EXPERIMENTAL INVESTIGATION AND PERFORMANCE EVALUATION OF HYDROFORMED TUBULAR BELLOWS IN INCONEL 625 ALLOY

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***Abstract* - Tubular Bellows are generally formed by hydroforming process is to achieve the uniformity in structure with adequate dimensional accuracy. This research investigation focused on evaluating the performance of the hydroformed tubular bellows expansion joints made up of inconel 625 (superalloy). The optical microscopic image has been used to find the variation in thickness of bellows. The flexibility and the fatigue property of the bellows were evaluated by using the spring rate test and life cycle test. The cross-sectional SEM (Scanning Electron Microscope) images were perfectly identifying the defects which presence on the surface of the convolutions of the bellows expansion joints.**

Keywords - Tubular bellows, Expansion Joints, inconel 625, Hydroforming

I. INTRODUCTION

Bellows are spring-like structures, which can be used as a pressure holding set up, to absorb the motion caused by variable fluctuations and thermal effects [1]. Bellows find wide spread application in aerospace, marine and nuclear industries. They are quite compact with the assemblies and efficient in performance of the piping system. Compared to pipe bends and expansion loops, bellows provide better output efficiency due to their inherent flexibility to absorb the multi directional movements.

Bellows are generally made up of stainless steel, titanium, brass, copper, aluminium etc. based on the applications and the functional environment [2]. The compression and expansion of the bellows makes the flow effectiveness. Among the unconventional metal forming processes, hydroforming draws considerable attention due to its capability in forming of complex shapes in a single step with varying cross sections and free from defects like bursting, wrinkling, or buckling [3],[4]. Many researchers have been carried out their research in the area of hydroforming and it was identified that the tube hydroforming is the one of the most hopeful technique for developing light weighted with high strength components [5]-[7].

B.H. Kang. et al performed the experiment in the metallic tubular bellows using a single step hydroforming process with controlled internal pressure and axial feeding. It was concluded that the metallic bellows can be made without cracks [8]. Compared to other forming methods of bellows, hydroformed bellows are results good in flexibility. In the hydroforming method, the bellows are formed by hydraulic pressure so that the impression of the die was not presented. Thus, smooth surface finish is feasible. The internal and external diameters of the bellows almost remain constant for each convolution in hydroformed method.

Though hydroforming was originally brought into the limelight for producing complex geometries with the minimal weight, the desirable work materials that can be used have still not been explored. A further detailed exploration is needed for high strength materials [9],[10], such as inconel 625(Superalloy). Inconel 625 material which exhibits good mechanical strength improved resistance to high temperature, corrosion and oxidation environments and better surface stability, is taken for this study. The inconel 625 have better resistance to cavity erosion and jet impingement erosion [11].

Superalloy development has relied heavily on chemical and process innovations, and has been driven primarily by the aerospace and power industries. The cost of the superalloy is considerably high, but its advantage over the thermal expansions and in corrosion resistance, surpasses the cost [12]. An intermittent process has been performed for joining the seam of sheet metal to tube form by using Plasma Arc Welding Process (PAW) and the tubes are subsequently pressurized and formed as bellows by hydroforming process. Considering thin sheet metals, PAW has its own advantages like less porosity, more tolerance to joint misalignment and good weld penetration [13]. The Expansion Joint Manufacturers Association (EJMA) has generated standard formulae to design such bellows. This paper deals with the experimental investigation of hydroformed bellows that suggests the desirability of superalloy for bellows.

II. EXPERIMENTAL PROCEDURE

Inconel 625 sheets of 0.2 mm thick were taken for the experiments. The mechanical properties of inconel 625 and its chemical composition are shown in Tables I and II. The sheet of 290 mm length and 120 mm breadth is rolled along the axial direction and joined as a tube form using Plasma Arc Welding (PAW). The seam welded tube is tested for weld defects in the weld zone by die penetrant and radiography tests. The welding strength has been ensured by the tensile test, which showed the breaking load of 2.2 kN and the tensile strength of 880 MPa.

