Finite Element Modelling of Bends and Creases during Folding Ultra Thin Stainless Steel Foils

K. Datta, H. Akagi*, H. J. M. Geijselaers and J. Huétink

The Netherlands Institute for Metals Research,

University of Twente, 7522 NB Enschede, The Netherlands.

*Nippon Steel Corporation, 6-3 Otemachi 2 Chome, Chiyoda-ku, Tokyo 100-71, Japan

Abstract: Finite Element Modelling of an ultra thin foil of SUS 304 stainless steel is carried out. These foils are 20 mm and below in thickness. The development of stresses and strains during folding of these foils is studied. The objective of this study is to induce qualities of paper in the foils of stainless steel such that a public sculpture of origami can be built with the foil. Finite Element modelling of the fold, reverse fold, junctions of multiple folds as well as the finger-dents are carried out to quantify the extent of straining the steel foil would undergo while an object of origami is folded with it. It is important to know the extent of straining the foil would undergo during folding operation. With this knowledge, the through-thickness microstructure and microtexture can be studied which influence the fracture toughness and low cycle fatigue properties of the steel foil. The foil with the requisite qualities of paper can then be manufactured.

1. Introduction

The objective of this work is to induce the attributes of paper in foils of stainless steel so that a public sculpture of origami can be folded with it. Origami is an ancient Japanese art of paper folding for fun. However, in the recent years, the figures folded by this technique have complex shapes and they closely resemble the objects portrayed. Nowadays, an origami artist has a choice with a variety of construction material with specific texture, colour and body. Origami has evolved to the level of sculpture (La Fosse, 2000) than merely a simple form of art. However, origami artists have not had a good experience of working with metal sheets or foils. Copper or aluminium based foils have shown rupture and dents, which cannot be accepted for display as a public sculpture. With an in-depth discussion with the renowned paper artist Paul Jackson, this project was launched. In short, the aim is to mimic qualities of paper in foils of stainless steel.

1.1 Background

The two lots of SUS 304 foil manufactured by Nippon Steel Corporation have been tried to be folded into origami shapes. The as-rolled foil (10 µm thick) dents more than the rolled and annealed one (20 µm thick). Fig. 1 shows cranes made with 10µm as-rolled stainless steel foil. Also the as-rolled foil is less stable and undergoes a phase change from austenite to martensite up on straining at the folds, or even when left on its own in a cooling atmosphere (like daily or seasonal drop in the ambient temperature). With respect to foldability, the annealed foil behaved a lot better than the as rolled foil. The annealed steel foil still requires improvement with respect to the following properties.

- Pliability: it should not rip open (brittle fracture) when a fold has gone through several forward – backward bendings. Thus the low cycle fatigue property with reversal of strain path needs to be improved, as well as the fracture toughness of the foil so that its failure limit can be extended to a larger strain and it fails by ductile mode.

- Complex crease nodes: at the node, which is the meeting point of several creases, the foil fails. This point of multi directional straining is a critical point and therefore, resistance to failure at such severe positions should be enhanced.

- Dent Resistance: the foil should have the optimum combination of hardening as well as ductility such that while folding, dents are not formed. So it should be strong enough to resist finger pressure so that permanent deformation does not set in, yet plastic enough to hold the folds when higher pressure is applied through the fold-lines.

- Surface light reflectivity: the foils are glossy, which is one reason that uneven topography shows after the foils are folded. A matte surface would hide any such topographical disorders. It may be brought out by controlled rolling of the last pass with a special work-roll as well as by chemical etching of the foils.

- Colour coating: an attractive object of origami like a yellow rose of friendship or a white (or light pink) crane of luck can be constructed only when the metal foil can be coated with colouring pigments. Colour coating of foils would require either electrochemical-deposition or mechanical spraying. It may give a better pliability as well as may render enough matte finish to hide any uneven topography on the final object of origami

