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Effects of cold roll dimpling process on mechanical properties of dimpled steel

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Abstract

In this paper, the effect of a dimpling process on the mechanical properties of the steel material was studied experimentally and numerically. Nano-hardness and tensile tests of steel samples prior to and after the dimpling process were conducted to evaluate the effects of the process on the mechanical properties. Numerical simulations of the dimpling process and tensile tests were done by Finite Element Analysis; they were used to quantify the amount of non-uniform plastic strains and residual stresses introduced and the manner, in which this was distributed through the sheet. The cold roll dimpling process resulted in developing the plastic strain and residual stress which could correlate to the modifications in the strength and stiffness of the dimpled steel when compared to plain steel originating from the same coil material. The simulation of the dimpling process and tensile tests of the plain and dimpled specimens predicted similar behaviour to the experimental measurements and tests.

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Keywords: Dimpling process; dimpled steel; mechanical properties, plastic strain; elastic modulus; residual stress; numerical methods.

1. Introduction

Dimpled sheet steel is cold-roll formed from plain sheet steel by the UltraSTEEL® dimpling process which was developed by Hadley Industries plc. The process uses a pair of rolls which are designed with rows of specially shaped

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teeth that stretch the surface forming the dimple shapes from both sides of the plain sheet as shown in Fig. 1(a). The dimpled sheet is then progressively formed into desired shapes by passing through a series of cold-rolled forming rolls.

The UltraSTEEL® process is complex, owing to the complex and interrelated nonlinear changes in contact, geometry and material properties that occur in the process and section forming; therefore, the effect its cold work has on the mechanical properties of the sheet steel and structural behaviour is not yet fully understood. The effect of the dimpling process on the mechanical and structural properties of the steel material has been the subject of some recent experimental and numerical investigations. Experimental tests were conducted through micro-hardness and mechanical (tensile) tests of plain and dimpled steel specimens [1,2] and they revealed that the strength of dimpled specimens was significantly greater than plain specimens originating from the same coil material, and this enhancement is a result of the cold work applied to the material during the dimpling process. Numerical models have been conducted to study the plastic strain induced during the dimpling process in order to understand the mechanism of the dimpling process [3-7]. In the recent studies [6,7], FEA models of the dimpling process were developed in which rotating rolls deformed the flat strip into dimpled strip via their teeth which had correct geometry. These above studies focused upon the plastic strains developed throughout the entire thickness of steel sheet which could be attributable to the increase of the strength of the material and subsequent products. However, the effects of the dimpling process that leads to modifications in the material properties including stiffness (elastic modulus) and strength by both plastic strains and residual stresses have not been yet investigated.

In this paper, the effect of the UltraSTEEL® dimpling process on the mechanical properties of the steel material was studied experimentally and numerically. Experimental tests included nano-hardness and tensile tests of steel samples prior to and after the dimpling process were conducted. Numerical simulations of the dimpling process and tensile tests using FEA were carried out to quantify the amount of non-uniform plastic strains and residual stresses introduced through the dimpled sheet. The dimpled sheet's resultant geometry and its data including plastic strains and residual stresses generated from the dimpling process were directly transferred to the tensile test simulations so that the effects of the process on the mechanical properties (stiffness and strength) of the dimpled steel could be evaluated.

2. Materials and methods

2.1. Tensile test

Dimpled sheet steel and plain steel (prior to the dimpling process) specimens were prepared according to the appropriate British Standard (BS EN 10002-1: 2001). The plain and dimpled sheet specimens were taken from the same galvanised coil, along the rolling direction. Each specimen was tested in aligned grips with serrated faces in a test rig which has a maximum load capacity of 50 kN. A calibrated extensometer of 50 mm gauge length was used to measure the longitudinal strain. The nominal thickness of the plain and dimpled specimens was 0.50 mm. Seven specimens of each type were tested to failure at a speed of 2.50 mm/min. The initial cross sectional areas of the specimens were measured so the stress could be calculated from the applied force. The procedure for measuring the cross-sectional area of the dimpled specimen and obtaining test data were described in [4]. The resulting stress-strain curves were plotted and the slope of the curves calculated, the yield stress was obtained at a strain level of 0.2%.

