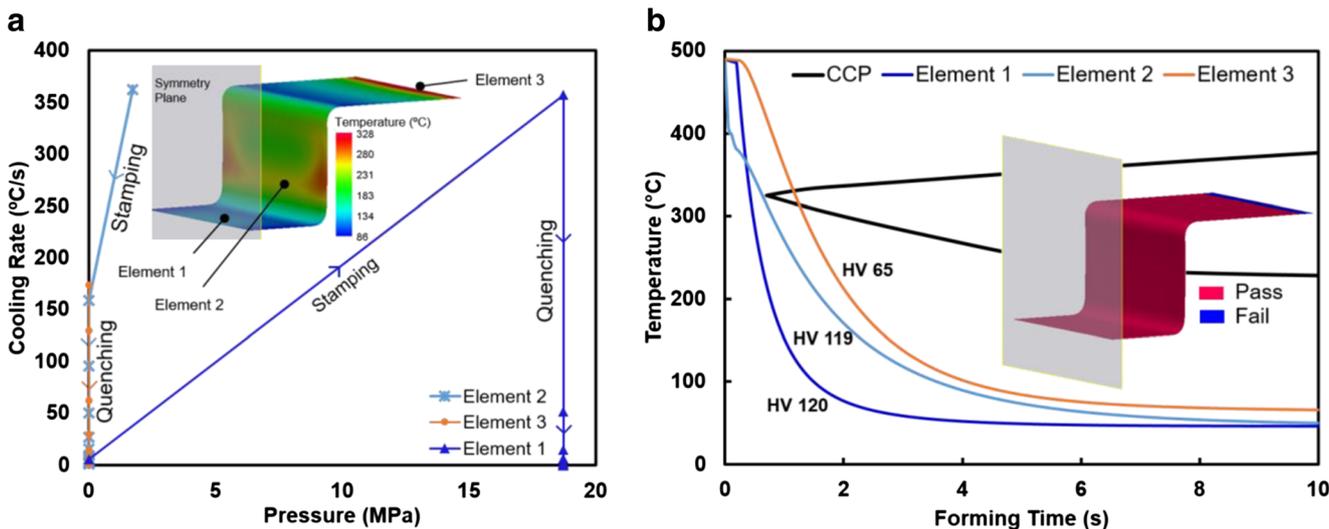


Fig. 11 **a** Cooling rate against contact pressure during forming. **b** Temperature evolution and continuous cooling precipitation diagram, for selected elements