TABLE I
The Mechanical properties of the inconel 625

Thickness (mm)	**Tensile breaking load (kN)**	**Yield load (kN)**	**Initial gauge length (mm)**	**Final gauge length (mm)**	**Tensile strength (MPa)**	**Yield Strength (MPa)**	**Elongation % on 50 mm gauge length**
0.2	2.3	1.6	50	75.9	920	640	51.40

TABLE II
The chemical composition of the inconel 625

Ni	**Cr**	**Mo**	**Fe**	**Nb**	**Mn**	**Si**	**Ti**	**Co**
62.37	20.52	8.32	4.67	3.22	0.27	0.27	0.22	0.12

Tubular bellows of 56 mm outer diameter and 39.8 mm inner diameter with 120 mm length were formed, using a hydroforming press of capacity 25 T. The tube was tested for circular uniformity, wall thickness and then the tube was filled with water and pressurized until circumferential yielding occurs. A total number of ten convolutions were formed, by forming one convolution at a time with a constant internal pressure of 5 MPa. Lin et al stated that the forming parameters such as internal pressure and punch velocity influence the expansion rate as well as the thickness distribution of the bellows in hydroforming and also reported that the minimum thickness after hydroforming should have atleast 80% of initial tube thickness [14].

The transformation from the tube form to bellows and its vertical cross section for the test analysis is shown in Fig. 1. The convolutions of the bellows are shown in Fig. 2. Once the bellows were formed, they were subjected to the dye penetrant test, to assess the surface defects in the weld zone. The internal flattened convolution of the bellows was transformed into U shaped convolution by the rolling process to achieve more flexibility of the bellows. The roll forming process imparts a substantial amount of cold work to the root of the bellows. This combination process has the added merit, that the bellows with extra deep convolutions can be formed as a replacement to the costlier diaphragm type bellows [15].

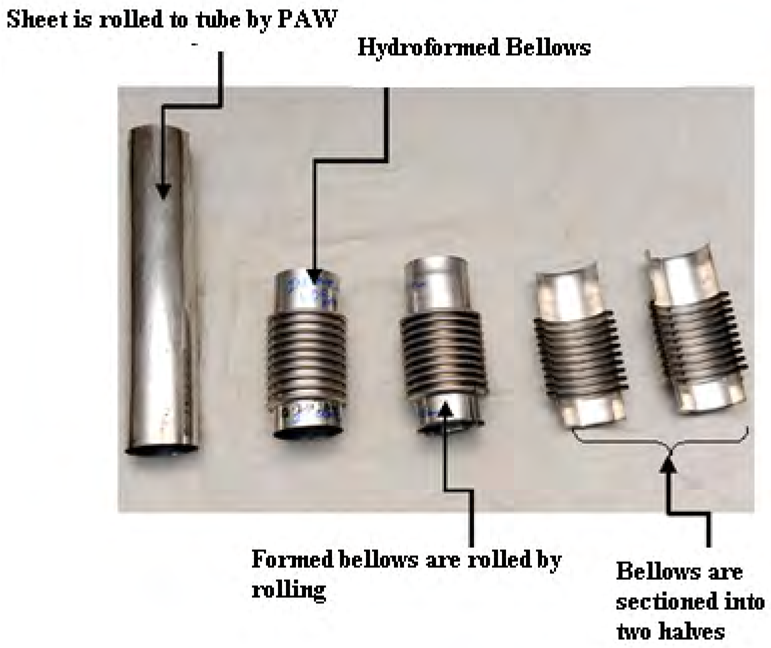

Fig. 1. Forming of Bellows

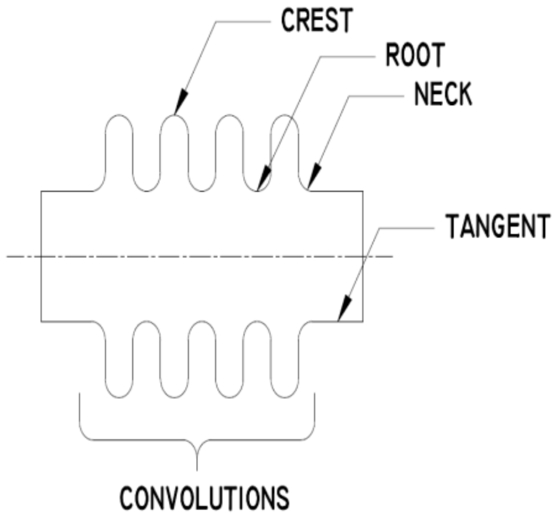

Fig. 2.Convolutions

To find out the uniformity of thickness throughout each convolution of the bellows, the thickness variation was measured using high resolution optical microscope. To evaluate the performance of the hydroformed bellows the spring rate and life cycle test have been conducted. Further the microstructure observation using SEM image identifies about the presence of defects in the convolutions.