2.2. Nano-hardness test

The multifunctional nano-hardness tester of micro materials at Loughborough University was adopted to test the hardness variation of the cross-section through a fine grid of micro-indentations on each region covering a reasonable area. In thickness direction, the grid consisted of 9 indents that covered as close as 50 μm to the edge of the sample. Vickers micro indenter was employed and the 500 mN load-controlled indentations were performed over 30 s ramp. Typical samples of plain and dimpled steel together with a grid of indentation points are shown in Fig. 2(a). For each plain or dimpled steel sample, nano-hardness values at all grid points were measured and then converted to elastic modulus values; they were used to evaluate the elastic modulus of the steel before and after the dimpling process.

2.3. Finite Element Analysis

Finite Element simulations were conducted using Marc (MSC Software Corporation, version 2016) in two stages: (1) the dimpling process was simulated first, and (2) tensile testing of the subsequent dimpled sheet was then simulated. Small mesh sizes and 3D solid elements were used. The plain strip of 75 mm in length, 12.50 mm in width and 0.90 mm in gauge thickness was generated and based on the dimensions of the plain strip, only quarters of the rolls were modelled, as shown in Fig. 1(b). The top and bottom rolls were modelled as rigid bodies, which rotated about their central axes. The steel strip was modelled as a deformable body with 37,980 solid elements; they were 3D, eight-node, hexahedral elements. The contact between the roll teeth and the steel strip was modelled as contact surfaces using 3D contact elements. The friction between the steel strip and the teeth was assumed isotropic and modelled by Coulomb's law with a friction constant of 0.30. A large strain, elastic-plastic material model with strain hardening using Von Mises yield criterion was used for the sheet steel to model the material nonlinearity. The material has a Young's modulus of 205 GPa and a Poisson's ratio of 0.30. Material properties of the plain steel strip were obtained from the tensile tests and their true stress-strain data were used for simulations, as illustrated in [7].

In the tensile test simulations, the dimpled sheet generated by the dimpling process were used in tension simulations. The dimpled geometry and the 'PRE STATE' procedure in Marc were employed to directly transfer resultant stress and strain data from the previous dimpling process simulation into the tensile simulation. One end of the sheet was fixed and a small incremental displacement was applied at the other end to axially stretch the strip to failure. Details of FE simulations can be found in [7].

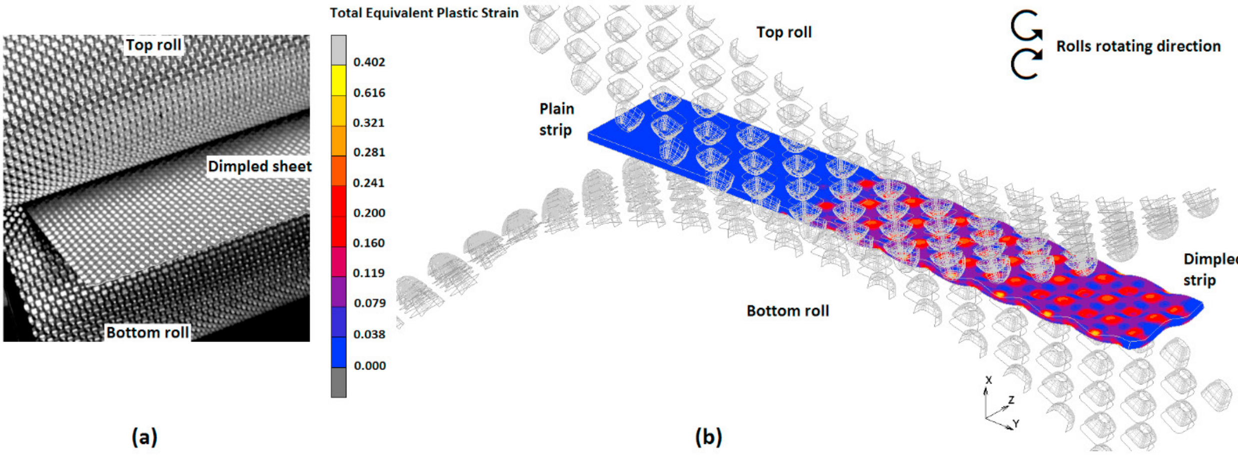

Fig. 1. (a) the UltraSTEEL® process and dimpled steel sheet (Courtesy of Hadley Industries plc); (b) the dimpling process by FEA simulation showing the plain steel and the resultant dimpled steel with plastic strains.