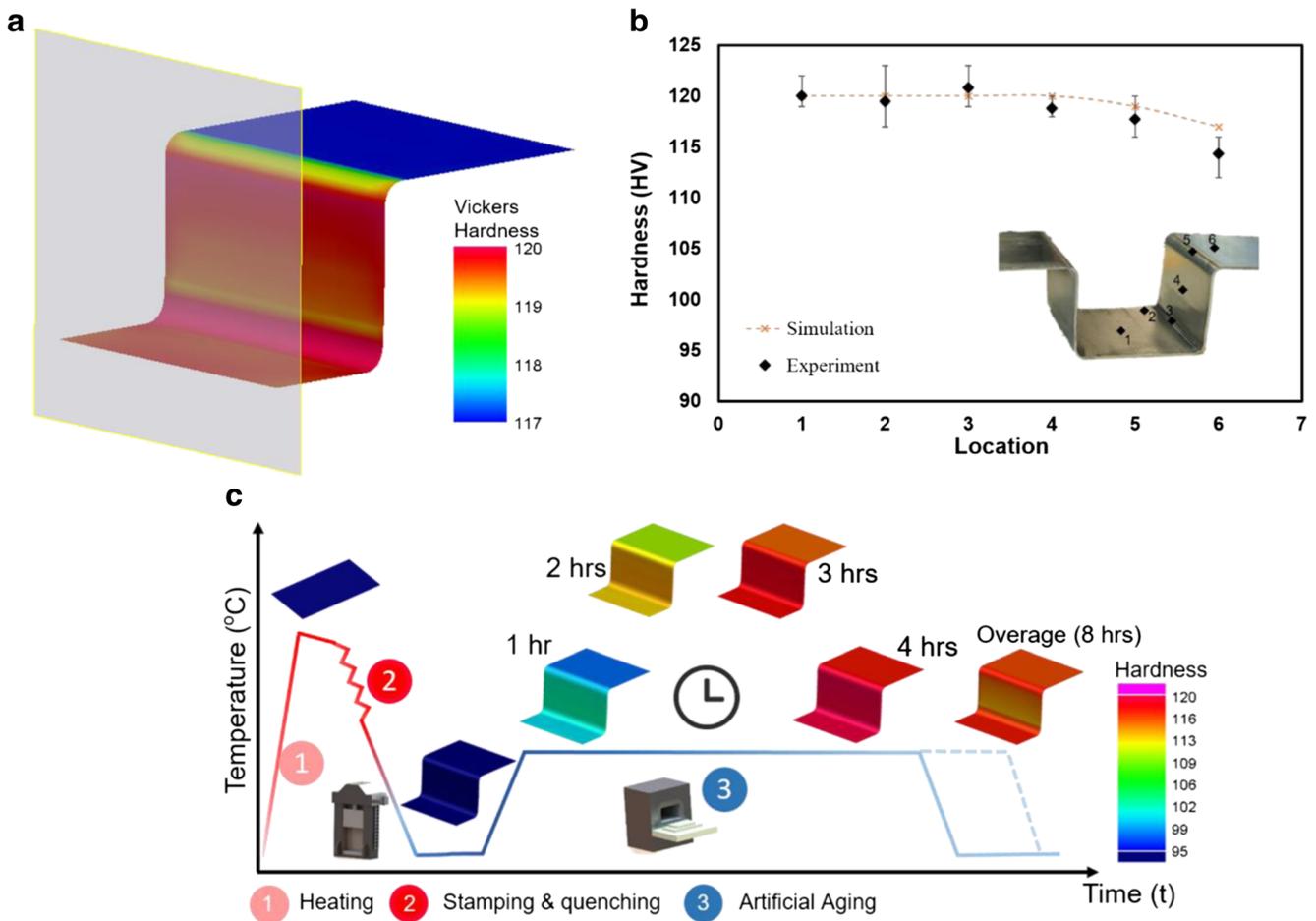


Fig. 12 ‘Tailor’ prediction. **a** ‘Tailor’-predicted hardness distribution under the artificial ageing condition: 4 h at 180 °C. **b** Hardness comparison between ‘Tailor’ prediction and experimental values. **c** Temperature and specimen hardness evolution during forming

is directly proportional to normalised dislocation density during artificial ageing at elevated temperatures, as shown in Eq. (4).

$$\begin{aligned} \sigma_{\text{total}} &= \sigma_{\text{dis}} + \sigma_{\text{ss}} + \sigma_i + \sigma_{\text{ppt}} \\ &= \sigma_{\text{dis}} + \sigma_{\text{ss}} + \sigma_i + \frac{\sigma_{\text{by}}\sigma_{\text{sh}}}{\sigma_{\text{by}} + \sigma_{\text{sh}}} \end{aligned} \quad (3)$$

$$\sigma_{\text{dis}} = A_0 \bar{\rho}^{n_2} \quad (4)$$

‘Tailor’ computes the artificial ageing conditions for the chosen optimisation method as well as generating the strength evolution, with the post-form strength expressed in terms of the Vickers hardness or the yield strength. Several post-form strength optimisation methods are available, such as ‘highest strength in shortest time’ and ‘greenest production’. For the hot stamping of the U-shape part in the current case study, the model predicted an optimal artificial ageing time of 4 h at a temperature of 180 °C. Figure 12a shows the ‘Tailor’-predicted optimal hardness distribution visualised in the original simulation software; Fig. 12b shows the hardness comparison between predicted and experimental results, where very good

agreements were achieved; Fig. 12c shows the temperature and predicted specimen hardness evolution during forming. As pre-straining accelerates the artificial ageing process, higher hardness values were observed on the bottom and side-wall of the formed part where the greatest deformation occurred.

