Journal of Manufacturing Processes xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Technical Paper

Dimpling process in cold roll metal forming by finite element modelling and experimental validation

V.B. Nguyen [a,c,*], C.J. Wang [a], D.J. Mynors [b], M.A. English [c], M.A. Castellucci [c]

[a] Department of Engineering and Technology, University of Wolverhampton, Telford Campus, Telford TF2 9NT, United Kingdom
[b] School of Engineering and Informatics, University of Sussex, Sussex House, Brighton BN1 9RH, United Kingdom
[c] Hadley Industries plc, P.O. Box 92, Downing Street, Smethwick, West Midlands B66 2PA, United Kingdom

ARTICLE INFO

Article history:
Received 9 July 2013
Received in revised form 14 February 2014
Accepted 17 March 2014
Available online xxx

Keywords:
Cold-rolled
Dimpling process
Finite element modelling
Plastic strain
Mechanical testing

ABSTRACT

The dimpling process is a novel cold-roll forming process that involves dimpling of a rolled flat strip prior to the roll forming operation. This is a process undertaken to enhance the material properties and subsequent products' structural performance while maintaining a minimum strip thickness. In order to understand the complex and interrelated nonlinear changes in contact, geometry and material properties that occur in the process, it is necessary to accurately simulate the process and validate through physical tests. In this paper, 3D non-linear finite element analysis was employed to simulate the dimpling process and mechanical testing of the subsequent dimpled sheets, in which the dimple geometry and material properties data were directly transferred from the dimpling process. Physical measurements, tensile and bending tests on dimpled sheet steel were conducted to evaluate the simulation results. Simulation of the dimpling process identified the amount of non-uniform plastic strain introduced and the manner in which this was distributed through the sheet. The plastic strain resulted in strain hardening which could correlate to the increase in the strength of the dimpled steel when compared to plain steel originating from the same coil material. A parametric study revealed that the amount of plastic strain depends upon the process parameters such as friction and overlapping gap between the two forming rolls. The results derived from simulations of the tensile and bending tests were in good agreement with the experimental ones. The validation indicates that the finite element analysis was able to successfully simulate the dimpling process and mechanical properties of the subsequent dimpled steel products.

1. Introduction

The cold roll forming process is the progressive forming of steel strip into a desired section by passing through a series of rolls, arranged in tandem. It is generally the most economic method of manufacturing sections. The optimum economic viability in manufacturing industry requires a minimisation of the amount of material used while the structural performance of roll-formed products relies on maintaining the stiffness and strength of the section. Additional bends introduced into the section such as 'intermediate stiffeners' can be a solution for these conflicting requirements. They have been found to improve the material properties of the finished product as the yield and tensile strength of the material increases within the deformed zone around the bends; however, such improvements are limited [1,2]. An alternative mechanism to improve the material and structural performance is to impart a deformation to the whole sheet. The UltraSTEEL® process or dimpling process, developed by Hadley Industries plc is an industrial manufacturing process which achieves this deformation. The process uses a pair of rolls which are designed with rows of specially shaped teeth that deform the strip creating the dimple shapes from both sides of the plain sheet prior to the traditional cold roll forming process [3], as shown in Fig. 1. Dimpled steel products are increasingly used in a wide range of applications, including wall studs, framing and roofing members, corrugated panels, vineyard posts, windows and door reinforcement and many other products.

The effect of the dimpling process on the mechanical and structural properties of the steel material has been the subject of some recent experimental investigations through micro-hardness, tensile, bending and compression tests of plain and dimpled steel specimens [3–7]. The tests revealed that the strength of dimpled

* Corresponding author at: Hadley Industries plc, P.O. Box 92, Downing Street, Smethwick, West Midlands B66 2PA, United Kingdom. Tel.: +44 121 555 1330; fax: +44 121 555 1331.
E-mail address: bac.nguyen@hadleygroup.co.uk (V.B. Nguyen).

http://dx.doi.org/10.1016/j.jmapro.2014.03.001
1526-6125/

Please cite this article in press as: Nguyen VB, et al. Dimpling process in cold roll metal forming by finite element modelling and experimental validation. J Manuf Process (2014), http://dx.doi.org/10.1016/j.jmapro.2014.03.001

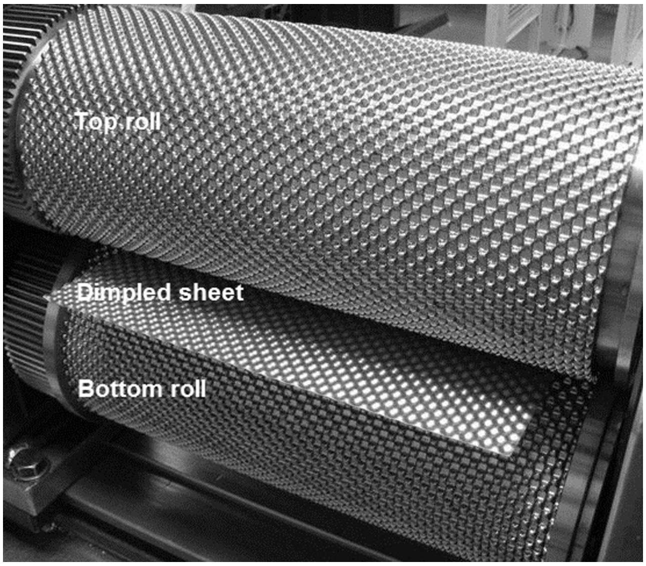

Fig. 1. The UltraSTEEL® process and dimpled steel sheet. Courtesy of Hadley Industries plc.

