



An improved DIC method for full-field strain measurement in tensile tests on aluminium alloys under hot stamping conditions

Siyi Chen, Ruiqiang Zhang^{*}, Zhusheng Shi, Jianguo Lin

Department of Mechanical Engineering, Imperial College London, London SW7 2AZ, UK

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ABSTRACT

Digital image correlation (DIC) outperforms other strain measurement technologies due to its versatility, accuracy, non-contact nature, and capability to capture full-field strains. However, for aluminium alloys like AA6082 under high-temperature and large-deformation conditions, the shiny effects observed in the gauge area degrade the quality of the captured deformation images, leading to failures in the DIC analyses. In this study, the source of the shiny effects was investigated by analysing the evolution of AA6082 specimen surfaces painted with speckle patterns during hot stamping deformation. It was found that the shiny effects were attributed to the exposure of the reflective base material due to paint peeling and cracking. To overcome these problems, the DIC method was improved by developing a novel procedure for generating more effective speckle patterns and utilising a cross-polarisation optical system (XPOL) to mitigate the shiny effects. The improved DIC method was applied to AA6082 in both uniaxial and biaxial tensile tests under diverse hot stamping conditions, along with applications to boron steel for comparison. These improvements significantly reduced the shiny effects and increased the time over which full-field strains can be measured for AA6082, reaching over 96% (up from 75%) of the fracture time in the uniaxial tests and even 100% in the biaxial tests. The improved DIC method enables the full-field strain measurement for aluminium alloys under hot stamping conditions, allowing for the accurate determination of their thermomechanical properties.

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1. Introduction

In recent years, the growing demand for lightweight components has led to the extensive adoption of hot stamping technologies in the automotive industry. Compared to cold forming processes, hot stamping enables the production of more complex parts with better precision [1]. The effort to reduce vehicle weight has led to a growing interest and application of light materials, notably high-strength grades of aluminium alloys like AA6XXX. The hot form and quench (HFQ®) process for stamping heat-treatable, high-strength aluminium alloys involves the solution heat treatment (SHT) of the blanks, rapidly forming them in cold dies, and immediate quenching to achieve dimensional accuracy and a

supersaturated solid solution microstructure, followed by artificial ageing to enhance the material's strength [2].

For precise simulation of industrial hot stamping processes, thermomechanical properties of sheet metals under hot stamping conditions are essential for the calibration of their constitutive models [3]. Mechanical properties, such as the yield strength and strain-hardening behaviours, are commonly obtained through uniaxial tensile tests using the Gleeble thermomechanical simulator which provides high heating and cooling rates, along with digital image correlation (DIC) for accurate strain field measurements [4]. The forming limit diagram (FLD), a crucial tool for evaluating the formability of sheet metals and calibrating the constitutive models, comprises a series of forming limit curves (FLCs) above which localised necking occurs resulting in material failure [5]. FLCs are often acquired from multi-axial tensile tests involving different major-to-minor strain ratios; however, accurately measuring FLCs under hot stamping conditions using standard Nakajima and Marciniak punch tests presents challenges [4–6]. A new biaxial test method, which has been applied to

^{*} Corresponding author.

E-mail address: r.zhang17@imperial.ac.uk (R. Zhang).

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successfully determine FLCs for boron steel 22MnB5 under hot stamping conditions, uses DIC technology to measure the full-field strains within the gauge area throughout the deformation, and a spatio-temporal method to analyse the full-field strains for determining the limit strains [7,8]. However, when applying DIC to aluminium alloys for measuring full-field strains in uniaxial or biaxial tensile tests under hot stamping conditions, it has been observed that problematic shining effects on captured deformation images can lead to failures in the DIC strain measurement, consequently impeding the determination of accurate thermomechanical properties and formability of the materials.

The purpose of this study is to develop an improved DIC technique that can be used for the full-field strain measurement throughout thermomechanical tests on aluminium alloys like AA6082 under hot stamping conditions. The source of the shiny effects was identified through a comprehensive analysis of the deformed AA6082 specimens, which involved utilising optical microscopy to examine their surfaces painted with speckle patterns. In the improved DIC method, the procedure for producing the speckle patterns on the specimen surfaces was optimised to reduce their debonding and cracking. Furthermore, a cross-polarisation optical system (XPOL) was implemented to minimise the reflective effects on the captured deformation images. The effectiveness of this enhanced DIC strain measurement method was tested by applying it to AA6082 in both uniaxial and biaxial tensile tests under hot stamping conditions, together with applications to 22MnB5 for comparison. The improvement resulting from the new bespeckling method and the DIC scheme with XPOL was examined. Additionally, the best processing parameters for the DIC software (i.e. GOM correlate 2018) were identified by conducting parametric studies.

2. Review of existing strain measurement methods

This section summaries and contrasts common strain measurement techniques for mechanical testing, highlighting the aptness of DIC methods for strain determination in various situations. It underscores the critical need to enhance DIC strain measurement methods, especially for full-field strain measurement of aluminium alloys under hot stamping conditions. To determine the mechanical properties of test materials, strain measurements are required while they undergo deformations under pre-set conditions. Several methods are available for measuring lengthwise strains in the uniaxial tensile tests; these include (i) strain gauges [9], (ii) longitudinal extensometers, including contact types and non-contact types (e.g. laser extensometers) [10,11], (iii) lateral extensometers [10], (iv) electronic speckle pattern interferometry (ESPI) [12,13], (v) photogrammetry [14] and (vi) DIC methods [15,16]. Non-contact strain measurement methods such as ESPI, photogrammetry and DIC can be used to determine full-field strains of the specimens used in biaxial tests [17]. Table 1 summarises the advantages and disadvantages of the popular strain measurement methods employed in the characterisation of materials.

Both the strain gauges and the contact extensometers rely on physical contact with the object for the monitoring of the distance change across the initial gauge lengths [9]. These devices are very accurate and precise, and they are typically inexpensive. Nonetheless, they are not always suitable for measuring strains at high temperatures and cannot provide full-field strains [17]. The ESPI relies on the interference of light and image processing algorithms to deduce the strains on a surface with high spatial accuracy [13]. While ESPI has the advantage of measuring full-field strains without the need to create artificial speckle patterns, its complex setup and high cost often make it unsuitable for strain measurements of engineering components or metallic specimens [12,13].

Photogrammetric methods, such as GOM Argus, measure the strains at the time only after the completion of tests [14]. On the other hand, real-time DIC techniques capture the specimen's deformation at high frame rates to generate continuous strain information [18]. The photogrammetric and DIC methods both calculate the full-field strains by digitally mapping the deformation of the random speckle patterns on the specimen surfaces between the reference and deformed images [15,16]. These methods are widely used for measuring strain fields due to their high spatial accuracy and non-contact nature.

In a uniaxial test, the strain measured within the gauge length of the specimen would represent the average strain across that specific gauge length. To mitigate the effects of necking on the average strain value, a large gauge length is generally used. However, varying the gauge length in uniaxial tensile tests under hot stamping conditions has a significant impact on the obtained stress-strain curves [19]. The definition of the gauge length is therefore of great significance to the characterisation of the tested materials. Vautrin et al. [20] proposed the use of optical methods based on geometrical correlations or light interference to obtain the full-field strain map of the tested specimen. The full-field strain measurement is an essential requirement for most biaxial tests. It also helps to overcome the issue of selecting a suitable gauge length for uniaxial tests by allowing the use of different virtual post-processing gauge lengths. Until the end of the 2000s, interferometric techniques like ESPI were more frequently employed than DIC. This trend changed with the introduction of modern computers and high-resolution digital cameras, as depicted in Fig. 1. Compared to the interferometric methods, DIC techniques have less strict testing environment requirements and simpler set up [21].