III. RESULTS AND DISCUSSION

A. Thickness Distribution of Bellows Convolution

The formed bellows were sectioned into two halves, by wire cut electro discharge machining (EDM), and the thickness measurements were made at specified locations, using optical microscope [16]. The average thickness variations calculated from the measured values in the crest and in the root are 0.196 mm and 0.198 mm respectively. The percentage thinning at the crest as well as in the root is less than 98% of the initial tube thickness, which is within the allowable limit. It is also observed that there is a variation in thickness between the crest and root as shown in Fig. 3. A similar observation of variation in thickness between the crest and the root was also reported by Satoshi et al [17]. It was recognized that the thickness variation was due to the pressure distribution in hydroforming process. Bihamta et al [18] stated that the thickness variation in hydroformed bellows is unavoidable, even by increasing the axial feed of the tube.

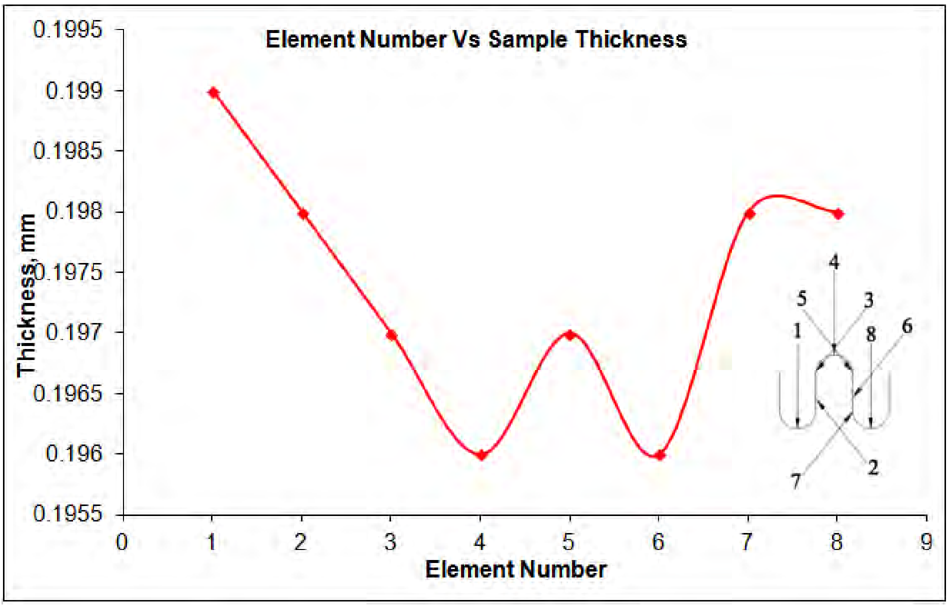

Fig. 3.Thickness Distribution of the convolution

B. Axial Stiffness (Spring Rate Test) of the Bellows

The axial stiffness (spring rate test) of the bellows is the load required to move the bellows per unit length. It also defines the flexibility of the bellows. The spring rate is measured and recorded manually in a spring rate testing machine, as shown in Fig. 4. The load required to deflect the bellows axially is the function of the geometry of the bellows. The obtained spring rate of the hydroformed bellows is 11.47 N/mm, which is less than the theoretical spring rate of 12.85 N/mm as per equation (1) which is obtained from EJMA. The results of the tested U shaped circular bellows show that the theoretical spring rate calculated as per EJMA, match with the practically measured spring rate [19]. Fig. 5 shows the variation of load vs. deflection for most bellows, indicating the motion extending into the plastic and elastic range.

$$Cf = [2rm / w]vs\left[1.82rm / (Dm \times tp)^{0.5}\right] \qquad (1)$$

where,

C_f = Spring rate

r_m = Mean radius of the bellow's convolutions in bellows.

D_m = Mean diameter of the bellow's convolutions for the U profile.

t_p = Bellows material thickness for one ply.

w = Convolution height.

