한국소성가공학회 2003년도 춘계학술대회 논문집 pp.240~243

심용접 튜브를 사용한 벌지 성형에서의 터짐불량 예측

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Numerical prediction of bursting failure in bulge forming using a seamed tube

J. Kim, Y.W. Kim, and B.S. Kang

Abstract

Finite element analyses for bursting failure prediction in bulge forming under combined internal pressure and independent axial feeding are carried out. By means of the FEM combined with Oyane's ductile fracture criterion based on Hills quadratic plastic potential, the forming limit and bursting pressure level are investigated for a seamed tube that comprises of weldment, heat affected zone(HAZ) and base material parts. Especially, in order to determine the material property of HAZ tensile tests for the base material and the weld metal are executed based on iso-strain approach. Finally, through a series of bulge forming simulations with consideration of the weldment and HAZ it is concluded that the proposed method would be able to predict the bursting pressure and fracture initiation site more realistically, so the approach can be extended to a wide range of practical bulge forming processes.

Key Words : Bulge Forming, Weld Properties, Rigid-Plastic FEM, Ductile Fracture Criterion, Seamed Tube

1. Introduction

In bulge forming of a tube, axial force is generally applied at the ends of the tube with internal hydraulic pressure simultaneously. Thus the tube can be fed into the deformation zone during the bulge operation allowing more expansion and less thinning so that the parts with desired specifications can be formed without any defects such as wrinkling, buckling, and bursting. By contrast with buckling and wrinkling which can be eliminated during final calibration stage, bursting is an irrecoverable failure mode. In order to obtain sound bulged products, it is necessary to predict the bursting behavior and to study the effects of process parameters on this failure condition in bulge forming processes[1].

A seamed tube used in bulge forming or hydroforming is generally produced by high frequency electric resistance welding(HF-ERW) after a roll forming operation. For a steel seamed tube, the parent metal has significantly lower yield strength and higher ductility than the weld metal. The quality of the weld

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in a tubular blank is critical for a successful forming operation. However, no previous study on the influence of the weld metal properties on the forming limit of bulge forming has been presented. In this study, finite element analysis combined with Oyane's ductile fracture criterion[2] is carried out to predict bursting failure in bulge forming processes with the consideration of the weld metal and HAZ. The two material parameters in the criterion come from analytical limit strains obtained from diffuse plastic instability based on Hills quadratic plastic potential. And then, by the assumption of iso-strain in both weld and base materials[3,4], and by tensile tests of base materials and weld metal, the material properties of HAZ are determined. As a result a portion of loads supported by weldment and HAZ can be calculated from the known base material hardening laws and known total load of a specimen. Finally, through a series of bulge forming simulations it is concluded that the current approach would be able to predict the bursting pressure and the fracture initiation site more realistically, so it can be extended to a wide range of practical bulge forming like hydroforming processes.

2. Weld properties of a seamed tube

2.1 Iso-strain method

The stress-strain relations of the base metal and weld metal can be easily obtained from tensile tests using the base metal-only and weld-only specimen cut from a seamed tube. However, for HAZ it is difficult to determine which area is the zone affected by welding heat. Hence, the assumption of iso-strain in both weld and base materials is introduced in this study. For the iso-strain method based on the rule of mixtures longitudinal strain is assumed to be constant across the specimen which is cut from the seamed tube, such that

$$\varepsilon_w = \varepsilon_{HAZ} \tag{1}$$

where the subscript w and HAZ refer to weld metal, heat affected zone, respectively. The weld metal and HAZ material data sets are fit to an appropriate hardening law as,

$$\sigma_w = K_w \varepsilon_w^{n_w}, \quad \sigma_{HAZ} = K_{HAZ} \varepsilon_{HAZ}^{n_{HAZ}} \tag{2}$$

where K and n are the strength coefficient and strain hardening exponent, respectively. In the tensile test using the specimens extracted from the HAZ containing a weld line, the total load on the specimen F is represented as,

$$F = \sigma_w A_w + \sigma_{HAZ} A_{HAZ} = \bar{\sigma}_{mixed} A_{mixed} \tag{3}$$

where $\bar{\sigma}_{mixed}$ is the average stress fitted to $\bar{\sigma}_{mixed} = K_{mixed} \varepsilon_{mixed}^{n_{mixed}}$ and A_{mixed} is the cross-sectional area of the specimen. Therefore the stress of the HAZ using Eqs. (2) and (3) is calculated as,

$$\sigma_{HAZ} = \frac{(K_{mixed} \varepsilon_{mixed}^{n_{mixed}}) A_{mixed} - (K_w \varepsilon_w^{n_w}) A_w}{A_{HAZ}} \tag{4}$$