DIC methods are commonly used for strain measurements of various engineering and biomedical materials [15]. These techniques have generated considerable interest in metallic testing, especially in situations where implementing other strain measurement approaches might be challenging. Such difficulty could arise from environmental conditions, such as high temperatures, the presence of high elastic unloading energy from the broken specimen, or the requirement for full-field strain measurement [10,15,22]. Nevertheless, DIC requires uniform-sized, random speckles on specimen surfaces that can be easily deformed together with specimen deformation [23]. Researchers have explored different painting solutions for improved DIC performance because the reduced ductility of the paints under high-temperature conditions causes the speckle patterns to crack and peel off the specimen surface when subjected to large strains [11]. In the past, DIC at high temperatures was applied to determine the coefficient of thermal expansion of nickel-alloyed steel at temperatures as high as 1200 °C [16]. Zhang et al. [4,7] successfully measured the full-field strains of boron steel specimens using DIC at temperatures up to 950 °C. Moreover, it was discovered that the adhesion of the paints to specimen surfaces dramatically improved after sandblasting [4]. Also, Alharbi et al. [24] claimed that the nital etching technique could be used to create valleys on the specimen surfaces to enhance paint adhesion. Despite the availability of non-painting techniques such as chemical etching and laser engraving [14,25], the use of airbrushes to paint specimens remains the most convenient and thus the dominant patterning/bespeckling method for generating the speckle patterns [11].

Non-contact strain measurement relies on observing the interaction between light and the specimen surfaces. Light is a form of electromagnetic waves with oscillating electric and magnetic fields that are aligned orthogonally to each other [26]. Unpolarised light consists of electromagnetic waves with random polarisation directions [26]; passing light through a linear polariser results in preferential absorption of the electric and magnetic vectors in

Table 1
Evaluations of commonly used strain measurement methods.

Measurement methods	Mechanisms	Advantages	Disadvantages
Strain gauges [9,17]	Strains are measured in a specific direction by monitoring changes in the electrical resistance of the metal foil. The principal strain can be measured by deploying multiple strain gauges in a rosette.	- Easy to install - Inexpensive - Accurate to ~0.5% of the measured strain	- Only provide local strains - Not suitable for very high-temperature applications (e.g. >250 °C)
Contact extensometers [10]	Tips of the extensometer are attached to the specimens during the entire deformation to measure the strain continuously.	- Highly precise - Common - Easy to use	- Rarely used under high temperatures - Not suitable for small or fragile samples
ESPI [12,13]	The interference of the light reflected from the specimen, that is illuminated by two coherent light sources, produces a speckle pattern. This is captured by a camera system and processed using dedicated software. A fringe pattern is generated by subtracting the reference and deformed speckle, which is then counted to provide the strain field.	- Excellent spatial accuracy (the spatial error is within 0.05–0.1 μm)	- High cost - The setup is often complex and laborious - Requires very low vibration levels
Photogrammetry (e.g. GOM ARGUS) [14]	Photos of the deformed workpieces with prepared grid patterns are taken from different angles after forming tests. The full-field strains are directly obtained by the photogrammetry software and are used to produce limit strains.	- A highly standardised process - Requires little input from the user - Non-contact	- Strain fields are obtained only after the test - Grid patterns are not suitable for small samples
DIC (e.g. GOM Correlate) [11,15,16]	Real-time strain field results are obtained by comparing speckle patterns between reference and deformed images at all time instances. It captures the specimen's deformation at high frame rates to continuously generate the strain information.	- Provides real-time strain results - Non-contact - Can be used in high-temperature strain measurement	- Accuracy depends on the quality of speckle patterns - Failures in the speckle patterns will invalidate the measurements

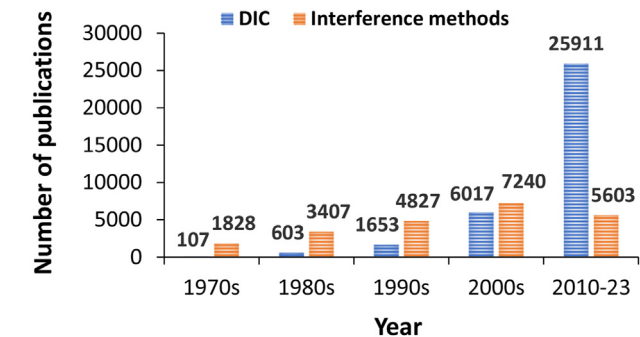


Fig. 1. Number of publications on Scopus containing keywords of DIC and interference methods. The latter category contains Moiré and holographic interferometry, photoelasticity, and ESPI.

certain directions, thereby causing linear polarisation (Fig. 2a) [27]. Malus's law governs the absorption of light in perfect linear polarisers ($I = I_0 \cos^2 \theta$ [28]), where I is the intensity and θ is the relative angle between the polariser and the incident light. Circular polarisers are composed of a quarter waveplate, made from birefringent material, positioned next to the linear polariser [26]. The waveplate introduces a 90° phase shift between the two components of linearly polarised light [26], creating a helical periodicity in the spatial-temporal domain of the waves, as demonstrated in Fig. 2b. XPOL, commonly known as cross polarisation and frequently used in photography, almost completely blocks the light when the two polarisers are arranged at a 90° angle to each other [26]. This effect is illustrated by the sinusoidal waves in Fig. 2c.

When light is reflected off rough surfaces via diffuse reflection, its polarity becomes randomised, and its intensity is reduced. However, reflection from smooth surfaces through specular reflection leaves its polarity and intensity almost unchanged [30]. These phenomena can be used to minimise specular reflections captured by the photosensor. This can be achieved if the light source is first polarised by a linear polariser; then, the light entering

the camera lens must pass through a second polariser, either linear or circular, that is positioned orthogonally to the first polariser [26]. Previously, this XPOL technique was successfully applied to DIC strain measurements in rigid body translation and uniaxial tensile tests at room temperature [30]. This approach enhanced contrasts between the white background and black speckles, which enabled the use of smaller subsets in the DIC analysis and led to a significant improvement in the spatial resolution of measured strain fields [30].

3. Experimental procedure

3.1. Materials, specimen designs and hot stamping testing conditions

The present study utilised 1.5 mm thick sheets of aluminium alloy AA6082 and boron steel 22MnB5. Both uniaxial and biaxial tensile tests were carried out under hot stamping conditions, and strain fields within the gauge area were measured using DIC, with or without the application of XPOL for comparison. Fig. 3a illustrates the dog-bone specimen design for uniaxial tensile tests, and Fig. 3b the cruciform specimen design developed by Zhang et al. [7] for biaxial tensile tests. The simulated temperature profiles were used to mimic the HFQ® process for AA6082, as shown in Fig. 3c, and the hot stamping for 22MnB5, as depicted in Fig. 3d. For instance, in Fig. 3c, AA6082 specimens were heated up to their SHT temperature of 535 °C, initially at a rate of 32 °C/s, and then at a lower rate of 5 °C/s as the temperature approached the target value to avoid temperature overshooting. After soaking at the SHT temperature for 60 s to complete SHT, the specimens were subsequently quenched at a rate of 60 °C/s to certain forming temperatures for the subsequent tensile testing until fracture. Following the deformation, finally, the specimens were quenched to room temperature. It is worth noting that the quenching rate after deformation, which is not of significance in the present study, is uncontrollable due to the fracture of the specimens. An example of a recorded temperature profile is presented in Appendix A.