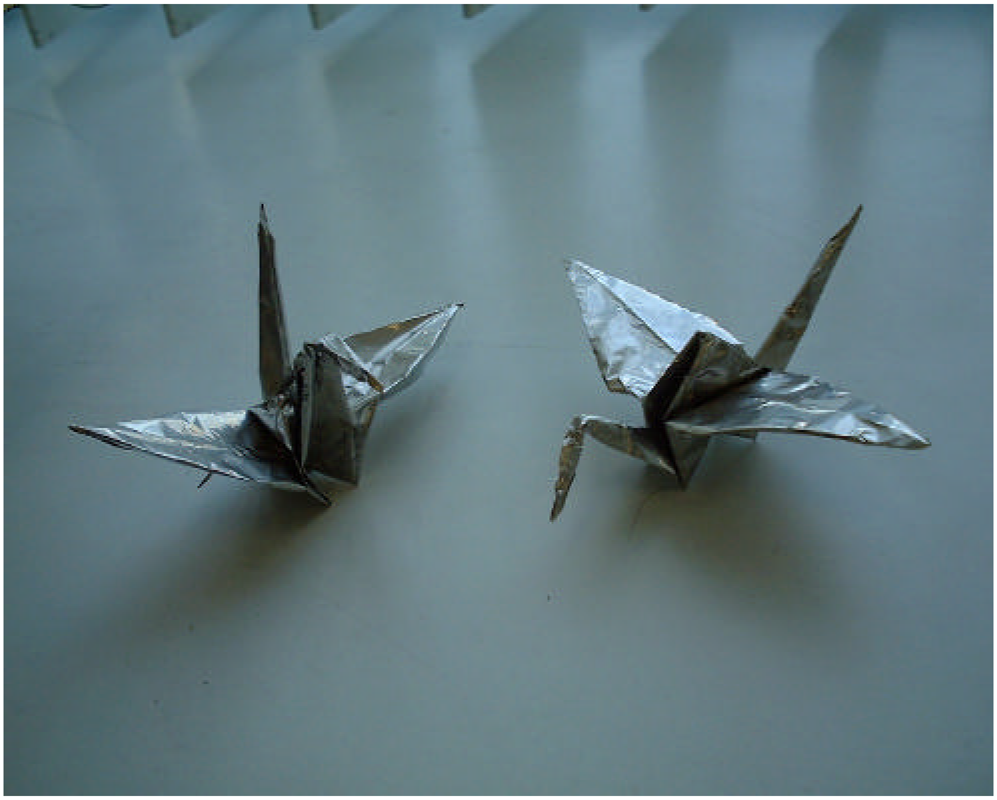


Figure 1. Cranes folded from 10m thick stainless steel foils.

1.2 A short description of the industrial relevance

This project is meant for an installation of a public sculpture. Therefore, it apparently does not have an industrial relevance. However, while up-scaling to a larger size of the object of origami, it will call for production of the metal foil in larger width or seamless welding of the foil to get a larger sheet. Also, as a spin-off of this project, metal foil can be used for packaging: especially, making boxes, carry-bags etc. Foils already have dedicated industrial use (Advanced Metal Foil, NSC, 2000). Produced under a strict integrated manufacturing process from melting to finishing, ultra-thin foil manufacturing with stable high quality of production is a technology by itself. Ultra-thin foil manufacturing started with the production of stainless steel foil suspension assemblies for hard disc drive (HDD) magnetic heads. Foils as thin as 10 µm and 400 mm wide are produced by Nippon Steel Corporation. It has excellent flatness as well as accurate thickness over entire width and length of the foil. These ultra-thin foils have a wide variety of other uses for the properties they ensure during service:

- Fatigue durability and etching property: springs for HDD as well as other springs, contact switches, printer belts, encoders, tape measures.

- Etching property: springs and gaskets.
- Electrical resistance: panel type heating elements.
- High temperature resistance: automotive metal substrates for catalytic converter.
- Corrosion resistance: diaphragm, lithium battery current collector, thin dry battery casing, electric cable sheath.
- Optically diffused reflection : flexible solar cell substrate.
- Specific surface properties: structurals like kitchen materials (honeycombs, sandwich panels and decorative boards), daily necessities (vibration-deadening foil and adhesive tape for lacing).

On top of this list, this work aims to attribute few more characteristics to the foil so that it can mimic paper and would be the right material to construct an object of origami.

2. Finite Element Modelling of the Ultra Thin Foils

A Finite Element model is built which simulates the folding action. Since both the length and the width of the foil are infinitely large compared with the thickness of the foil, the out-of -plane parameters do no vary significantly. Therefore a plane stress/strain formulation is sufficient to model the through thickness variation in strain around the folded part of the foil. A 2D plane strain model with CPE4 elements is built. Figures 2 (a – e) demonstrate the sequence of steps involved in a simple folding operation. The foil lies on a rigid analytical surface like a table and another rigid analytical surface on top of the foil acts as the press like fingers. The bottom right half of the foil is tied to the table and one corner node is encastered. Since the foil is first folded over, contact pair is established between the remaining half of the bottom layer which makes contact with the rigid surface on top which presses the foil down. The mechanical and other physical properties for SUS 304 stainless steel foil are obtained from Nippon Steel Corporation (Advanced Metal Foil, NSC, 2000). The elastic-plastic material option is chosen. An implicit static analysis is carried out in four steps as follows with a few intermediate steps to ensure physically realistic boundary conditions.

a. The top left corner is moved a little along 22 direction.

b. It is then moved to right along 11 direction towards the right hand edge.

c. The analytical rigid surface on top descends up on the folded foil and squashes it down.

d. Contact pair is removed.

