Welding has a number of detrimental effects on the structural integrity and in-service performance of the weldments. These detrimental effects are due to imperfections induced by the welding in the weldments, of which the structural shape change behavior, residual stresses and the weld solidification cracks that are reported to have very severe degrading effects on the mechanical strength and which may possibly can lead to catastrophic failure. A number of catastrophic failures of high pressure vessels of thin-cylindrical shells and other similar structures due to longitudinal and circumferential welds are reported in the literature. Both weld residual stresses and distortions can significantly affect the performance and reliability of the welded components. Therefore, these must be critically dealt while design and manufacturing phases, to ensure intended in-service use of the welded component.
2.1 Introduction

The reliability and high performance of thin-walled cylindrical components are of paramount importance in aerospace, marine, aeronautical structures, pressure vessels and nuclear applications. Welding is the mandatory integrating technique available for joining those components of critical equipments, where the specific strength and cost effectiveness are the major design constraints.

Tremendous efforts have been made in the past few decades by numerous researchers showing a remarkable development in new welding techniques for better quality products capable of excellent in-service performance against thermal and structural load bearing features. Despite of these considerable innovations in high temperature joining techniques, still the problems of weld induced imperfections like residual stresses and distortions are the major challenges for the welding engineers due to the complex nature of the welding phenomena.

Masubuchi [1] and Connor [31] discussed various types of welding induced distortions, residual stresses in thin walled structures and the respective control and mitigation techniques. Distortions are considered as the most common defects that occur during welding, which can adversely affect the dimensional accuracy and thus lead to expensive corrective work. Hence, it is very essential to forecast the distortions in advance in order to minimize the negative effects, so that it helps in improving the quality of welded parts and finally to reduce the manufacturing costs as well. Deo et al. [32] presented a panel with angular distortion, that is transverse to the welding direction and caused by shrinking near the fusion zone resulting in a change in the angle of the parts.
Chin-Hyung Lee et al. [33] have carried out three dimensional FE analysis to estimate the residual stresses in circumferential welds of steel pipes with inside radius to wall thickness ratio ranging from 10 to 100. They have also illustrated the variation in residual stresses at different circumferential locations and the effects of diameter on residual stress distributions. Shim Y et al. [34] considered a ramp heat input and included the effect of moving arc in their analysis. They also investigated the effect of various ramp times and observed that 20% of the actual heat input time is the best ramp time. Liang Wang et al. [35] have investigated the effect of laser travel velocities with constant power and the laser powers with constant velocity on the distribution of residual stress during laser welding of thin wall plates. In this study, net heat input during welding process was also varied. Spina et al. [36] evaluated the effect of welding speeds on the weld profiles and distortion of the components during laser welding of AA 5083 sheets using numerical simulations. This study revealed that as the welding speed reduced the net heat input increased and vice versa. Brickstad et al. [37] numerically simulated a multi-pass circumferential butt-welding of stainless steel pipes using a non-linear thermo-mechanical Finite element analysis (FEA) to study the variation in weld heat inputs. They also studied the variation in the through-thickness of the weld and HAZ on the axial and hoop stresses for austenitic stainless steel pipe welds and their sensitivity against weld parameters. Kazuo Ogawa et al. [38] investigated the residual stress in penetration nozzles by considering different nominal heat inputs and weld speeds at constant weld power for different weld passes. Chaowen Li et al. [39] carried out three dimensional FEA of temperatures and stresses for increasing weld speeds with constant power on different samples. The above study reveals that increase in weld speed at constant power, increases the net heat input. Kermanpur et al. [40] studied the effect of variation in net heat input for a GTAW circumferentially butt welded pipes. The study revealed that
increasing the heat input resulted in a wider weld pool along with a higher maximum
temperature in the HAZ. Wu. C.S et al. [41-42] used different levels of heat inputs with different
welding currents by keeping welding speed and voltage as constant for two different arc welding
processes (double sided and plasma) in the numerical simulation. They also carried out
numerical analysis to predict the temperature field and weld pool shape as a function of welding
speed with constant laser power and current. Gery et al. [43] investigated the effect of variable
welding speeds and energy inputs on the transient temperature distribution, shape and boundaries
of fusion zone and HAZ. Dean Deng et al. [44] examined the influences of heat input on the size
of HAZ, welding residual stress and distortion during numerical simulation of electro slag
welding process. Dean Deng et al. [45] performed four different cases of welding simulations
with constant weld current, voltage and speed to clarify the influence of phase transformation on
the residual stress and welding deformation. Teng et al. [46] carried out welding simulations on
T–shape fillet welding plate and discussed on buckling strength of welded joints and the effect of
flange thickness, penetration depth and restraint conditions on distortions and residual stresses.
Long et al. [47] predicted the temperature variations, fusion zone and HAZ as well as
longitudinal and transverse shrinkage, angular distortion and residual stress for various welding
speeds and plate thicknesses. Díaz et al. [48] carried out the comparative analysis on distortion
of TIG welding of austenitic and duplex stainless steels by considering two different net heat
inputs for both the stainless steels. Jiang et al. [49] studied the effect of different welding heat
inputs and layer numbers on residual stresses and deformation in repair welds of stainless steel
clad plate. Yanhong Tian et al. [50] investigated the effect of heat input and welding speed on
the temperature field, especially on the shape and dimensions of the weld pool. It can be
observed from the above detailed literature survey that no focused studies had been undertaken
to study the effect of different conditions of weld speeds and powers with constant heat input on
the variation in temperature distributions and residual stresses. Further, literature survey also
reveals that no studies have been reported on the variation in longitudinal and circumferential
residual stresses along the radial distance from the outer surface as a function of different weld
speeds and powers with constant heat input. The relationship between weld speed and power
versus residual stress and their distributions at constant heat input can be established, through FE
modeling. Further, these FE models can be used for optimizing the weld parameters for obtaining
sound welds.

