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Design and Development of Hole Drilling Equipment for Residual Stress Measurement

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***Abstract*:** *Residual Stresses are stresses that reside, or are stored in a material, when the material isn't subjected to an external force or stimuli. These stresses are present in practically all materials owing to a multitude of factors. The Hole Drilling Equipment employs a semi destructive technique for measuring these residual stresses. This paper describes a novel equipment design, conforming to ASTM International, and analyzes the experimental results of the equipment tested on a sample specimen. The results are then assessed in light of established trends found in published literature. The hole drilling apparatus measures stress at localized points. The technique involves drilling a small hole in the pre-stressed part which relieves the stress at that location. A strain gauge surrounding the drilled hole measures the relieved strains. The properties of the material are then used to calculate the relieved stress, from the strains. The relieved stress is numerically equal to the residual stress originally present at the hole region.*

Keywords: *Residual Stress, Hole Drilling Technique, Semi Destructive Residual Stress Measurement*

1. Introduction

Residual Stresses (RS) are the stresses that exist in a body/structure, not subjected to any external applied force. These stresses, in general, depend on the mechanical and metallurgic history of the material. As the design of engineering components becomes more complex there is an increasing interest in how residual stresses affect the performance of mechanical parts. This is because structural failure is caused by the combined effect of residual and applied stresses. Consequently, it serves as a crucial factor in premature failure of structures and considerable decrease in their service life time. Residual Stresses are classified in three categories [1]:

Type I Residual Stress: These are often referred to as macroscopic residual stresses which depend on macroscopic parameters such as plastic deformation, thermal expansion, structural deformation etc.

Type II Residual Stress: This type mainly arises due to the heterogeneity and anisotropy of the material. Such properties are characteristic of polycrystalline and multiphase materials. These stresses equilibrate within a number of grain dimensions.

Type III Residual Stress: These are stresses present over atomic dimensions and therefore equilibrate within grain size. These are a common result of imperfections and dislocations on atomic scale.

Due to their destructive nature it is important to be able to at least estimate the magnitude and orientation of residual stresses. There are many methods of measuring Residual Stresses, but certain circumstances may require one method over another. There are three broad categories of Residual Stress measurement; destructive, semi-destructive, and non-destructive [2].

- Destructive: Contour Method, Slitting Method etc.
- Semi Destructive: Hole Drilling Method, Ring-core method, Deep-hole method etc.
- Non Destructive: X-Ray Diffraction, Neutron Diffraction, Ultrasonic method etc.

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The hole-drilling method is a semi-destructive residual-stress measurement technique (localized damage) in which a hole is drilled into the centre of a rosette strain gage, which is adhered to a test specimen, while strain measurements are taken. Afterwards, relating the strain to stress via elasticity theory gives a relatively accurate pre-hole stress profile.

2. Design of Equipment

The basic design encompasses the following essential components and is designed according to the protocols and constraints set by "American Society for Testing and Materials International –E837 2016 [3]"

2.1. Tripod

The tripod stand consists of a triangular base plate, legs, a welded hollow sleeve and two detachable concentric hollow sleeves. The base plate and welded sleeves are made from stainless mild steel. The base plate consists of three through holes of diameter 0.375 inches for legs and a larger bore for welding with a sleeve.

2.2. Microscope

A microscope is instrumental to the accuracy of the experiment. Therefore, a microscope with a focal length of 5 cm, a magnification of the order 5X, with a lens diameter of 0.95 inches and a tube length of 4 inches is employed. The microscope plays a crucial role in aligning the center of the drill with the center of the strain rosette.

Fig. 1: Microscope being used to align the drill sleeve

2.3. Strain Rosette

The strain rosette is adhered to the work piece which encapsulates the drilling region. A delta and rectangular strain rosette is used with this equipment according to the specifications set by ASTM International [3].

The BE120 10CA strain rosette has a maximum hole diameter of 3 mm which can be drilled and the BE 120 1CG has a maximum allowable hole diameter of 2.5 mm. Both the diameters conform within our requirements as per the diameter of the drill bit and ASTM International standards.

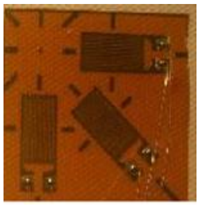

Fig. 2: BE 120 10 CA

Fig. 2: BE 120 1 CG

2.4. Strain Meter

The strain rosette is integrated with 'Strain Sert Company HW1-D' strain meter with a least count of 1μ strains. The integration is achieved by meticulous soldering of the strain rosette wires, that connect to the strain meter.