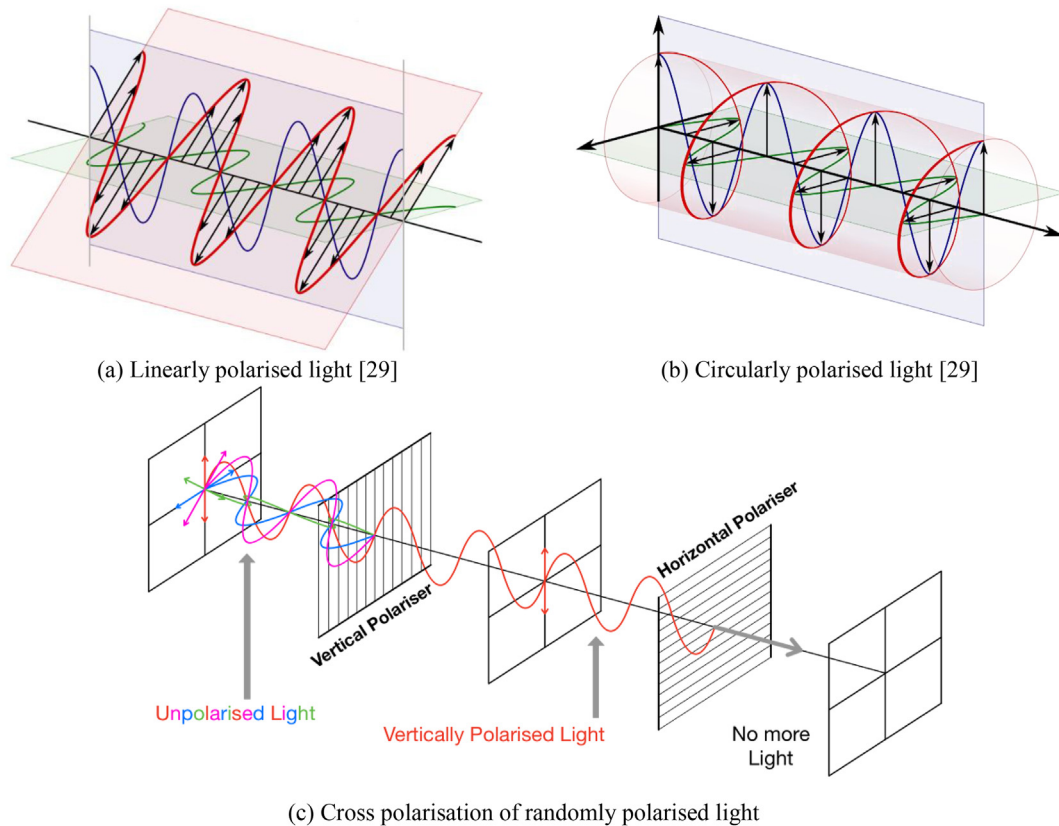


Fig. 2. Electric and magnetic vectors of linear and circular polarisation of electromagnetic waves in spatial domain [29], and how cross-polarisation blocks light with random polarisation angles.

Detailed testing parameters (i.e. temperatures and effective strain rates) for 22MnB5 in uniaxial tests and AA6082 in uniaxial and biaxial tests are tabulated in Table 2.

3.2 Experimental set-up.

3.1.1. Uniaxial and biaxial tensile tests

Materials characterisation under hot forming conditions, which requires high heating and cooling rates to mimic the thermal cycles, was carried out using a Gleeble 3800 thermomechanical physical simulator, as depicted in Fig. 4a. The polarisation state of the light is illustrated in the bottom left corner of Fig. 4a, and the XPOL technique was employed to filter out the specular reflections from the specimen surface. This technique will be explained further in Section 3.2.2. During the uniaxial tensile tests, as shown in Fig. 4b, dog-bone specimens were held by a pair of custom-made grips inserted between the water-cooled copper jaws in the Gleeble. Shao et al. [19] explained that these grips were designed to align the specimen surfaces painted with random speckle patterns with the camera and reduce the heat conduction between the water-cooled jaws and the specimens by minimising the contact area. A pair of K-type thermocouple was welded to the mid-length of each specimen to monitor the temperature at the location, as shown in Fig. 4b. It also provides signals to the Gleeble for temperature feedback control. By leveraging direct resistance heating and air cooling, the temperatures were controlled with impressive efficiency, including a maximum heating rate of over 10,000 °C/s and quenching rates of over 50 °C/s [31], while maintaining a temperature accuracy within ± 0.5 °C [1].

For the biaxial tensile tests, the Gleeble-compatible biaxial tensile rig developed in Ref. [32] was utilised. As shown in Fig. 4c, this setup was designed to fit within Gleeble 3800, exploiting its

accurate hydraulic and temperature control systems. It features four independent movers that are driven by the Gleeble clamp, through the slider-crank mechanism, allowing for movement along the two orthogonal directions. Different loading conditions can be realised by altering the ceramic linkages between the mechanical components of the biaxial rig; more details can be found in Ref. [32]. This method can achieve different proportional strain paths without changing the specimen design. Additionally, it also eliminates issues associated with lubricants and frictional effects in conventional punch testing [32]. Direct resistance heating was used to heat the cruciform specimens, and compressed air from air nozzles was used to cool them.

In both the uniaxial and biaxial tensile tests, the stroke control setting of the Gleeble was used to obtain a constant strain rate by using the relationship $\Delta l = l_0[\exp(t \cdot \dot{\epsilon}_t) - 1]$ [4]. This equation assumes uniform and isothermal deformation across the specimen gauge length, where l_0 represents the initial gauge length, t represents the deformation time, and ϵ_t and $\dot{\epsilon}_t$ are the intended true strain and strain rate, respectively [4].

3.1.2. XPOL technique for taking deformation images

A 200-Watt (output power) white LED lamp was used to illuminate specimens inside the test chamber of the Gleeble (Fig. 4a). The LED array can generate 65,000 lux at 1 m away when attached to a 55° reflector [33]. A focusing mechanism was used to further concentrate the light on the specimen surfaces, which can improve the brightness by maximally 10 times when used 1 m away from the target [34]. The deformation images of the specimens were recorded using the Photron FASTCAM MINI UX high-speed camera along with a Nikon ED AF MICRO NIKKOR 200 mm lens. A special holder was additively manufactured to securely attach a linear