3. Results and discussions

3.1. Nano-hardness and FEA results

The simulation of the UltraSTEEL® process deformed the plain sheet into the dimple, as shown in Fig. 1(b) and a cross section in Fig. 2(b), which also illustrated the distribution of equivalent plastic strain. Plastic strain was found to initiate and increase around tooth contact sites, and there was a 'cap' of higher plastic strain at the sheet surface on the opposite side to the tooth. This is clearly the region in which the greatest strain hardening occurs. The shape and distribution of plastic strain on a plane cutting through the dimple peaks is shown in Fig. 2, in which a microscope image of the dimpled cross section is also illustrated in Fig. 2(c). The numerical values of the thickness at the dimple peak (Side 2) and slope (Side 1) were 0.77 mm and 0.90 mm, respectively, indicating that the sheet thickness was reduced at the centre of the dimple. These thinning values compared well with the experimental observation from the actual dimpling process. The nano-hardness field measured results shown in Fig. 2 correlated well with the FE plastic strain distribution. The light blue shaded regions indicate low values whilst the darker shaded regions with a red dark centre indicate higher values.

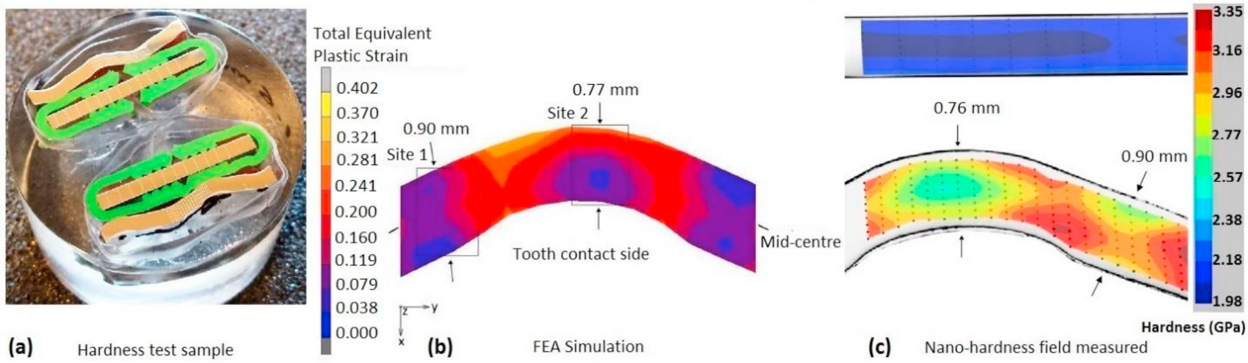

Fig. 2. (a) indentation grid points of plain and dimpled steel samples; (b) modelled dimple and plastic strain distribution; (b) nano-hardness field measured. The regions of sections across the peak, valley and mid-centre line were labelled as Site 2, Site 1 and Mid-centre.

Further verification of the FE simulation was provided by comparison of predicted plastic strain pattern to experimental results on work hardening via nano-hardness tests, as shown in Fig. 2(b). Load nano-hardness tests were carried out on the grid regions of the dimple and through the thickness of the dimple at the slope and peak regions. The average values and their standard deviation of the nano-hardness H for the original plain steel (taken at 99 data points) and the dimpled steel (taken at 306 data points) were 2.71±0.1 and 3.5±0.1, respectively. It clearly shows that the cold work by dimpling process significantly increases the hardness (implying the plastic deformation) of the steel material.