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.

Besides experimental tests, 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. An initial review of the numerical models for the dimpling process has been presented in Nguyen et al. [9]. Some are presented here again together with the latest investigation. Hartley and Pillinger [8] introduced one of the first numerical models for the dimpling process in which an elastic–plastic model was used within the finite element analysis. In this investigation, only one dimple was formed by spherical indenters that centred at each corner of a square steel plate and translated normally to the plate surface. It was found that plastic strain developed throughout the plate, and higher plastic strain was generated at the plate surface on the opposite side to the intender. Despite illustrating some important features of the dimpling process, this model was not able to predict accurately the amount of plastic strain induced during the dimpling process because in the actual process, each indenter (tooth) has a more complex geometry and contacts the plate via a rotational movement on the periphery of a roll. A finite element model of the dimpling process was later developed by Wang et al. [10] in which rotating rolls rotating rolls deformed the flat strip into dimpled strip via their teeth which had correct geometry. The plastic strain developed in the dimples together with the effect of rolling setup, were studied. However, these models have not been fully calibrated on the basis of physical measurements of the process and the mechanical properties of dimpled sheet. In addition, the dimpling process involves the complex and interrelated nonlinear changes in contact, geometry and material properties of the dimpled steel sheet. Recently, Nguyen et al. [9] proposed a practical finite element approach of modelling the dimpling process and subsequent dimpled products. In this approach, a simplified process was developed in which the top and bottom rolls were translated vertically to deform a square plate into a dimple. This generic dimple geometry was used to generate dimpled products – if it was a very large dimpled product then shell elements were used instead of three dimensional (3D) elements. Only the geometry of the dimple was transferred from the dimpling process, the material properties of the dimple were given from a separate tensile test on a dimpled steel sample. It has been approved that this simplified model was a powerful method to practically represent large dimpled products as the model significantly reduced number of elements used that saved computational costs. In this approach, residual stresses and plastic strain developed during the dimpling process were not included in the simulations as there is no method available to incorporate these data for dimpled steel. The simplified approach in Nguyen et al. [9] was used to practically represent dimpled products in cold forming processes. This approach can be summarised as following steps: (1) simulating a simplified dimpling process that deform a flat steel plate into a dimple, (2) use this generic dimple geometry to generate dimpled strip – if it is a very large dimpled product then shell element approach instead of 3D element approach is applied instead. It should be noted that only the geometry of the dimple is transferred from the dimpling process in step (1), material properties of the dimple is given from a separate tensile test on a dimpled steel sample, (3) simulating the cold forming process that develop the dimpled strip into a desired dimpled product (4) simulating the dimpled products subject to mechanical tests (for example, under tension, bending or compression tests). However, it would be ideal to simulate the actual dimpling process and retain the resultant data, i.e. stress and strain data, of the dimpled sheet from the previous dimpling process simulation. Hence, both the dimpled sheet geometry and material properties generated from the dimpling process are used in the next simulations including mechanical testing on the dimpled sheet. The plastic strains and residual stresses, thus, would be retained in the dimpled steel material; this allows gaining insight into the dimpling process and its effects on the mechanical properties of the dimpled steel, and thereby optimising the process.

In this paper, finite element (FE) modelling of the actual dimpling process was first developed. In this simulation, a long flat steel sheet was transported through a pair of rotating rolls and deformed into a dimpled steel sheet. The dimpled steel sheet was then subjected to tension and bending, in which the dimple geometry and material properties data were directly transferred from the dimpling process. The plastic strains and residual stresses are retained in the dimpled steel material which allowed the mechanical and structural properties of the dimpled steel to be assessed accurately. Physical measurements and mechanical tests were initially conducted on dimpled steel sheets [9] and the experimental results were compared with the FE results. The end purposes of performing mechanical tests and FE simulations including tension and bending on the dimpled sheet were to evaluate the FE simulation of the dimpling process. Simulations of plain steel sheet under mechanical testing were carried out in parallel with dimpled sheet in order to assess the effects of the dimpling process and to further evaluate the FE results. Furthermore, different values of process parameters including friction and tooth overlapping gap were used in modelling to investigate the effects of process parameters on the work hardening of the dimpled sheet and its structural capacity.

The ideal approach is used in this paper to accurately simulate the whole manufacturing processes starting from a plain steel strip to the final dimpled products subject to mechanical tests in consecutive steps: (1) simulating an actual dimpling process i.e. rotating rolls, that deforms a flat steel strip into a dimpled strip, (2) use the subsequent dimpled strip (generated from the first dimpling process) as a desire dimpled product in which the geometry of the dimpled strip together with its material data including stress/strain data generated from the dimpling process – step (1) are directly transferred to the next loading step simulation, and (3) simulating the dimpled products subject to mechanical tests (for example, under tension and bending tests). The new approach presented in this paper can gain insight into the dimpling process and its effects on the mechanical and structural properties of dimpled steel products, and hence to optimise the process later in the future.

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