Fig. 3: HW1-D Strain Meter

2.5. Electric Motor Drill

An electric motor drill which runs at 35,000-40,000 RPM (under no load) is used in the equipment. To account for the minor hole depth the torque of the drill is limited to 0.04 – 0.2 Nm. The diameter of the carbide burr is 1.6-2.4 mm. The electric drill is encased in a sleeve with an inner diameter of 1.35 inches and outer diameter of 1.94 inches. This sleeve is threaded and then connected to gear which is meshed with the pinion gear of stepper motor. The electric drill penetrating the surface of the work piece can be seen in "Fig. 5".

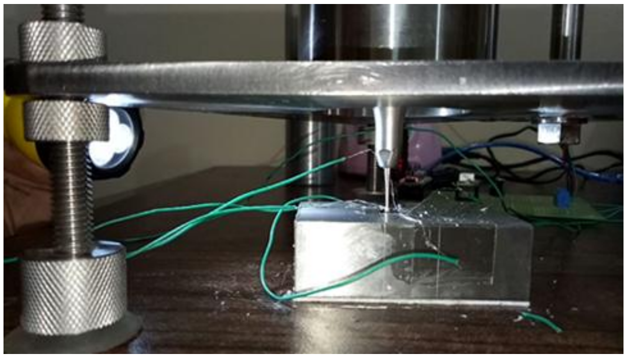

Fig. 4: Electric Drill in Operation

2.6. Stepper Motor

The linear motion of the drill is acquired through the use of a stepper motor and a gear assembly. The driven gear is attached to the drill housing sleeve which meshes with a pinion gear. The pinion gear is driven by a stepper motor - controlled through a microcontroller. The employed gear ratio of pinion to driven gear is 5.33:1 Further, each revolution of the driven gear traverses the drill by 2.11 mm. The internal threads per inch of the driven gear is 12.

A NEMA 17 Stepper Motor is used. Stepper Motor allows stepping of the driven gear to rotate at as low as 1.8 degrees. Thus, 1.8 degrees revolution of the stepper motor provides 2 microns of linear movement.

The complete assembled hole drilling equipment is attached, "Fig. 6". This is a contemporary design in the sense the equipment efficiently manages to be portable, operationally simple and renders the provision of automated and precise incremental hole drilling.

Fig. 6: Complete Assembled Equipment

3. Experimental Procedure

A welded sample of Stainless Steel 304 was employed for the experiment. The physical properties of the material, germane to the experiment are as follows:

Young’s Modulus: 200 GPa, Poisson’s Ratio: 0.29

Initially, the strain rosette is carefully adhered to the work piece following precise surface cleaning and polishing procedures. The strain rosette is then connected to the strain meter.

Following which, the microscope is used which aids in aligning the drill sleeve concentric to the rosette center. A cross reticle placed at the objective lens aids in setting the housing concentric with the center of strain rosette.

For thin samples, we drill in one go. However, for a thick sample, we divide the thickness in a number of steps in accordance with ASTM International [3]. After each step the drill is moved in the opposite direction using respective command input from the microcontroller. The strain readings are then recorded at each step. The process is repeated until the desired hole depth is achieved. For our experiment, a carbide drill bit was employed. The residual stresses were measured across the central weld bead line in a series of 8 steps.

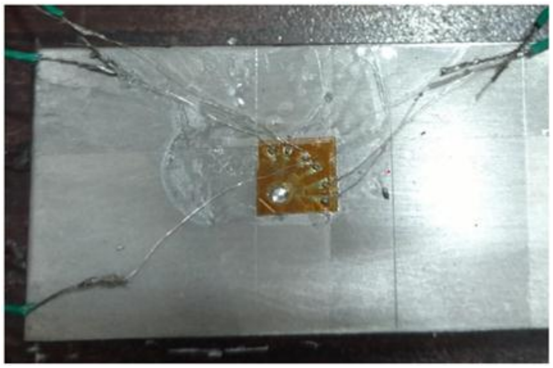

Fig. 5: Welded Stainless Steel 304 after Hole Drilling Experiment

4. Experimental Results

The following strain values were recorded, on the central weld bead line, for the respective hole depths

Table I. Strain Readings On Weld Bead

Steps	Hole Depth (Microns)	ϵ1(µm)	ϵ2(µm)	ϵ3(µm)
1	50	-6	-8	-12
2	100	-17	-13	-17
3	150	-28	-21	-30
4	200	-42	-38	-43
5	250	-54	-52	-56
6	300	-75	-59	-59
7	350	-84	-71	-76
8	400	-92	- 87	-110