There have been numerous investigations that pertain to the numerical analysis with
experimental validation to understand the temperature distribution, distortions and the residual
stresses. During welding, the weld component may undergo severe thermal cycles because of
high concentrated heat source in the region of weld centre, which in turn results in distortion and
residual stresses in the weld metal in longitudinal as well as in circumferential directions. There
are a few studies that deal with the measurement of thermal cycles and optimizing the important
welding process parameters such as welding speed, heat input, weld sequence and clamping
conditions etc for butt welding of plate.

Sattari-Far I., et al. [51] presented a three-dimensional thermo-mechanical analysis to investigate
the effect of welding sequence on welding deformations in pipe–pipe joints and showed that a
suitable welding sequence can substantially decrease the amount of welding distortions for a
particular geometry. Rybicki E.F., et al. [52] developed a mathematical model for predicting
transient temperature distributions, residual stresses, and residual deflections for girth-butt welds
and compared temperature profiles for a two-pass welded pipe. They validated their predicted
residual stresses and residual deflections based on a FE representation against individual passes,
temperature dependent elastic-plastic constitutive behavior with the data obtained from a welded 304 stainless steel pipe.

Goldak et al. [53,75] described the deformations and stresses during butt-welding of a pipe from the analytical temperature field during welding. They have adopted a thermo-elastoplastic material model in their FEA. They have included the influence of volumetric changes due to phase transformations on the deformations (radial shrinkage) and the residual stresses. They have compared the radial shrinkage and residual stresses calculated using their model with the experimental values. Dong. Y., et al. [54] discussed the three-dimensional FEM of residual stresses in a girth-welded, with a main emphasis on modeling procedures for the global residual stress characteristics. They have suggested the shell element model with a heat source moving along the circumferential joint, which is cost effective and capable of predicting the global residual stress features. They have presented the effects of pipe wall thickness and welding speed on residual stresses as well.