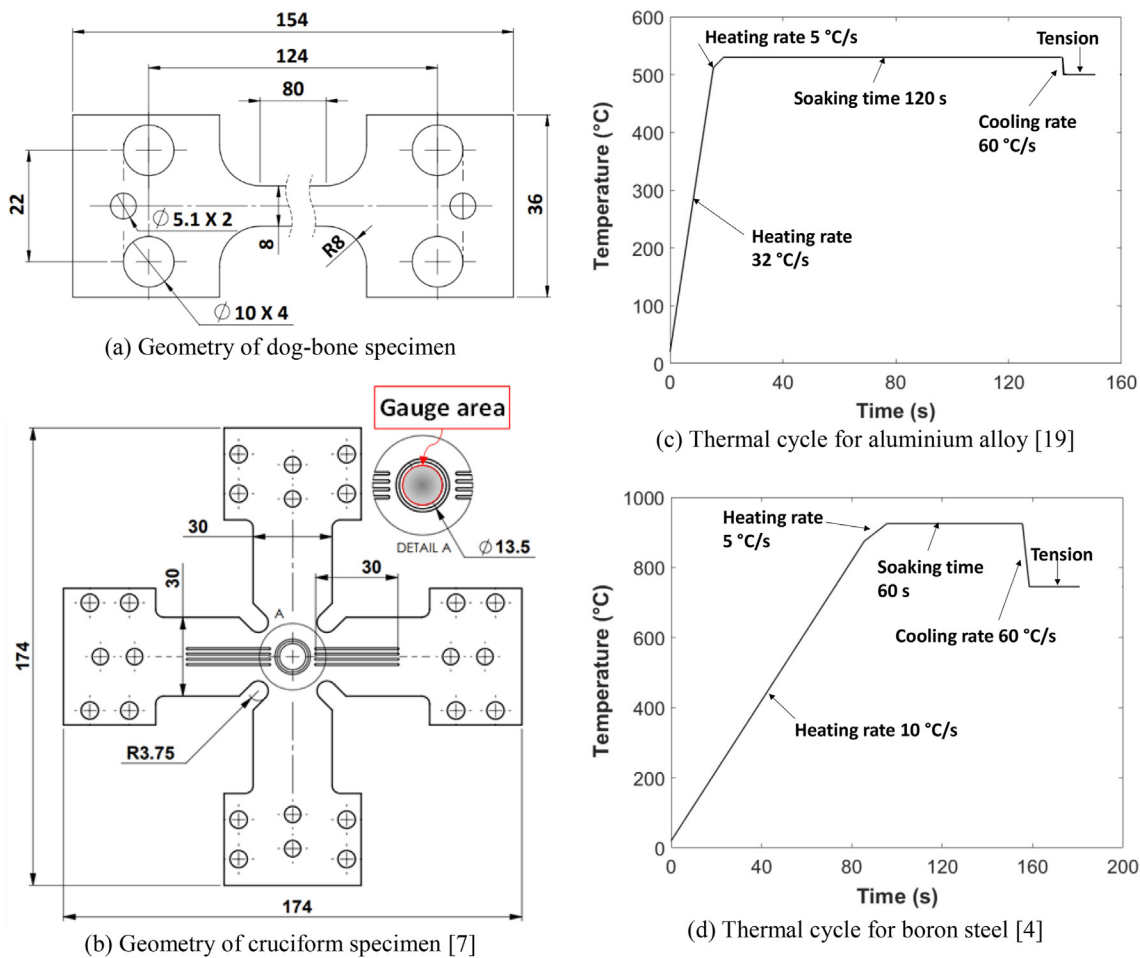


Fig. 3. Specimen designs for uniaxial and biaxial tensile tests (dimensions: mm) [7] and the associated thermal cycles used for AA6082 [19] and 22MnB5 [4] sheets under their hot stamping conditions.

Table 2
A summary of testing conditions (temperature and effective strain rate) used in the present study.

Test and material	Uniaxial tests on AA6082				Uniaxial tests on 22MnB5	Biaxial tests on AA6082	
Temperature (°C)	400	400	500	500	750	440	510
Strain rate (s ⁻¹)	0.1	0.5	0.1	0.5	0.2	0.1	0.1

polariser filter to the front of the focus mechanism, as depicted in Fig. 4a. An additional linear (or circular) polariser was installed onto the camera lens to achieve cross-polarisation. The camera lens was positioned perpendicular to the specimen surface, and the lens was adjusted to achieve the right amount of exposure and focus before the tests. The high-speed camera was controlled using a laptop, and the frame rate was adjusted according to the strain rate to capture sufficient frames (at least 250 frames per second) during each test.

3.2. Improved arts to produce random speckle patterns on specimen surfaces

In the present study, random speckle patterns were generated by spraying VHT FLAMEPROOF™ high-temperature ceramic paints on the specimen surfaces. The paints can withstand temperatures up to 1093 °C without losing their colour or integrity [35]. The flat black SP102 paint was used as the base layer and the flat white SP101 paint was applied as speckles. Although the white paint is

more ductile at high temperatures, the black paint was used as the base layer due to its better compatibility with the XPOL technique, which reduces the specular reflections from the polished metal surface and darkens the originally shiny spots.

To enhance the adhesion of the paints, all existing coatings or oxide layers on the specimen surfaces were removed using P600 grit Silicon Carbide (SiC) abrasive papers. The specimen surfaces were then ground and coarsened with SiC papers: P600 for aluminium alloys and P120 for boron steel. This process created microscopic valleys/pits on specimen surfaces to anchor the paint liquid, resulting in better paint adhesion [36]. The higher hardness of the boron steel necessitates the use of a lower grit number to attain a surface roughness comparable to that of aluminium alloy, which helps to ensure consistently robust paint adhesion to the material's surface, according to our experience. The specimens were subsequently painted using an airbrush, which was favoured over other bespeckling techniques due to its ease and efficiency. The air pressure of the airbrush affects the size of the speckles, with

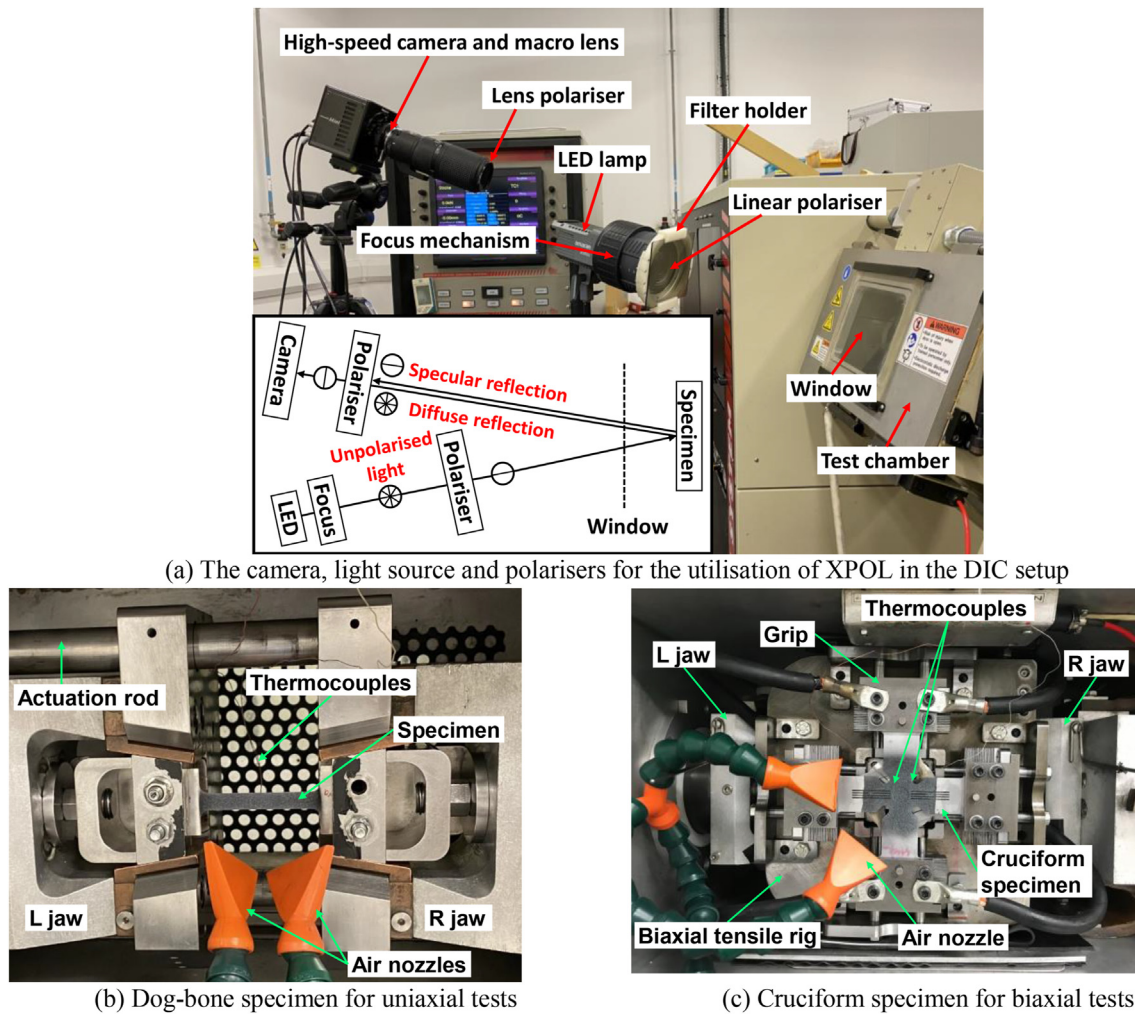


Fig. 4. Experimental setups for uniaxial and biaxial thermomechanical tensile tests using the Gleeble machine.

higher pressure producing finer speckles [30]. Therefore, to achieve the highest possible spatial resolution in the DIC strain measurement, the maximum pressure setting of 30 psi was selected.

In summary, the following steps were taken to generate random speckle patterns on specimen surfaces.

1. Remove any dirty and oxide layers from specimen surfaces using abrasive papers.
2. Roughen up the specimen surfaces using abrasive papers.
3. Clean the roughened specimen surfaces with acetone and disposable wipes.
4. Generate a thin background layer by spraying the black paint on the cleaned specimen surfaces using an airbrush to cover the gauge area.
5. Produce the random speckles by spraying the white paint using an airbrush or an aerosol.