As shown in Eq. (4), the stress-strain relation for the HAZ of the seamed tube is largely dependent on A_{HAZ}. Hence, the determination of an appropriate method for measuring A_{HAZ} is crucial and thus micro-hardness profile is used in this work. Figure 1 shows measuring process of the micro-hardness by a micro-hardness test machine. The micro-hardness profile of a seamed tube with 2.6 mm thickness and 50.8 mm outer diameter is plotted in Fig. 2. This profile indicates that the weldment and HAZ width is approximately 8 mm and 37 mm respectively.

2.2 Tensile test results

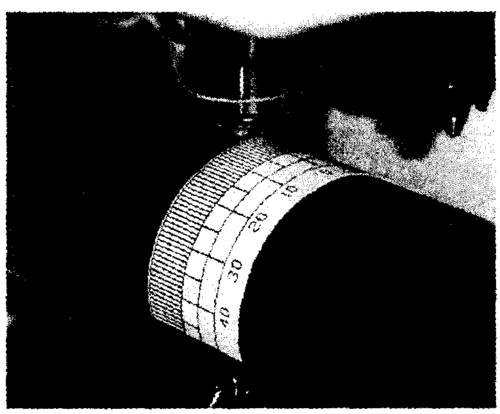


Fig. 1 Hardness measuring process using a micro-hardness test machine

Table 1 Material properties of the base, weld and HAZ

	Strength coefficient, K [MPa]	Hardening exponent, n	Material constant, C_1	Material constant, C_2
Base metal	587.8	0.126	-0.1170	0.0236
Weld metal	766.3	0.191	-0.1174	0.0357
HAZ	543.0	0.106	-0.1167	0.0199

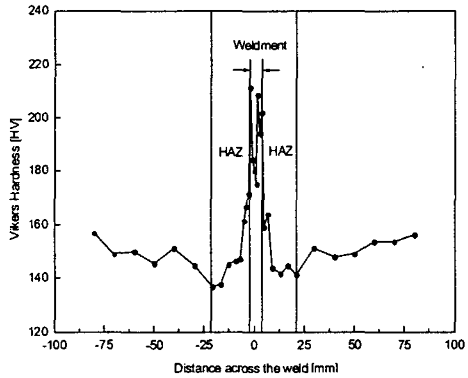


Fig. 2 Micro-hardness profile of a seamed tube with thickness 2.6 mm

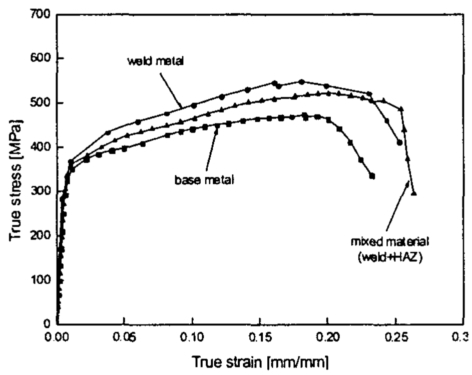


Fig. 3 True stress-strain curves obtained from tensile tests

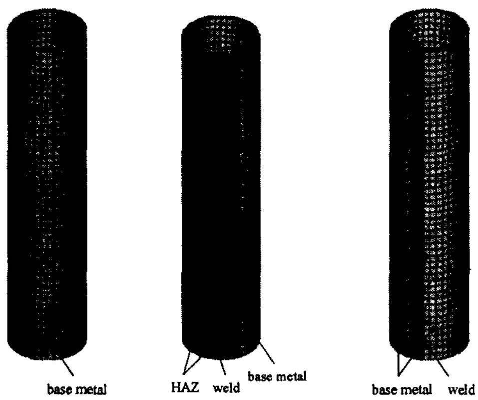
Five specimens of the base metal alone, five weld-only specimens and five specimens containing a weld line and HAZ, which are cut from the seamed tubes, are prepared for the tensile test. Experimental stress-strain data for the base metal, the weld metal and material containing the weld and HAZ (refers to *mixed* in Eq. (3)) are plotted in Fig. 3. They are given by average of each data for the five specimens.