4 Conclusion

The capability of the KBC-FE simulation technique in enabling multi-objective simulations was successfully demonstrated through the case study of the hot forming of the U-shaped part from the aluminium alloy AA6082. The hot stamping of aluminium alloys encompasses unique features that require extensive expert knowledge. The blank experienced non-isothermal conditions and non-linear loading paths, which has a significant effect on the material formability as it is highly sensitive to the thermo-mechanical history. The post-form strength is affected by pre-existing dislocations, the quenching rate, as well as the level of strain and precipitation

formation. However, these advanced features cannot be modelled by conventional FE simulation software but require advanced predictive models introduced in the functional modules. By utilising KBC-FE, the component's formability and post-form strength under hot stamping conditions could be easily predicted without the need of subroutines, and results were successfully experimentally verified. By combining expertise on different aspects of hot forming processes in the form of the advanced functional modules, the formed U-shaped part could be rigorously assessed. In the absence of KBC-FE, the predictive models contained within different modules would have had to be studied separately, requiring cross-disciplinary knowledge from users, leading to an extremely time- and resource-consuming process with no assurance of quality.

The KBC-FE simulation technique offers a new approach for the computation of advanced predictive models, benefiting researchers as well as engineers. It provides essential functionalities tailored to individual needs; it is easy to implement and flexible to operate. This technique is not limited to aluminium alloys but can be applied to a broader range of materials and forming processes. KBC-FE will bring research to practice faster, increases scientific model applications, and provides integrated scientific-based design solutions for the sheet metal forming industry.