Fig. 5a and b shows the random speckle patterns on AA6082 and 22MnB5 dog-bone specimens, respectively, accompanied by microscopic images to illustrate the sizes and distributions of the white speckles. As can be seen, the improved procedure employed to generate the speckle patterns resulted in excellent randomness of the distributions, shapes and sizes of the speckles.

3.3. DIC data post-processing for strain calculations

Recorded videos for specimen deformation were converted into pictures using the commercial software Photron FASTCAM Viewer (PFV4®). These pictures were then imported to the commercial software GOM Correlate 2018 for DIC analysis. Image adjustment functions of PFV4® (e.g. changing contrast and sharpness) were not used because GOM Correlate automatically calibrates imported pictures. However, the background noises of recorded images were reduced by trimming the irrelevant areas of the pictures.

In GOM Correlate, facet size (FS) is the width of facet squares and point distance (PD) is the distance between facet centres; both are defined in the reference image. Interpolation size (IS) characterises the degree of interpolation performed during calculations (e.g. bi-linear, bi-cubic, bi-quintic) [37]. Increasing IS enables poor-quality facets to be evaluated using values from adjacent subsets. This is because larger subsets produce better pattern matching and, consequently, better tracking accuracy, due to increased uniqueness from a bigger area [15]. Spatial resolution can be improved with higher subset densities by using smaller FS or PD values, especially the latter which has a stronger influence on the spatial resolution [15,37]. Following sensitivity studies presented in Section 4.3, it was determined that the values of FS = 19 and PD = 16

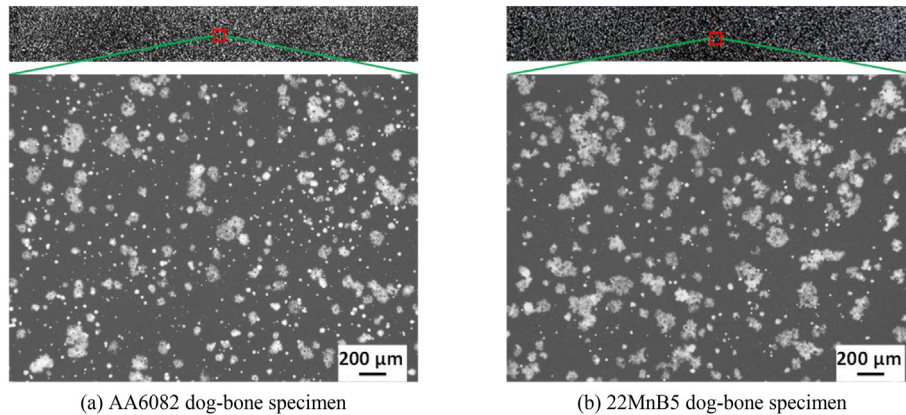


Fig. 5. Specimens painted with random speckle patterns by following the improved procedure, together with a magnified local area viewed using optical microscopy. White dots are the speckles painted on the black background.

(without using GOM's interpolation function) maximise the useable normalised deformation time for each test before reaching the point where the strain field measurement fails. Three computation modes exist in GOM, i.e., Standard, More points, and High accuracy [37]. They differ in how the facet locations are used to calculate displacement fields [37], but their results are generally comparable. Hence, the Standard computation mode was used for all analyses in this study.

4. Experimental results and discussion

4.1. Evolution of specimen surfaces with speckle patterns during deformation

Fig. 6a and b presents the gauge area from the uniaxial tensile tests of the dog-bone specimens of AA6082 at 500 °C and 0.1 s⁻¹ and 22MnB5 at 750 °C and 0.2 s⁻¹, at different normalised

deformation times (t/t_F , where t is the current time, and t_F is the fracture time), alongside an enlarged region near the specimen fracture location obtained using optical microscopy. These specimens were painted with speckle patterns and then deformed in the uniaxial tensile tests under hot stamping conditions. The gauge area of the specimens was recorded using the high-speed camera, with its lens aimed at the middle of the specimen where the highest deformation occurred. As can be seen in Fig. 6a, when the t/t_F value exceeded around 70%, the painted specimen surfaces began to exhibit a pattern of shiny spots, and the pattern became more pronounced as the normalised time increased. Unsurprisingly, the appearance of the shiny spots prevented successful DIC strain measurement. The microscopic images of fractured areas revealed tiny cracks in the speckle patterns. During the deformation, as shown in Fig. 6a, tensile stresses opened and widened these cracks along the tensile direction, and the exposed substrate material AA6082 exhibited a shiny appearance in the high-speed camera

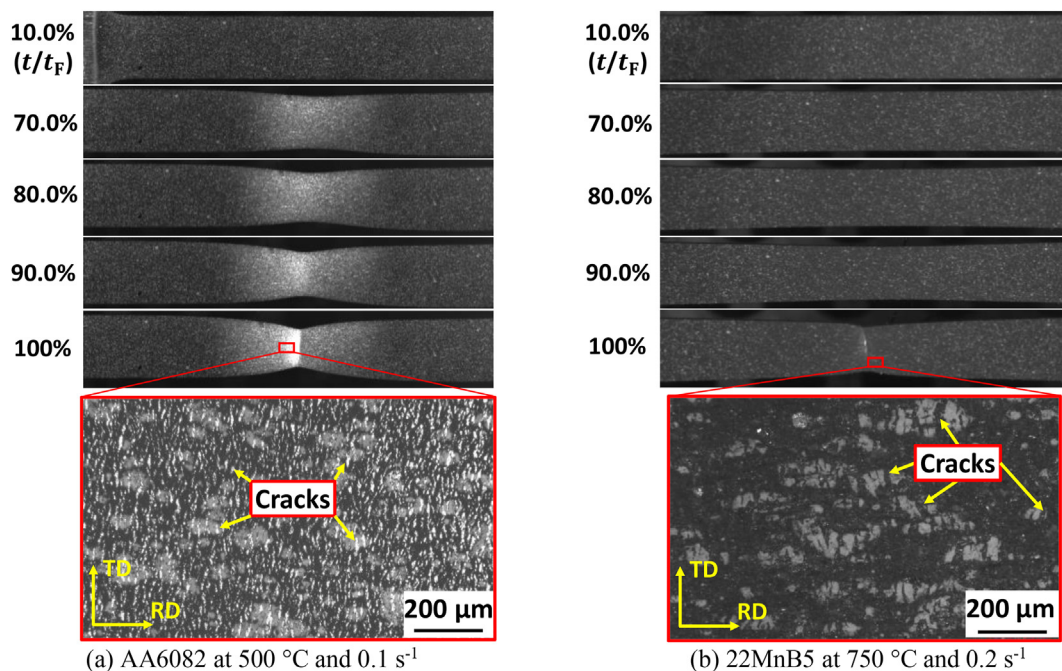


Fig. 6. Recorded specimen surfaces using the high-speed camera, at different normalised times (t/t_F : 10%, 70%, 80%, 90% and 100%, where t is the current time and t_F is the fracture time) in the uniaxial tensile tests under hot stamping conditions, together with an enlarged region near the fracture of the specimens obtained using optical microscopy showing the cracks in the speckle patterns. RD is the rolling direction, and TD is the transverse direction.

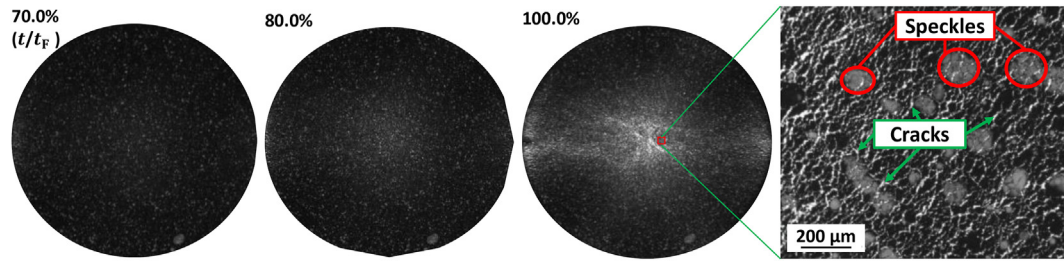


Fig. 7. Recorded gauge area of the AA6082 cruciform specimen deformed in an equi-biaxial tensile test under hot stamping conditions at 440 °C and 0.1 s⁻¹, showing the cracks in the random speckle patterns painted on the specimen surface at different normalised deformation times (t/t_F).