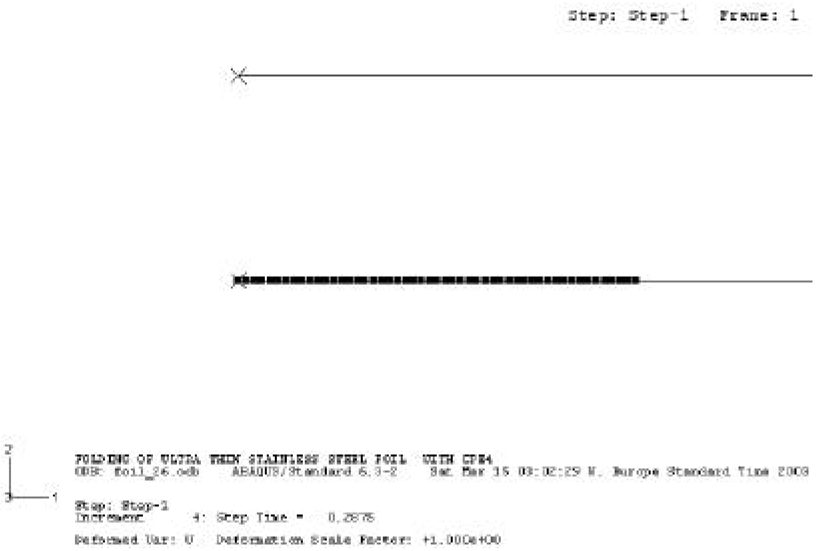


Figure 2 a. The foil lying on a rigid surface with the rigid press on top.

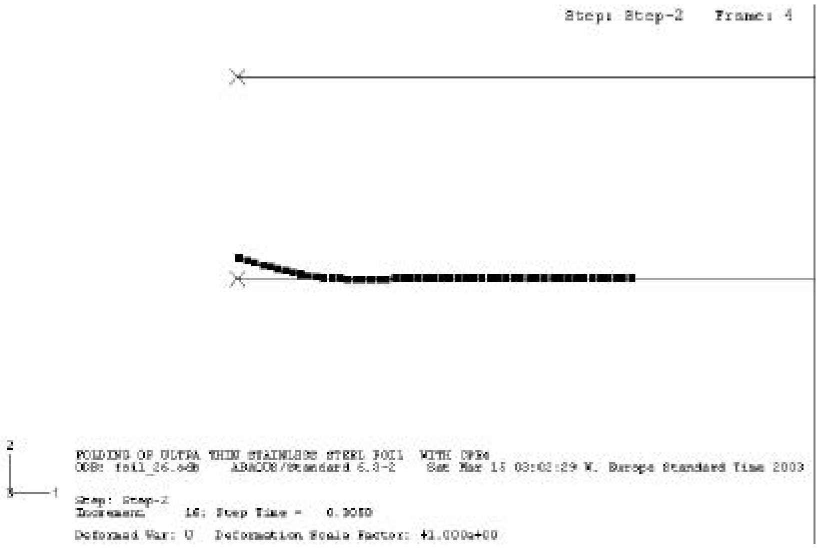


Figure 2 b. One corner of the foil lifted from the surface.