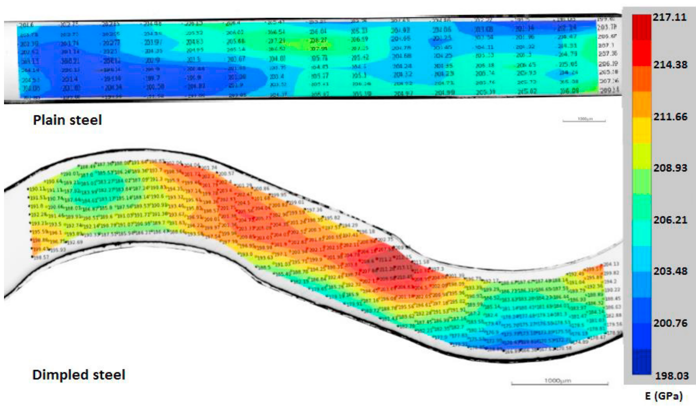

Fig. 3. elastic modulus filed measured values; these were obtained from nano-hardness test data for both original plain steel and dimpled steel

The elastic modulus values of plain and dimpled steel, which were converted from the nano-hardness data, are represented in Fig. 3. It can be seen that the values of elastic modulus of dimpled steel is greater than those of original plain steel especially at the region in which the greatest strain hardening occurs at the valley of the dimple (between Site 1 and Site 2), with the maximum of 217 GPa. However, in average the values of elastic modulus deemed to be similar for both plain and dimpled steel. The average values and their standard deviation of the elastic modulus E for the original plain steel and the dimpled steel were 204±2 GPa and 210±4 GPa, respectively, indicating that the dimpling process did not cause any considerable changes in the elastic modulus.

3.2. Tensile test and FEA results

Experimental results of 7 repeated tests show that the plain steel specimens had a yield stress of 284.20±1.58 MPa, a tensile strength of 342.90±0.79 MPa, and a elongation of 26.00±1.85 % (the results are reported as mean±standard deviation); dimpled steel specimens had a yield stress of 367.60±3.74 MPa, a tensile strength of 429.30±2.54 MPa, and a elongation of 11.06±1.38 %. The dimpled specimens had greater yield and tensile strengths but less elongation than the plain specimens.

Typical FE force-extension curves of plain and dimpled sheets are shown in Fig. 4, which also presents typical force-extension curves from the tests. The lack of a yield plateau in the case of dimpled sheet steel is the result of the strain hardening generated during the dimpling process. This could make the dimpled sheet much stronger than they had previously been in flat form. Integration of the force-extension curves up to the fracture point yielded the work of fracture; by comparing the work of fracture of plain and dimpled steel, the amount of cold work exerted on the dimpled steel sheet was determined. The effect of the dimpled shape on the mechanical properties, was rather small, compared to the amount of cold work (less than 1%), as interpreted from the curves. However, residual stresses had influence to the material stiffness of dimpled steel as it clearly showed in the closer view in Fig. 4(b) that the slope of dimpled steel curve slightly reduced before it reached the yield; this was also observed in previous tensile tests [4]. The FE results also captured this phenomenon as in the simulation the plastic strain and residual tress data were transferred from the dimpling process as shown in Figs. 4(b) and 5(a).

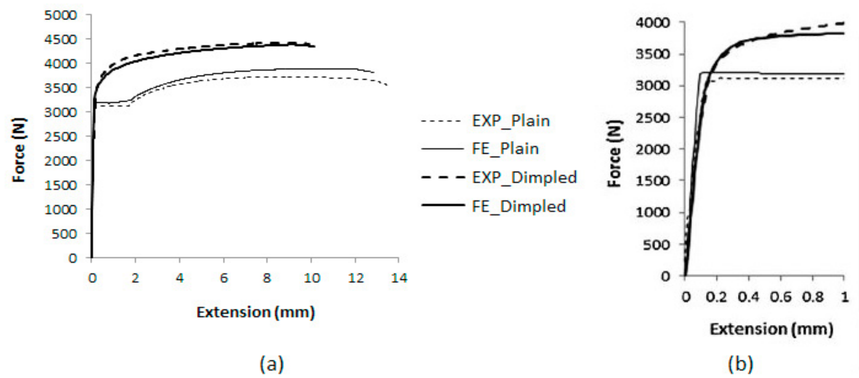

Fig. 4. (a) tensile test and FEA results; (b) plastic strain and residual stress data at the beginning of tensile test simulation.