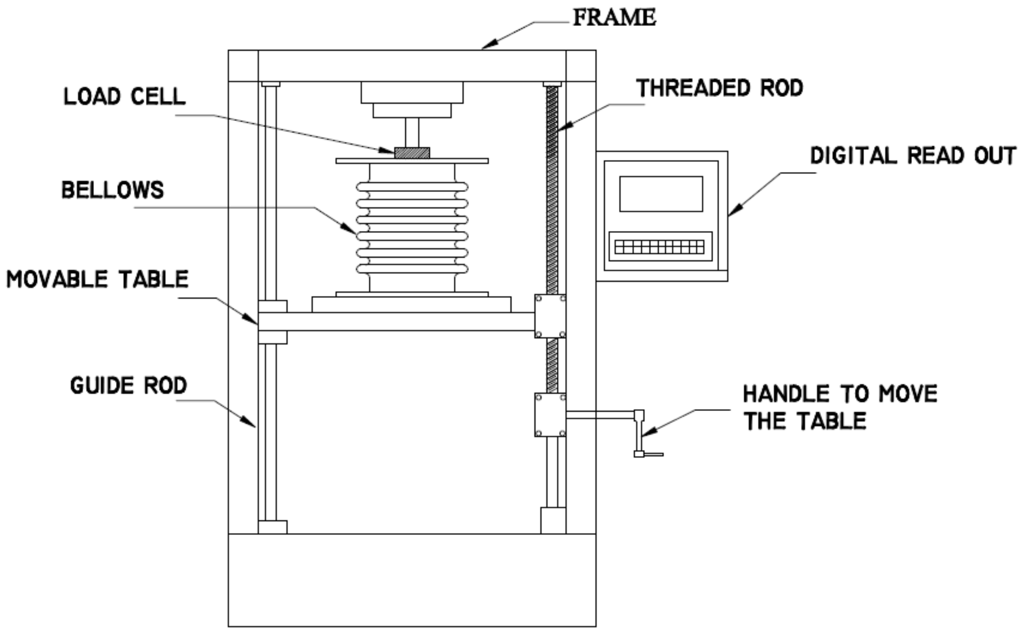

Fig. 4.Set up for Spring Rate Testing of the Hydroformed bellows.

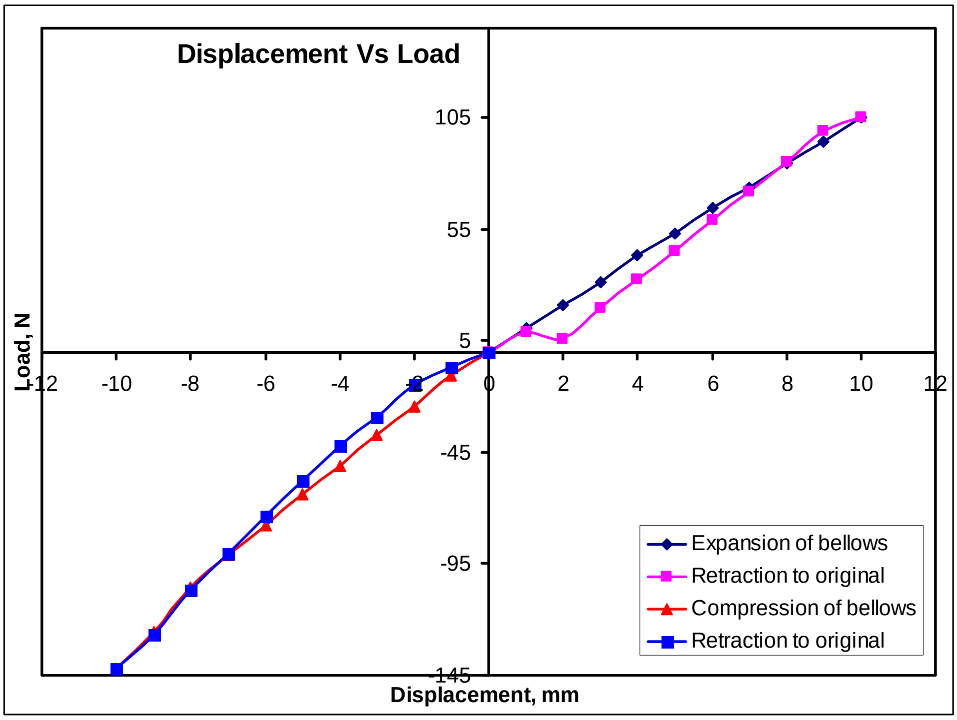

Fig. 5.Spring Rate of the Hydroformed bellows.

C. Life Cycle Test

A life cycle test was conducted to evaluate the life of the bellows. The observed experimental values were compared with the EJMA code, to ensure that the observed values are more than those of the designed life cycle. The bellows were tested for the designed movements in the axial direction, with or without internal pressure. The life cycle test on the bellows was carried out as per the standards of EJMA, and the setup is shown in Fig. 6. The bellows are fixed in suitable fixtures on a reciprocating machine, with an internal pressure of 0.1MPa. To maintain the internal pressure constantly throughout the bellows, one more additional compensated bellow may be assembled, and then 10 sets are constituted totally for the life cycle test.