The strain readings are then computed further by employing the following equations as stated in E837-2016 ASTM International [3].

$$P = -(Ep)/(\bar{a}(1+v)) \tag{1}$$

$$Q = -(Eq)/(\bar{b}) \tag{2}$$

The values for p and q are calculated using arithmetic operations applied on the recorded strains, as per ASTM International .The values for the aforementioned constants (a¯) and (b¯) were acquired from E837-2016 ASTM International. The constants (a¯) and (b¯) depend on the nature of strain rosette employed, the incremental hole depth and the hole diameter.

$$\sigma_x = P - Q \tag{3}$$

$$\sigma_y = P + Q \tag{4}$$

The calculated values of P and Q were then further computed from 'Eq. 3' and 'Eq.4' to yield the normal stresses (σx, σy) along both axis. The stress profile is illustrated in "Fig.4"

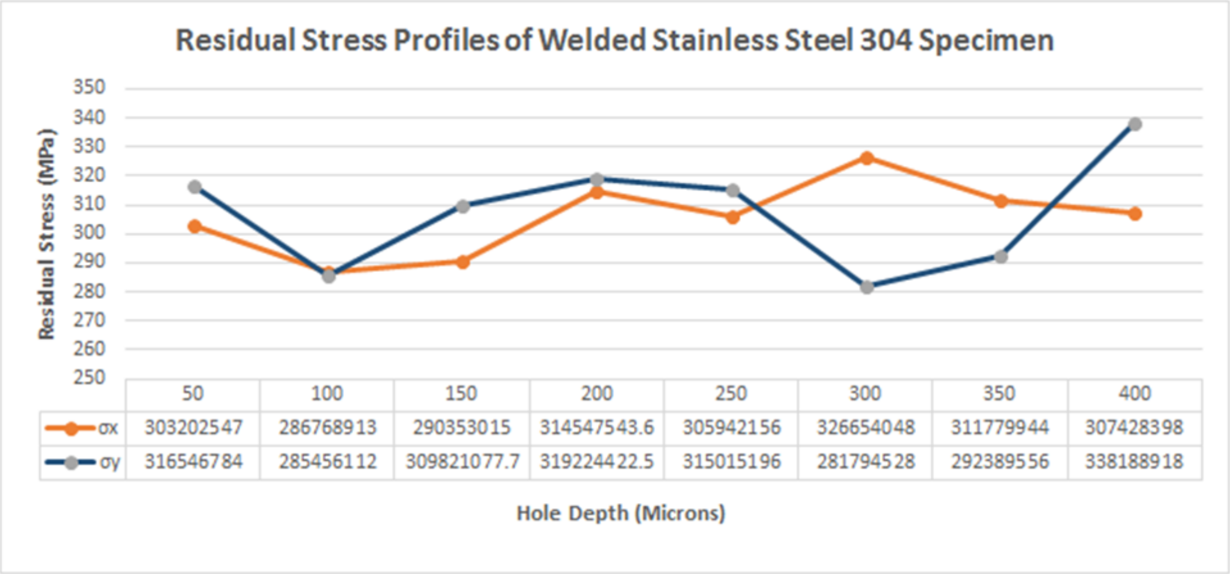

Fig. 6: Residual Stress Profiles of welded stainless steel 304

5. Analysis of Results

The trend observed in the residual stress profiles across the weld bead line is normally tensile in nature at the subsurface. However as depicted in published literature, at around a depth of 1 mm or greater, it transmutes to compressive stresses. The aforementioned experiment illustrates the stress profiles of up to 0.4 mm depth, and thereby no change in nature of stresses is observed. The general development of residual stress in a welded specimen starts off with significant tensile stresses in the subsurface fusion region which are then largely observed to shift to compressive stresses deeper into the cross section of the weld bead. Further into the weld bead, the compressive stresses are then again seen to shift to tensile stresses [4].

As expected and proven by literature, significant residual stresses are present in the weld region with comparatively minimal residual stresses in the base metal. Additionally, it is therefore, also safe to say that the residual stresses will have a probable presence in the Heat Affected Zone of the weld. Consequently in event of material failure, the welded structure is highly susceptible to fail/fracture from the weld region.

It is pertinent to note that the residual stresses calculated from this technique might show marginal disparity, to the stress values computed from other residual stress measurement techniques. However in all events, the general development and the resulting stress profiles are wholly compliant.

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