STUDY OF FRACTURE BEHAVIOUR AND STRAIN PATH DURING TUBE HYDRFORMING PROCESS

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Abstract. Forming limit diagram (FLD) is a tool which is widely used to measure the material formability of hydroforming process. It is well known that strain based FLD is dependent on strain path which the material undergoes during the course of deformation. This work is based on understanding the deformation and fracture behaviour of as-received (AR) tube and annealed tube during hydroforming process. The strain path is being measured at different locations of the AR tube as well as annealed tube and is co-related with the microhardness value to understand the localization and fracture behaviour. The annealed tube tends to fracture suddenly from the weld line and fracture surface study reveals sudden dominant brittle mode of fracture indicating the impact of weld notch on the fracture process and thus giving lower limiting strains and hardness value.

Keywords: *Tube hydroforming; Strain path, Microhardness, ERW tube, DIC*

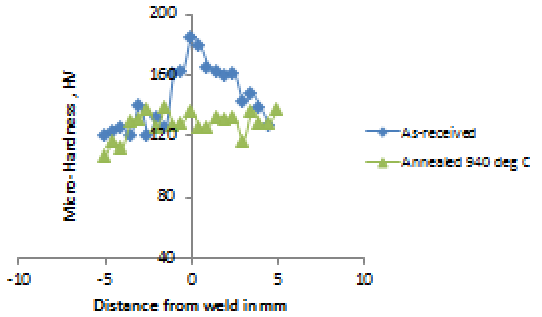
1. Introduction

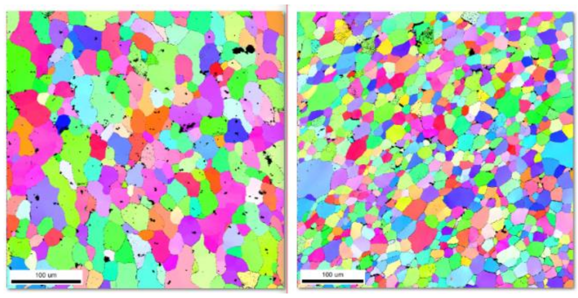
Tube hydroforming process is an advanced manufacturing technique which is widely employed for manufacturing of tubular components in automotive, aerospace industries as well as in producing household appliances because of it being a near net shape manufacturing technique [1]. Comparing with conventional stamping techniques, tube hydroforming offers several advantages like lightweighting, increased reliability, part consolidation, high strength part and tighter dimensional tolerances [2]. In the past, several researchers have worked on obtaining the forming limit diagram for tube hydroforming with varying loading paths as well as different geometrical conditions (l/d ratio) in order to achieve variety of stress state viz: uniaxial drawing, plane strain and biaxial stretching[3,4]. Stretching side of FLC is obtained by Li et al [5] by using “elliptical bulge test” methodology to obtain higher strain ratio in biaxial region. Chen et al.[6] have also conducted elliptical bulge test on laser welded and ERW tubes and compared the FLD for the two sets of tube and reported that laser welded tube have higher formability than their ERW counterparts. In all the above reported work only final fracture is analysed with no discussion on strain paths. The strain path analysis has only been reported by Yang et al[7] to establish FLD using complex strain paths and analytical model was used to validate on SS304 stainless steel tube.

This work is an extension of previously reported work on formability of DQ ERW steel tubes [8]. In the present work the understating of fracture behaviour and its correlation with strain path will be discussed and the effect of annealing on the fracture location and strain path will be studied.

2. Experimental details

The material used in this work is ERW DQ steel tube of 57.15mm diameter and 1.6mm thickness. The weld width alongwith HAZ is estimated around 7.5mm using microhardness test [8]. The EBSD of As-received material alongwith microhardness reveals that weld material has relatively finer grain size and higher hardness and thus higher strength co-efficient than base metal. This indicates the heterogeneity across the tube circumference. For detail material characterisation of as-received tubes refer to our earlier work [8]. In an attempt to reduce the heterogeneity and homogenize the material, the as-received tube is annealed to 950 degree C for 30 minutes. The microhardness profile and EBSD (in thickness direction) alongwith the true stress strain curve shown respectively from figures 1-3 indicates that annealing process has considerably able to homogenised the material and thus able to significantly reduce the heterogeneity caused due to welding process.





(a) (b)