As listed in Table 1, the HAZ property has lower work hardening aspect than the base metal. In order to determine the material constants in Oyane's ductile fracture criterion for base metal, weld and HAZ, the limit strains based on the plastic instability are calculated. From two arbitrarily chosen limit strains, the two material constants for each material are obtained as listed in Table 1.

3. Prediction of bursting failure in bulge forming

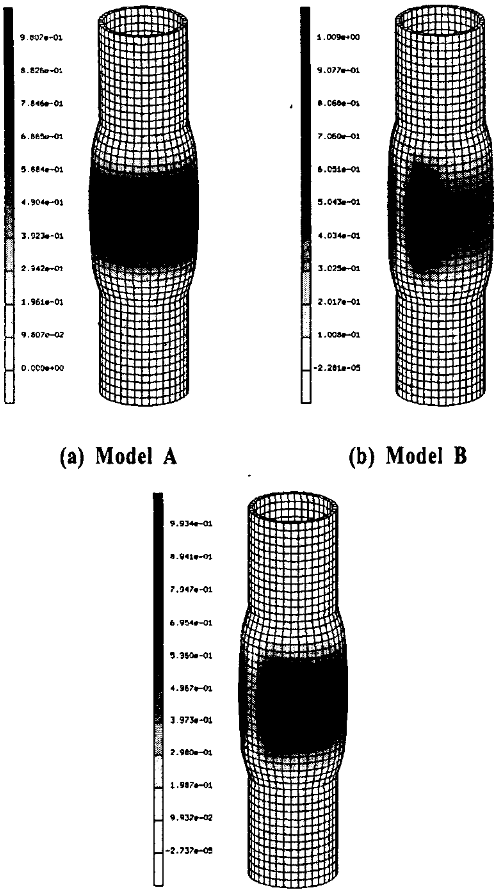
In order to numerically predict bursting failure during bulging process of a seamed tube, the finite element simulation combined with the ductile fracture criterion has been carried out. Three finite element models are created for the base metal alone(Model A), for including weld and HAZ as well (Model B), and for including weld-only (Model C). Figure 4 depicts these finite element models. In order to observe the bursting failure, high internal pressures under relatively low axial feeding are applied.

Figure 5 presents the distribution of the ductile fracture integral value I calculated from a self-developed rigid-plastic FEM program. The condition of bursting failure is satisfied when and where the integral I approaches 1.0. As can be seen in Fig. 5, distributions of the ductile fracture integral value appear to be largely different each other.



(a) Model A (b) Model B (c) Model C

Fig. 4 Finite element models



(a) Model A (b) Model B

(c) Model C

Fig. 5 Distribution of the ductile fracture index I

For model A, since the material property is the same over all elements as the base metal, no variation of the maximum value of I at the middle of the tube is observed along the circumferential direction. However, for model B, which contains the weld and HAZ, the maximum value of I, i.e. the potential initial fracture site, takes place near the weld line, which coincides with one of the actual bulging test in Ref. (5). In the case of model C, though the fracture location is somewhat similar with model B, all other behaviors, except that near the weldment, are the same as model A. Therefore, the finite element model containing weld and HAZ is the best model among the three models to describe the bursting behavior numerically.

4. Concluding remarks

By contrast with buckling and wrinkling, bursting is an irrecoverable failure in bulge forming processes. In this work, by means of the FEM combined with the Oyane's ductile fracture criterion, the forming limit and the bursting pressure level are investigated for a seamed tube that consists of weld metal, HAZ and base material. Especially, in order to determine the material property of HAZ tensile tests for base material and weld metal are executed based on iso-strain approach. From the results it is found that the work hardening of HAZ is lower than that of base metal. Finally, through a series of finite element analyses with consideration of weldment and HAZ it is shown that initial fracture takes place on HAZ near the weld line and that is more realistic result in view of actual bulge forming operations using a seamed tube.

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