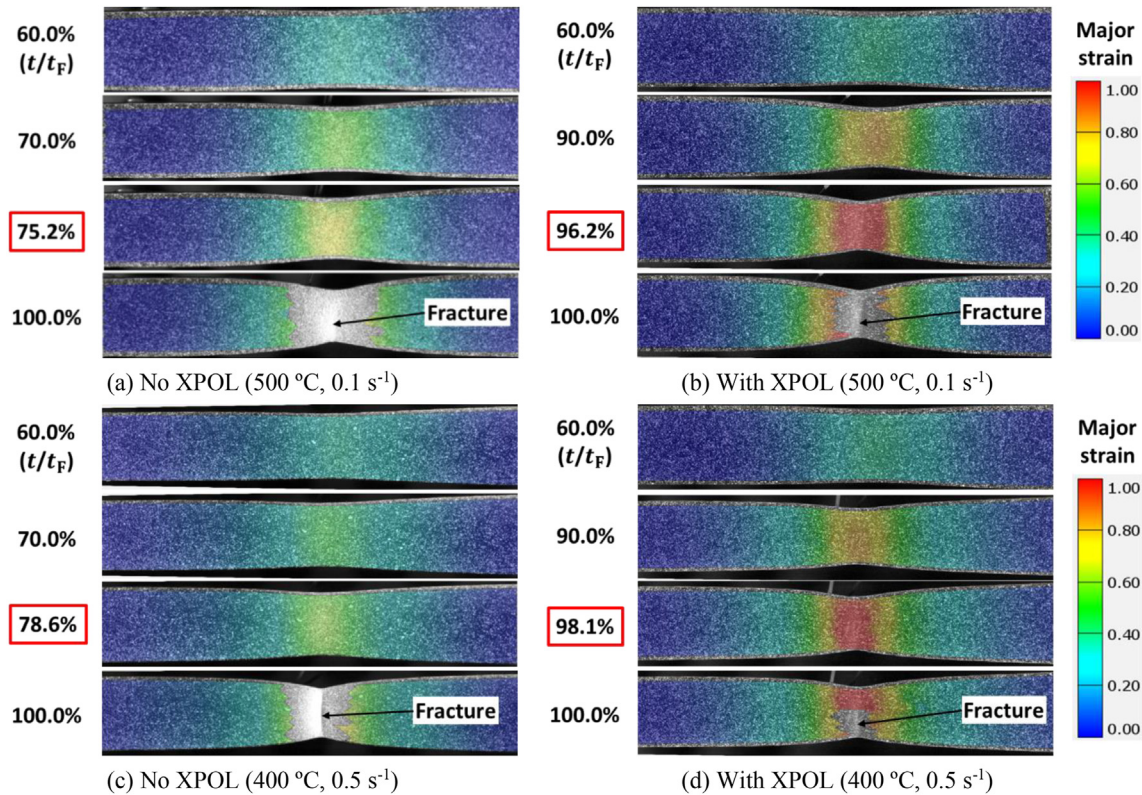


Fig. 8. Comparison of the strain fields obtained with and without the use of XPOL for AA6082 at different normalised times (t/t_F), in uniaxial tensile tests under two different hot stamping testing conditions. The normalised deformation times marked with a red box show the last frame of the full-field strain measurement beyond which localised failing of measurement occurs.

footage. The cracks were likely caused by reduced paint ductility at high temperatures, resulting in the speckle patterns becoming less ductile than the substrate material. Unlike AA6082, as shown in Figs. 6b and 22MnB5 under hot stamping conditions displayed little shiny effects when the t/t_F surpassed 70%. This phenomenon was attributed to the rapid oxidation of substrate steel that matched the colour of the black background paint more closely than aluminium.

Fig. 7 shows the gauge area of an AA6082 cruciform specimen, which was deformed in equi-biaxial tension under hot stamping conditions at 440 °C and 0.1 s⁻¹, captured at three normalised deformation times of 70%, 80% and 100% using the high-speed camera. In line with findings from the uniaxial tensile tests, the exposure of the aluminium substrate in the form of tiny cracks on the speckle patterns was observed at elevated normalised deformation times, such as 80%, resulting in deleterious shiny spots on the captured gauge-area images.

4.2. Applications of XPOL to uniaxial tests for strain measurement using DIC

To minimise the adverse effect of those shining spots, uniaxial tensile tests utilising the XPOL technique for the DIC strain measurements were carried out on both AA6082 and 22MnB5 specimens under hot stamping conditions. Comparisons were made between the strain fields measured with and without the utilisation of XPOL.

4.2.1. Aluminium alloy (AA6082)

Fig. 8 shows the strain fields obtained at different normalised deformation times from the uniaxial tests on AA6082 at different forming temperatures and strain rates under two different settings (i.e. with and without utilising the XPOL technique), along with the normalised time right before the failure of full-field strain

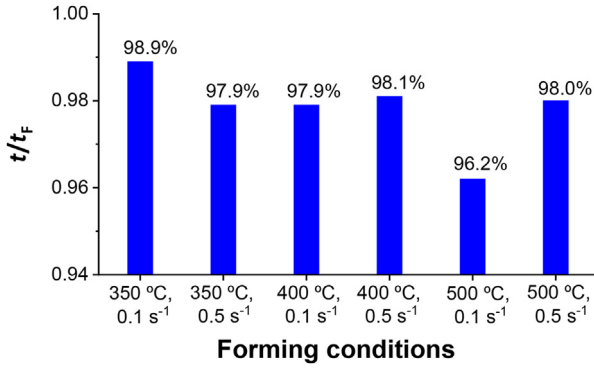


Fig. 9. The normalised times (t/t_F) right before the failure of the DIC full-field strain measurement using XPOL, in the uniaxial tensile tests on AA6082 under hot forming conditions at different deformation temperatures and strain rates.

measurement marked by the red rectangle. As can be seen in Fig. 8, utilising XPOL considerably extended the normalised time over which the full-field strain measurement is successful. For instance, at 500 °C and 0.1 s⁻¹, the strain fields within the gauge area from the beginning of the deformation to 75.2% (t/t_F) were measured without using XPOL (Fig. 8a). In comparison, 96.2% was attained after using XPOL (Fig. 8b). For the test at 400 °C and 0.5 s⁻¹ (Fig. 8c and d), the measurable t/t_F ratio increased from 78.6% to 98.1%.

Fig. 9 presents the normalised time prior to the failure of full-field strain measurement in the uniaxial tensile tests on AA6082 under six different hot stamping conditions. As can be seen, the application of XPOL resulted in a consistent increase of this normalised time to over 96%. It also demonstrates that the improved DIC strain measurement performed almost equally well at all listed deformation temperatures and strain rates. Additionally, slight variations (i.e. less than 3%) in the final normalised time values

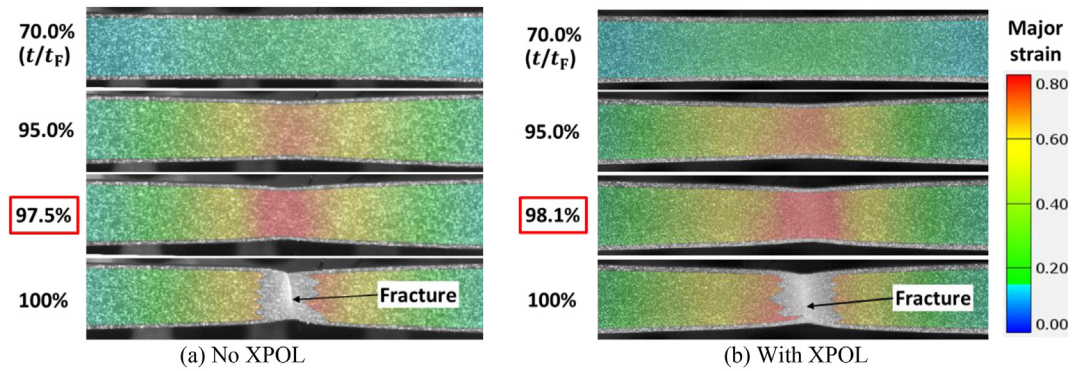


Fig. 10. Comparison of the strain fields at different normalised times (t/t_F) obtained with and without the use of XPOL technique for 22MnB5 in uniaxial tensile tests under hot stamping conditions at 750 °C and 0.1 s⁻¹. The normalised time marked with a red box is the last time right before the failure of the full-field strain measurement.