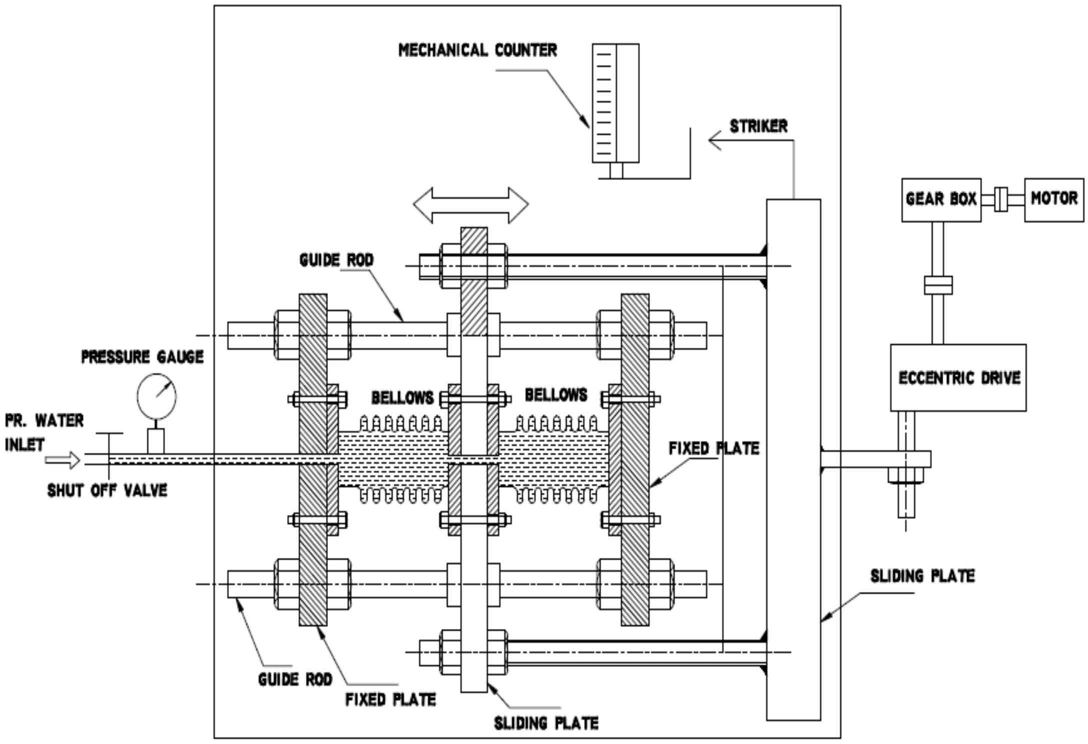

Fig. 6.Set up for Life Cycle Testing

Each cycle of the test involves a compression and expansion of the bellows. The cycles were monitored using a mechanical counter with a measuring capacity of 32 cycles per minute. For every 1000 cycles, the bellows were observed visually with the die penetrant test to ensure that condition of bellows. Further, monitoring the internal pressure using a pressure gauge ensures the stability of the bellows throughout the cycle. The designed cycle life of the bellows was 9470 cycles by the EJMA code, which is obtained from equation (2). After the cycle test, the bellows were subjected to the pressure test and helium leak test to ensure their stability.

$$Nc = \left(1.86e6 / \left(St - 54e3\right)\right)^{3.4} \qquad (2)$$

where,

$$St = 0.7 \times \left(S3 + S4\right) + \left(S5 + S6\right)$$

Nc = Number of life cycles

s_3 = Meridional membrane stress due to internal pressure

s_4 = Meridional bending stress due to internal pressure

s_5 = Meridional membrane stress due to deflection

s_6 = Meridional bending stress due to deflection

From the life cycle test it was observed, that the bellows can withstand more than 50,000 cycles without any failure, which is five times more than the designed life cycles by the EJMA code. The increase in the life cycle of the hydroformed bellows can be due to the superior mechanical and material property of the inconel 625 alloy. Zhu et al [20] have suggested that the need for the selection of proper material based on the operating medium.

D. Microstructure Observation of the Bellows

The surface morphology of hydroformed inconel 625 bellows was observed by SEM. The formed bellows were sectioned in the axial direction by wire cut EDM, to evaluate the morphology of the parent metal as shown in Fig. 7, as well as the cut section of the bellows at the crest, shown in Fig. 8. Though there is a significant effect of the compressive and expansion stress in the hydroformed bellows, cracks were not observed.