Fig.1 – Microhardness Profile

Fig.2 – IPF map after annealing (a) base metal (b) weld metal

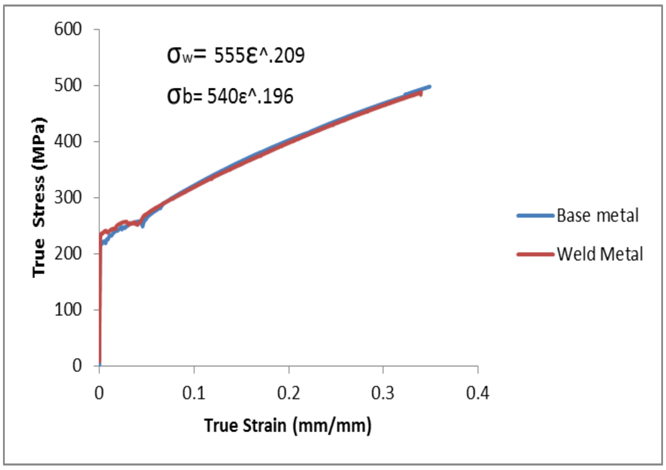
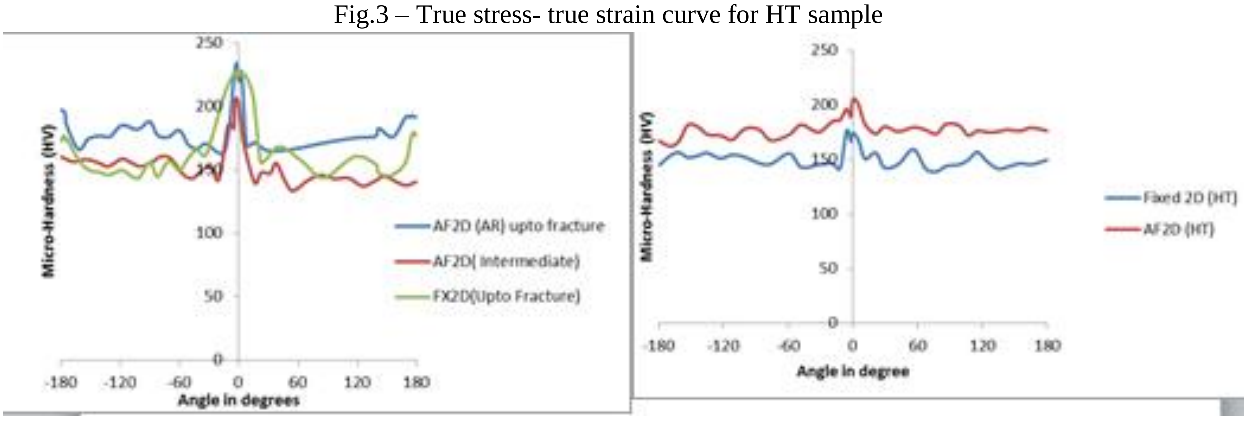


Fig.3 – True stress- true strain curve for HT sample

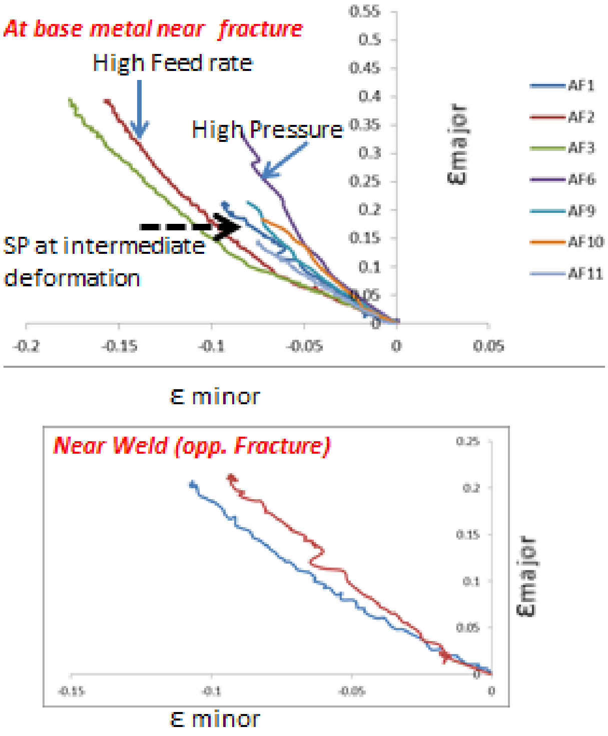


(a) (b)

Fig.4 – Microhardness profile for (a) AR and (b) HT sample after fracture (Note AF2D denoted axial feed with L/D=2 and FX2D denotes fixed condition with L/D=2).

3. Determination of Strain path

Tube hydroforming experiments were performed on a CNC hydroforming system having press capacity of 200 Ton and maximum pressure generating capacity of 1500 bar. The experiments were carried out at L/D =2 and different strain paths were generated by varying loading paths between two extremes of advanced feed and advanced pressure type. Black and white paints were sprayed on tube surface to form special speckle pattern which is used by GOM –ARAMIS digital image correlation (DIC) system to measure strains during online tube hydrobulging experiments. The strain paths were measured at the point of fracture in the base metal as well as same set of experiments were carried out with weld being kept in front of camera so as to capture the strain path near the weld i.e. opposite of the fracture position and shown in figure 5. The strain path for annealed sample is shown in figure 6. The microhardness value alongwith standard deviation is listed in table 1 giving a good indication of deformation heterogeneity across the circumference of the tube for different working conditions.