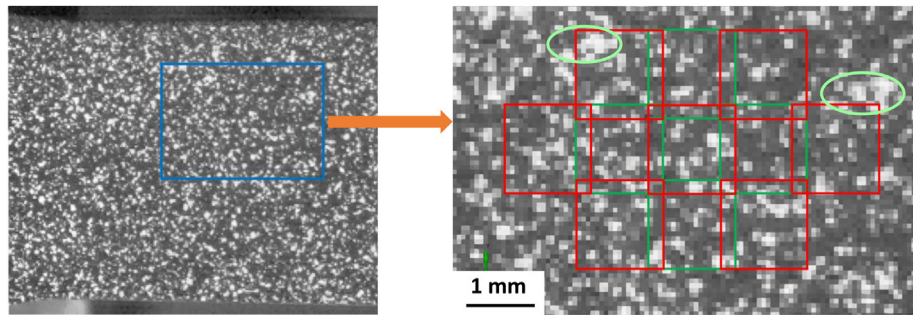


Fig. 11. Facet distributions on speckle patterns when FS = 19 and PD = 16 (3-pixel overlaps between subsets). Green ovals marked out examples of large speckles.

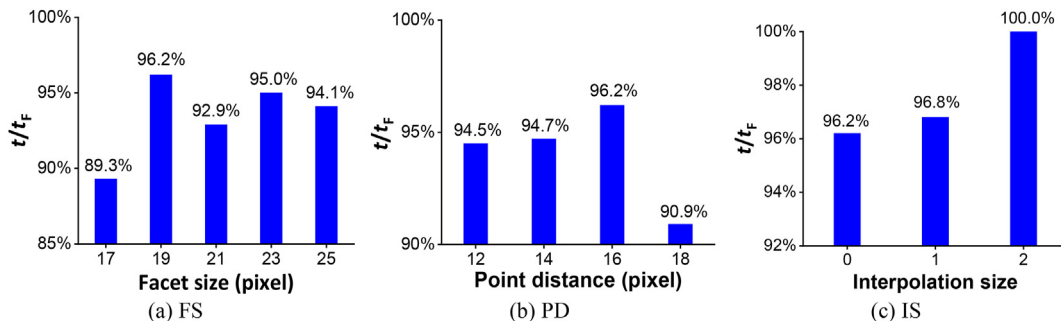


Fig. 12. DIC measurement results with the application of XPOL of the same test with identical DIC settings besides the parameters labelled on the x-axes. The values of FS = 19, PD = 10, IS = 0 were applied to the DIC parameters which were not indicated in the plots. The y-axes indicate the extent of useful strains achieved by the DIC analyses.

Table 3
Settings selected in the GOM Correlate software that maximise the normalised time for useful strain field measurement in each test.

Facet size (FZ)	Point distance (PD)	Strain tensor neighbourhood	Computation setting	Interpolation size (IS)
19 pixels	16 pixels	1	Standard	0

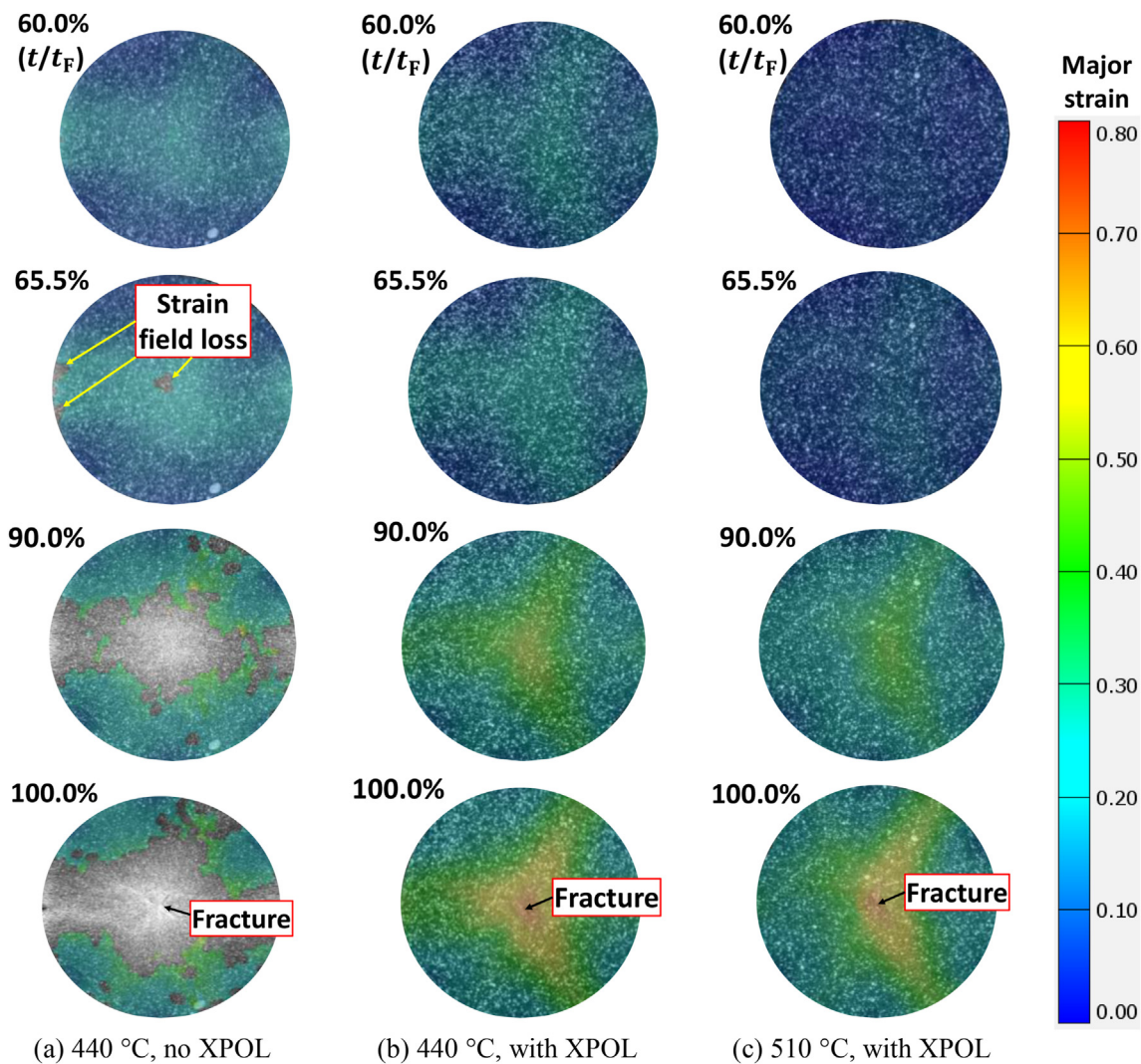


Fig. 13. Strain fields in the central thinned area of AA6082 cruciform specimens at different normalised deformation times (namely 60%, 65.5%, 90% and 100%), measured using DIC with and without using the XPOL, in equi-biaxial tensile tests at a strain rate of 0.1 s^{-1} and different temperatures.

before the loss of full-field strain measurement under different forming conditions can be observed, likely due to factors such as the quality of the speckle patterns and the deformation conditions. However, these variations are negligible in the practical applications. It is worth noting that the performance of the DIC measurement was not significantly affected by the type of polariser used in the camera lens, whether it was linear or circular.