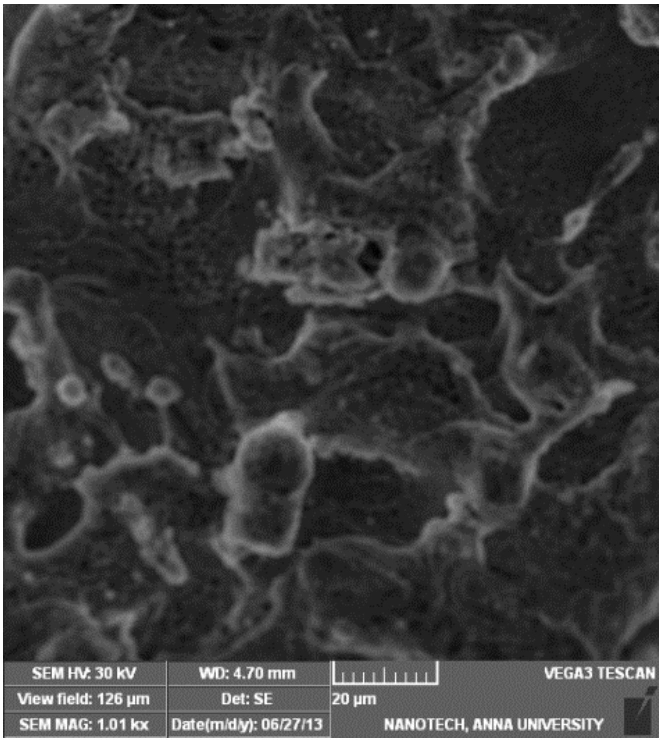

Fig. 7.Microstructure of parent metal of the tube

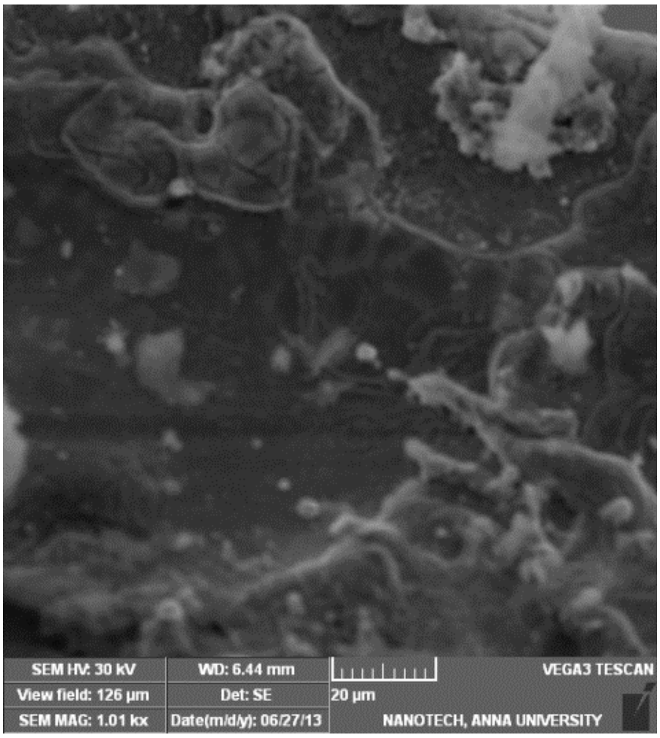

Fig. 8.Microstructure of the cut section of the bellows at the crest

IV. CONCLUSION

The performance oriented evaluations of hydroformed tubular bellows using superalloys have been investigated. The inconel 625 bellows exhibits better performance as a material that can be suitable to construct the bellows. Tests, such as thickness distribution, spring rate, microstructure observation and life cycle tests were conducted, from the test results; the following conclusions have been drawn.

1. The forming stages of each convolution and the thickness distribution have been measured. The thickness variation measured in the crest is 0.196 mm and in the root is 0.199 mm. Thus, the thinning of the

hydroformed bellows is maintained as 98% of the initial tube thickness of 0.2 mm, which is within the allowable limit.

2. The spring rate of the hydroformed bellows is 11.47 N/mm, which is less than the theoretical spring rate of 12.85 N/mm as per the EJMA code.
3. The life cycle of the bellows was observed to be more than 50,000 cycles, which is five times greater than the cycles designed by the EJMA code. From this it was concluded that there is an increase in the life cycle of the hydroformed bellows using inconel 625.
4. The SEM images show the surface morphology of the hydroformed bellows and it ensures that no cracks were found in the formed surface.

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