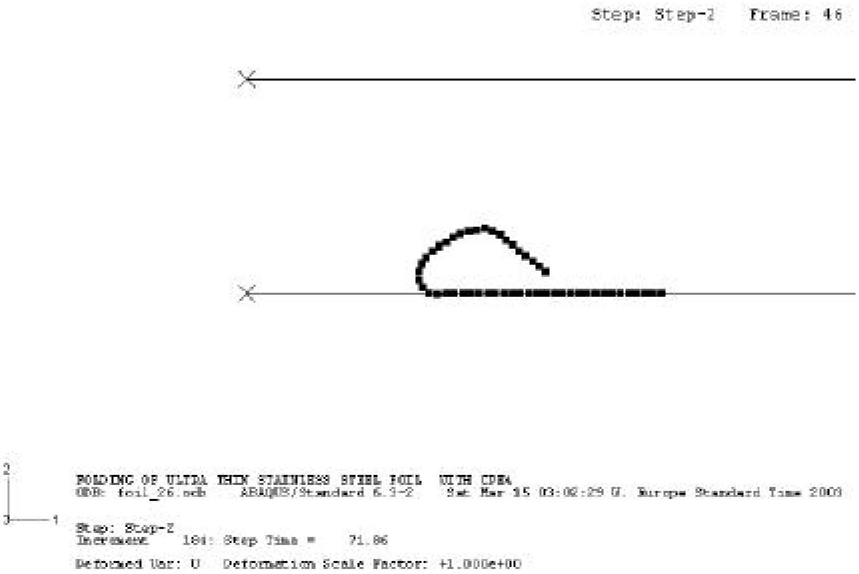


Figure 2 c. The foil being folded around the center.

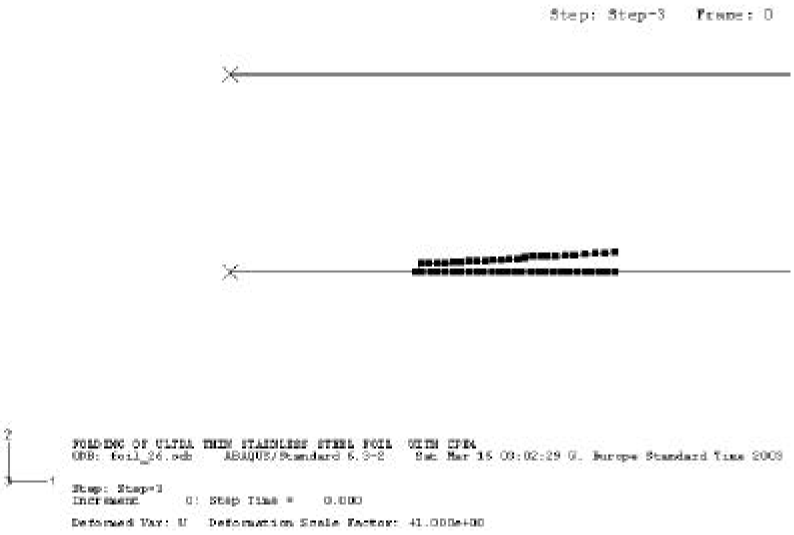
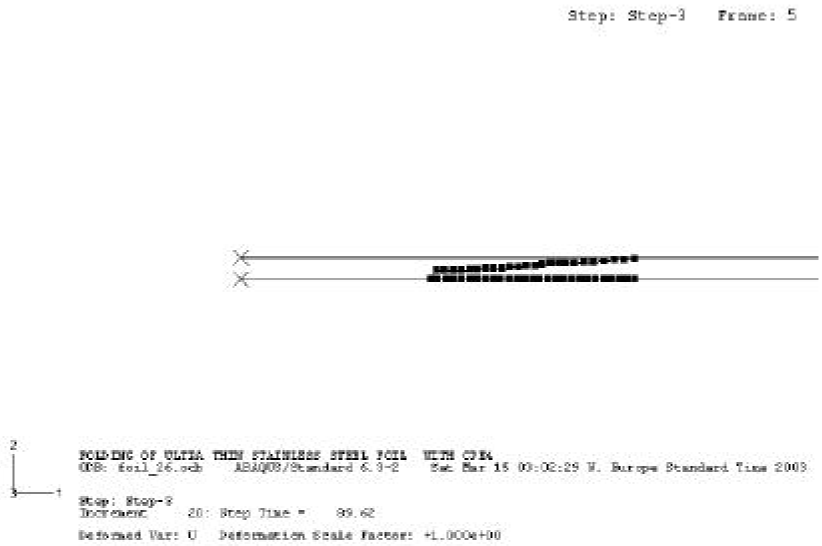


Figure 2 d. The folded foil.



```
Step: Step-3   Frame: 5

FOLDING OF ULTIA THIN STAINLESS STEEL FOIL  WITH CPE4
ODB: foil_26.odb    ABAQUS/Standard 6.3-2    Sat Mar 15 03:02:29 W. Europe Standard Time 2003

Step: Step-3
Increment     20: Step Time =    99.62

Deformed Var: U   Deformation Scale Factor: +1.000e+00
```

Figure 2 e. The top rigid surface descends to squash the foil down.