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References

- Gubbi J, Buyya R, Marusic S, Palaniswami M (2013) Internet of Things (IoT): a vision, architectural elements, and future directions. *Futur Gener Comput Syst* 29:1645–1660
- Kaur PD, Chana I (2014) Cloud based intelligent system for delivering health care as a service. *Comput Methods Prog Biomed* 113: 346–359
- Chang V (2017) Towards data analysis for weather cloud computing. *Knowl-Based Syst* 127:29–45
- Ren L, Zhang L, Wang L, Tao F, Chai X (2017) Cloud manufacturing: key characteristics and applications. *Int J Comput Integr Manuf* 30:501–515
- Tao F, Cheng J, Qi Q, Zhang M, Zhang H, Sui F (2017) Digital twin-driven product design, manufacturing and service with big data. *Int J Adv Manuf Technol* 94:3563–3576
- Guo L (2016) A system design method for cloud manufacturing application system. *Int J Adv Manuf Technol* 84:275–289
- Allwood JM, Childs THC, Clare AT, De Silva AKM, Dhokia V et al (2016) Manufacturing at double the speed. *J Mater Process Technol* 229:729–757
- Zhong RY, Lan S, Xu C, Dai Q, Huang GQ (2016) Visualization of RFID-enabled shopfloor logistics Big Data in Cloud Manufacturing. *Int J Adv Manuf Technol* 84:5–16
- Lu Y, Cecil J (2016) An Internet of Things (IoT)-based collaborative framework for advanced manufacturing. *Int J Adv Manuf Technol* 84:1141–1152
- Elsevier (2017) R Code Viewer. In: <https://www.elsevier.com/authors/author-services/enrichments/rcodeviewer>. Accessed 09/01 2018
- Autodesk (2017) Fusion 360. In: <https://www.autodesk.com/products/fusion-360/overview>. Accessed 09/01 2018
- ESI (2017) ESI Cloud - cloud based virtual engineering solutions. In: <https://cloud.esi-group.com/>. Accessed 09/01 2018
- Bloeck M (2012) 5 - Aluminium sheet for automotive applications. In: Rowe J (ed) *Advanced materials in automotive engineering*. Woodhead Publishing, Sawston, pp 85–108
- Bolt PJ, Lamboo NAPM, Rozier PJCM (2001) Feasibility of warm drawing of aluminium products. *J Mater Process Technol* 115:118–121
- Wang L, Sun Y, Ji K, Luan X, El Fakir O, Cai Z, Liu X (2017) Fast warm stamping of ultra-high strength steel sheets. Patent application number: 1713741.5
- Wang A, Zhong K, El Fakir O, Liu J, Sun C, Wang L, Lin J, Dean TA (2016) Springback analysis of AA5754 after hot stamping: experiments and FE modelling. *Int J Adv Manuf Technol* 89:1339–1352
- Xiao W, Wang B, Zheng K (2017) An experimental and numerical investigation on the formability of AA7075 sheet in hot stamping condition. *Int J Adv Manuf Technol* 92:3299–3309
- Zhou D, Yuan X, Gao H, Wang A, Liu J, El Fakir O, Politis DJ, Wang L, Lin J (2016) Knowledge based cloud FE simulation of sheet metal forming processes. *J Vis Exp* 118:e53957
- Gao H, El Fakir O, Wang L, Politis DJ, Li Z (2017) Forming limit prediction for hot stamping processes featuring non-isothermal and complex loading conditions. *Int J Mech Sci* 131:792–810
- Kami A, Dariani BM, Sadough Vanini A, Comsa DS, Banabic D (2015) Numerical determination of the forming limit curves of anisotropic sheet metals using GTN damage model. *J Mater Process Technol* 216:472–483
- Zhang Q, Dhawan S, Luan X, Du Q, Liu J, Wang L (2018) Investigation and constitutive modelling of high strength 6xxx series aluminium alloy: precipitation hardening responses to FAST (Fast light Alloys Stamping Technology) and artificial ageing. *International conference on processing & manufacturing of advanced materials processing, fabrication, properties, applications (Thermec' 2018), Paris, France*
- Milkereit B, Wanderka N, Schick C, Kessler O (2012) Continuous cooling precipitation diagrams of Al–Mg–Si alloys. *Mater Sci Eng A* 550:87–96
- Shercliff HR, Ashby MF (1990) A process model for age hardening of aluminium alloys—I. The model. *Acta Metall Mater* 38(10): 1789–1802
- Mohamed MS, Foster AD, Lin J, Balint DS, Dean TA (2012) Investigation of deformation and failure features in hot stamping of AA6082: experimentation and modelling. *Int J Mach Tools Manuf* 53:27–38
- Ablat MA, Qattawi A (2017) Numerical simulation of sheet metal forming: a review. *Int J Adv Manuf Technol* 89:1235–1250
- Bellenger E, Benhafid Y, Troussier N (2008) Framework for controlled cost and quality of assumptions in finite element analysis. *Finite Elem Anal Des* 45(1):25–36
- Luan X, Zhang Q, El Fakir O, Wang L (2016) Uni-Form: a pilot production line for hot/warm sheet metal forming integrated in a

- cloud based SMARTFORMING platform. The 3rd international conference on advanced high strength steel and press hardening (ICHSU2016), Xi'an, China
28. Liu X, Fakir OE, Meng L, Sun X, Li X, Wang L (2017) Effects of lubricant on the IHTC during the hot stamping of AA6082 aluminium alloy: experimental and modelling studies. *J Mater Process Technol* 225:175–183
 29. Wang A, Zheng Y, Liu J, El Fakir O, Masen M, Wang L (2016) Knowledge based cloud FE simulation - data-driven material characterization guidelines for the hot stamping of aluminium alloys. *J Phys Conf Ser* 734:032042
 30. Wang A, Liu J, Gao H, Wang L, Masen M (2017) Hot stamping of AA6082 tailor welded blanks: experiments and knowledge-based cloud – finite element (KBC-FE) simulation. *J Mater Process Technol* 250:228–238
 31. Liu J, Wang A, Zheng Y, Liu X, Gandra J, Beamish K, Wang L et al (2017) Hot stamping of AA6082 tailor welded blanks for automotive applications. *Procedia Eng* 207:729–734
 32. Lin J, Liu Y, Farrugia DCJ, Zhou M (2005) Development of dislocation-based unified material model for simulating microstructure evolution in multipass hot rolling. *Philos Mag* 85:1967–1987