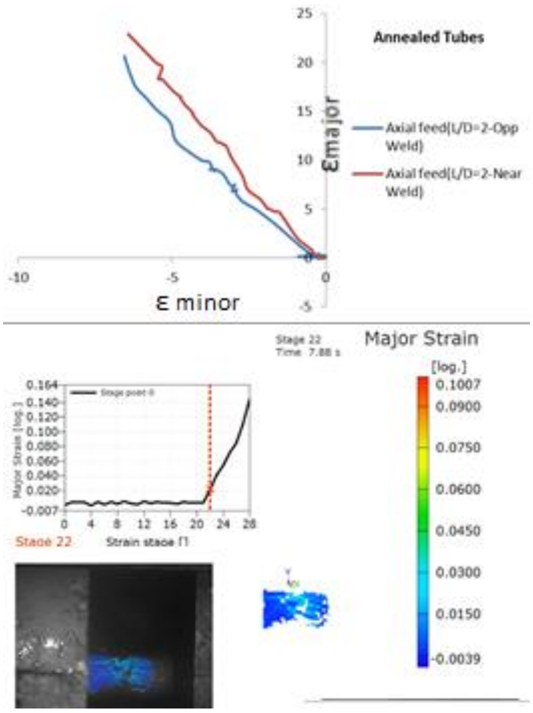


Fig.5 – Strain path for Axial feed L/D =2 (AR) Fig.6 – Strain path for Axial feed L/D =2 (HT)

It can be observed from figure 4 showing microhardness value for deformed sample of (a) AR tube and of (b) annealed tube that there is large variation throughout microhardness value for AR tube. Zero degree position is the weld position whereas the burst position is at 180 degree in case of figure 4(a) i.e. for AR tubes. One can clearly state by looking at the variation of hardness value that the point of fracture (near 180 degree) has highest hardness due to strain hardening effect and that is where strain localization takes place. The weld region already has higher hardness and strength and after hydroforming there is very little deformation occurs near weld as (almost 1/3rd of the base metal) evident from strain path comparison shown in figure 5 and therefore there is not much increase in hardness. The hardness of tube deformed till fracture in fixed condition also follows the same pattern and same fracture location but is slightly lower which is because the forming limit and hence strain hardening for fixed condition is lesser than the axial feed condition because of severe extent of thinning and strain severity owing to no material feeding in the critical region as explained in previous work [8].

On the other hand observing the microhardness value of annealed tube till fracture reveals that there is just a slight variation in hardness value throughout the circumference of the tube. In case of annealed sample the crack was observed at weld region (0 degree). Not much variation in hardness value indicates that there is very little or almost no strain localization occurring before fracture which is quite clear from strain path diagram of annealed tube as can be seen in figure 6, where strains at weld (fracture point) and at opposite to weld (i.e. base metal) is following almost the same path indicative of uniform deformation. The repeated fracture of annealed tube at weld with lesser degree of deformation showing almost no strain severity and much lower bulge height being obtained (note that bulge height for annealed sample is at max 4 mm whereas AR tube gives bulge height from 9-15 mm for different conditions indicating of that weld notch is playing a major role in fracture initiation and acts as a primary stress raiser. Fracture surface study of annealed tube presented in figure 7 also indicates the presence of large percentage of flat cleavage plane indicating the dominant mode of failure as brittle.

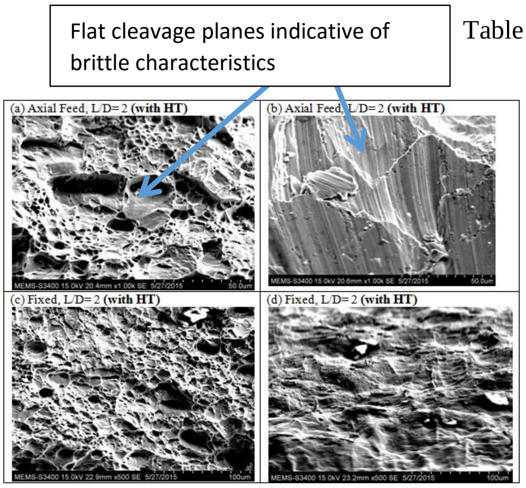


Fig.7 – Fractographs of annealed tube

Table 1 Microhardness value of different sample and its std. deviation

(Note - * indicate SD for base metal only)

Condition	HV Weld	HV HAZ	HV Base	SD
As-Received (AR)	170-180	150-160	120-135	20.9 (7.2*)
Annealed (HT)	130-140	120-130	120-140	8.96
Axial feed (AR) Intermediate deformation	~200	170-190	140-160	17.45(7.71*)
Axial Feed (AR) upto fracture	~240	210-240	180-200	18.51 (10.08*)
Axial feed HT upto fracture	~200	180-195	165-180	10.8

4. Conclusion

In this work a brief analysis of the deformation behaviour in terms of strain path and microhardness across the circumference of the tube is presented for AR tube as well HT tube in annealed condition. The changing position of fracture in case of annealed tube was studied and analysed using fracture surface. Initial investigation reveals that notch in case of HT tubes is crack initiating site and in future a detail analysis will be carried to understand the impact L/D ratio has on crack location.

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