3. Results and Discussion

Fig. 3 shows the plot for the equivalent plastic strain along a path from one edge of the foil to the other. The analysis is carried out for a 100 mm long and 10 μm thick foil of SUS 304 stainless steel.

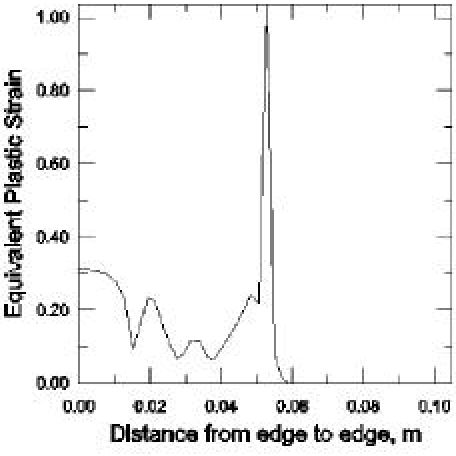


Figure 3. Variation in equivalent plastic strain along the length of the foil.

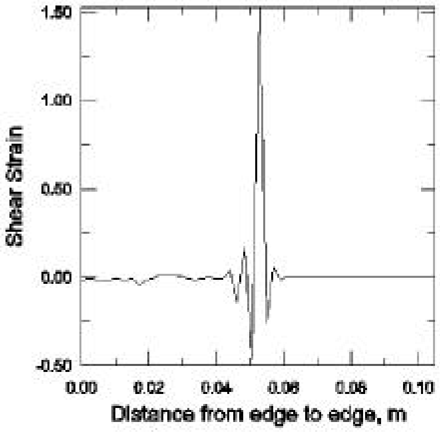


Figure 4. Shear strain developed along the length of the foil.

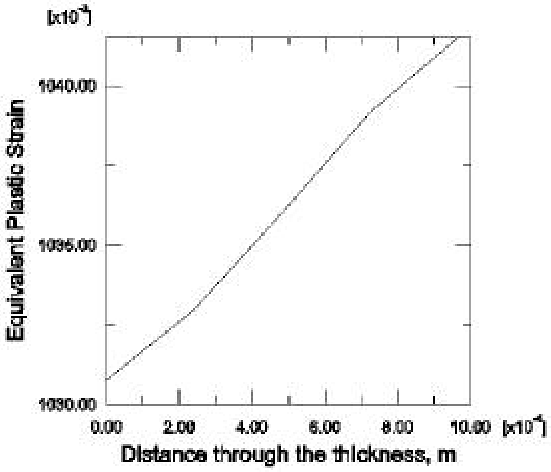


Figure 5. Equivalent plastic strain through the thickness of a folded foil.

Figure 4 shows the development of shear strain along the length of the foil. For both Figures 3 and 4, the values are extracted from mid-thickness of the foil. It can be seen that the region of the fold line is very critical where there is a sharp rise in plastic strain observed. This region is prone to failure as also has been observed by folding these foils. With the help of this simple finite element model of folding, the local variations in the principal and shear components of plastic strain can be quantified. This, in turn would help in identifying the factors that cause fracture of the foil at such critical locations.

4. Conclusion

A simple model of ultra thin stainless steel foil gives important information on the states of stress and amount of principal and shear strains that develop within the foil during a folding operation. With this knowledge, the effect of thickness as well as the microstructure and micro-texture of the foil can be studied to enhance fracture toughness, dent-resistance and low cycle fatigue properties of the foil.

5. Further Work

Finite element modelling of reverse folds and junctions of multiple folds will be carried out for different foil thickness and post rolling heat treatments. The foldability of colour-coated foils will also be studied.

6. Acknowledgements

The authors would like to thank origami artists Mr. Paul Jackson and Mrs. Miri Jackson for their valuable comments on stainless steel foil as a material for making origami. They are also thankful to Mr. Toshiki Yabuta of Nippon Steel Corporation for continued encouragement. They would like to thank Professor Frans Spaepen of Harvard University for his advice on mechanical testing of ultra thin foils. The authors are grateful to the Netherlands Institute for Metals Research (NIMR) and to Nippon Steel Corporation (NSC) for their permission to publish this work.

7. References

1. Advanced Metal Foil, Nippon Steel Corporation, Catalogue no. NM-SF-000401, April, 2000.
2. Michael G. LaFosse, Origamido, Rockport Publisher, ISBN: 1-56496-639-9, 2000.