4.2.2. Boron steel (22MnB5)

For comparison, XPOL was also applied to 22MnB5 for the DIC strain measurement in the uniaxial tensile tests under hot stamping conditions. As shown in Fig. 10a and b, at $750\text{ }^{\circ}\text{C}$ and 0.1 s^{-1} , there is a slight increase in the normalised time right before the failure of full-field strain measurement, raising from 97.5% (no XPOL) to 98.1% (with XPOL). Similar phenomena were also observed under other hot stamping conditions. This slight increase

could have been a result of the utilisation of XPOL or the experimental fluctuations.

4.3. Effects of FS, PD and IS on strain calculation

DIC analysis in GOM Correlate divides the surface into smaller subsets/facets whose deformations are tracked. Among the parameters that need to be selected, the most influential ones are the FS, PD and IS. Captured speckle patterns, such as the one depicted in Fig. 11, reveal relative sizes of individual facets to random speckles. Even when painted speckle patterns were well distributed, some paints would cluster together forming large speckles [15], as illustrated in Fig. 11. The selection of FS and PD represents a balance between spatial resolution and tracking accuracy. Experimental results revealed that it would be undesirable to alter the FS value from 19 pixels. This is because the subsets need to capture a

balanced proportion of dark and bright pixels [15]. The large speckles in the speckle pattern shown in Fig. 11 may overflow facets smaller than 19×19 pixels; thus, any further decrease in the FS would result in spatial aliasing [15]. Conversely, oversized facets would lead to poor spatial resolution as it results in too few strain-tracking subsets [15].

The relationships between the robustness of the DIC strain measurement (t/t_F at the last useable frame) and the selection of the GOM parameters (viz., FS, PD and IS) are presented in Fig. 12. Under the precondition of not employing IS (i.e. $IS = 0$), the full-field DIC strain measurement was optimised with $FS = 19$ (Fig. 12a) and $PD = 16$ (Fig. 12b) since these specific parameters yielded the highest t/t_F value. Increasing the IS enhanced the sub-pixel resolution of DIC measurements [23] and delayed the rupture of the strain field. As shown in Fig. 12c, the t/t_F ratio improved from 96.2% to 100.0% when IS was raised from 0 to 2. Nevertheless, using a large degree of interpolation may cause the calculation of strain across the cracks on the speckle patterns, which is a result that has no physical meaning [23], or conceal important phenomena like slip bands [15]. Therefore, the lowest necessary IS was selected (i.e. $IS = 0$) to avoid calculating the invalid strain results across the cracked speckle patterns. Besides the FS and the PD, little difference in strain measurements was attributed to other GOM parameters (e.g. the strain tensor neighbourhood and the computation setting). Table 3 summarises the values that produced the highest t/t_F ratios in full-field strain measurement for speckle patterns generated using the procedure described in Section 3.3; these settings were used in all DIC analyses in the present study.

4.4. Application of XPOL to biaxial tests on AA6082 for strain measurement

The improved DIC method was further applied to AA6082 cruciform specimens in biaxial tensile tests recently developed for materials formability evaluation. As illustrated in Figs. 7 and 13a, the shiny effects had previously hindered the DIC strain measurement of the AA6082 cruciform specimens. Fig. 13 shows the improvement in the DIC strain field measurement after the application of the XPOL technique to AA6082 deformed under hot stamping conditions. As can be seen in Fig. 13b and c, the implementation of this technique has enabled the acquisition of full-field strain data almost continuously up to the final fracture of the specimen (i.e. $t/t_F = 100\%$) under two different forming conditions. This represents a significant improvement from the previous results in an equi-biaxial test where the accurate strains could not be obtained when t/t_F exceed 65.5% (Fig. 13a). Because the XPOL technique filters out the shiny effects from cracked locations rather than filling up these cracks, some errors may be introduced. However, the errors can be ignored owing to the small dimensions of the cracks, as shown in Fig. 6. It should be noted that there is no difference regarding the application of XPOL technology to strain measurement in uniaxial and biaxial stretching tests.

5. Conclusions

An improved DIC method has been developed for measuring full-field strain of aluminium alloys under hot stamping conditions. The improvements encompass refining the procedure for generating speckle patterns on specimen surfaces and utilising the cross-polarisation optical system (XPOL) to minimise the shining effects

on deformation images captured by cameras. From this study, the following conclusions can be drawn.

- 1) An optimised procedure for creating the speckle patterns on specimen surfaces is established. This process helps to maintain the integrity of the speckle patterns under high-temperature and large-deformation conditions.
- 2) The deformation of both AA6082 and 22MnB5 specimens under hot stamping conditions creates tiny cracks in the speckle patterns painted on these specimens, leading to a reflective appearance that adversely affects the deformation image quality.
- 3) The utilisation of the XPOL technique significantly enhances the robustness of the DIC strain measurements for AA6082 in thermomechanical tests by reducing the shiny effects from speckle pattern cracks. It improved the normalised deformation time for strain measurement of AA6082 from approximately 75% to over 96% in uniaxial tensile tests, and in biaxial tests, nearly 100% was achieved.
- 4) The benefits of the XPOL technique are less noticeable in strain measurements for 22MnB5 compared to AA6082, because the oxidation of the steel substrate significantly reduces shiny effects. The improvement for 22MnB5 in uniaxial tensile tests under hot stamping conditions was found from 97.5% to 98.2% for the trial conducted at 750°C and 0.1 s^{-1} .
- 5) For speckle patterns studied in this paper, the most robust strain measurements are obtained with the default values of 19 for the facet size and 16 for the point distance in GOM Correlate, given that the interpolation is not applied.

CRediT authorship contribution statement

Siyi Chen: Investigation, Methodology, Software, Writing – original draft. **Ruiqiang Zhang:** Investigation, Methodology, Supervision, Writing – review & editing. **Zhusheng Shi:** Supervision, Writing – review & editing. **Jianguo Lin:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing.

Conflicts of interest

The authors declare that there is no conflicts of interest.

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Appendix A. Recorded temperature history

Fig. A1 presents the time-temperature profile recorded at the centre of a uniaxial dog-bone AA6082 specimen during a hot stamping test, where the red curve traces the temperature measurements from the onset of deformation until thermocouple detachment. The temperature evolution closely matches the control inputs as presented Fig. 3 in Section 3.1, indicating excellent thermal control during the whole tests.

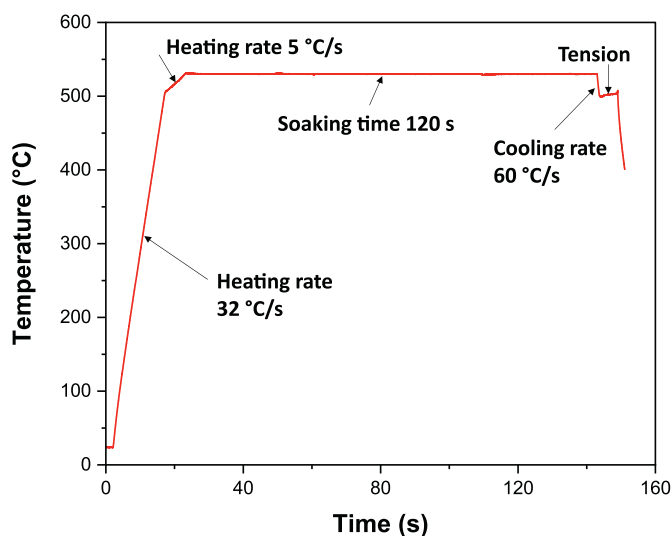


Fig. A.1. Thermal cycle recorded by a thermocouple pair at the centre of an AA6082 specimen during its thermomechanical test.

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