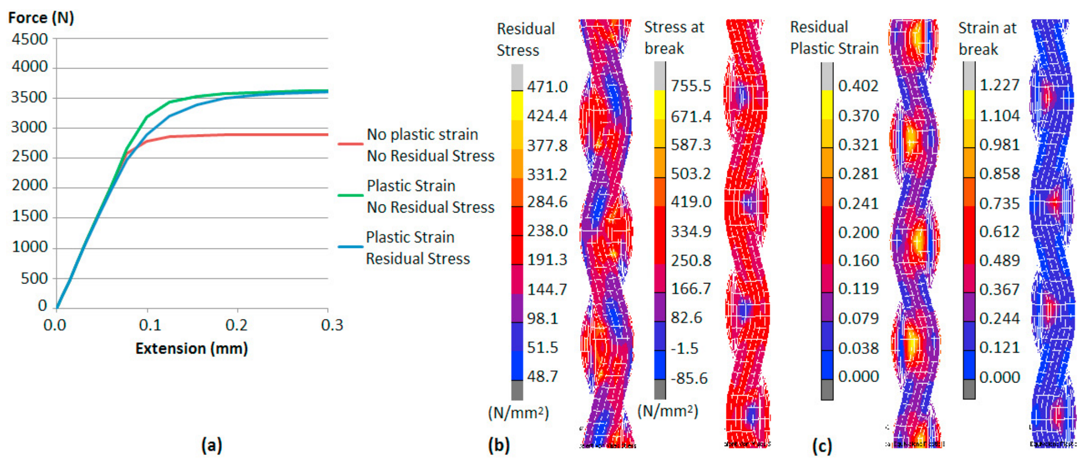

Fig. 5. (a) FE tensile test simulations with different initial data; dimple geometries and data for tensile test before stretching (data transferred from the dimpling process) and at breaking point: (b) residual stresses and stresses at break, (c) residual plastic strains and strains at break.

Fig. 5(a) illustrated the plastic strains and residual stresses effects by including and not including them in the simulations, they were present at the beginning of the tensile tests as shown in Fig. 5(b) and 5(c). By this way, in the tensile simulation the effects of residual stresses on the dimpled steel behaviour were included. The effect of residual stresses on structural behaviour of dimpled steel structures was also observed in FE analysis of columns under compression [8].

4. Conclusions

The cold roll formed UltraSTEEL® dimpling process is complex and overall, the influence it has on the mechanical properties of the sheet steel has not yet fully understood. The effects of the process that leads to modifications in the mechanical properties including material stiffness and strengths through plastic strains and residual stresses have not been yet investigated, and this paper presented innovative work on these issues. The nano-hardness and tensile tests of plain and dimpled steel sheets prior to and after the dimpling process were conducted to investigate the effects of the dimpling process on the mechanical properties of the dimpled steel. The test results revealed that the cold work by dimpling process significantly increases the hardness, and hence the plastic strain hardening but did not cause any significant changes in the elastic modulus of the steel material.

For dimpled sheet specimens, the increase in the yield stress and tensile strength were observed in both tensile tests. The increase of the yield stress and tensile strength obtained from the simulation were satisfactorily validated by hardness and tensile tests. Numerical simulations of the dimpling process and tensile tests by Finite Element analysis were carried out to identify the amount of non-uniform plastic strains and residual stresses introduced. Based on these, the effects of the dimpling process on the mechanical properties of the dimpled steel, including the material stiffness were evaluated. The simulation illustrated that during the dimpling process, various levels of plastic strain developed throughout the thickness of the steel sheet, resulting in strain hardening. This, in turn, changed the mechanical properties of the steel material and correlated to the increase in strength observed in the experimental tests. However, the FEA simulations also revealed that the presence of residual stresses in the tensile test specimens (which were not included in previous studies) reduced the material stiffness and strengths of the dimpled steel.

On-going work includes an extended testing program to investigate the effects of the dimpling process on the mechanical and structural properties of the dimpled steel material and subsequent products with a focus on the residual stress generated by the dimpling process. This involves the use of Finite Element analysis and further experimental validation.

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