Karlsson. R.I., et al. [55] have presented a three-dimensional FEM which can predict the temperatures, stresses, and deformations in a single-pass butt-welded pipe. They have observed the residual compressive hoop stresses in the weld and the residual circumferential stress variations, especially in the beginning and end regions of the weld. Fricke. S. et al., [56] have demonstrated a technique that has been developed for numerical simulation of the welding process and validated with the results of welding on austenitic pipe welds. They have accounted for the effect of inter-pass cooling which causes sensitization of the HAZ, the effect of gap width on the resultant weld residual stresses, or the effect of the ‘last pass heat sink welding’ (welding of the final passes while simultaneously cooling the inner surface with water) producing compressive stresses in the root area of a circumferential weld in an austenitic pipe.
Lundback et al. [57] have developed a model for weld deposition which is able to describe the material behaviour over a large strain, strain rate and temperature range in welding. They have validated their model with the physical model by measuring temperature and deformations. The phase changes for optimizing residual stresses and distortions are the concern of recent Investigators. Murugan et al., [58] insisted that in a multipass welding operation, the residual stress pattern developed in the material vary with each weld pass. They have measured the residual stresses after each pass using X-ray diffraction method and compared the peak temperatures attained at different points during weld bead deposition for both carbon steel and stainless steels.

Dean Deng et al. [59] employed both experimental and the FE methods to investigate the welding residual stress distribution in medium thick-walled austenitic stainless steel pipe in multiple passes. They have developed a model to simulate the temperature fields there by the welding residual stress field. Lee et al. [60] developed a three-dimensional FEM for the accurate simulation of circumferential welding that can incorporate the three-dimensional effects. They have conducted parametric studies with inside radius to wall thickness to investigate the effects of pipe diameter on residual stresses.

Teng et al. [61] employs the technique of element birth and death to simulate the weld filler variation with time in T-joint fillet welds using thermal elasto-plastic analysis considering the effects of flange thickness, welding penetration depth, and restraint conditions on the residual stresses and distortions. Chang et al. [62] aimed at analyzing the thermo-mechanical behavior and evaluation of the residual stresses in butt-welded joints and presenting the data to confirm the validity of currently employed fabrication processes in welded structures and improving further. Kiyoshima et al. [63] develop a method based on variable length heat sources which is
time-effective computational approaches for practice engineering analysis of multi-pass joints. They analyzed a dissimilar metal with J-groove joint with axis-symmetric geometrical shape and discussed the influence of heat source model (type) on welding residual stress and distortion. Chakrapani Basavaraju [64] developed an axisymmetric FE evaluation of hoop shrinkage associated with circumferential butt welds in thin wall stainless steel pipes. Bachorski M.J. et al. [65] used linear elastic finite-element modelling technique that has been developed based on shrinkage volume approach to predict post-weld distortion in single V butt welded plates.

Arc welding is an effective joining method to produce high strength welded structures. Due to the non-uniform expansion and contraction of the weld metal and surrounding base metal by heating and cooling cycles during welding, thermal stresses occurs in the weld and the adjacent areas producing significant residual stress fields. These high magnitude residual stresses of the order of yield strength of the material within the HAZ can be a major threat for the in-service structural integrity of welded structures. The strains produced during the heating phase always induce plastic deformation of the metal. The stresses resulting from these strains combine and react to produce internal forces that cause a variety of welding distortions. The problems of reduced strength of the structures in and around the weld zone due to residual stresses and fitment/appearance issues due to poorly fabricated and distorted structures is a major concern of the welding industry for decades. Therefore, precise prediction of stress fields and distortions patterns (transient and residual) is of critical importance to ensure the in-service structural integrity of these welded structures. GTAW and Gas Metal Arc Welding (GMAW) process are the obvious selection in this regard due to excellent weld joint features. In general these welds are commonly produced by single or double "V" joint configuration penetrations and single or multiple pass arc welding processes.
2.2 Distortion

One of the most troublesome problems a welding engineer usually encounters is that of welding distortion. Welding, however, induces thermal strains in the weld metal and base metal regions near to the weld, resulting in stresses due to non-uniform heating and cooling cycle, which in turn combine and react to produce internal forces that cause bending, buckling, and rotation. These displacements are termed as welding distortions [1]. During the joining of components by welding, the highly localized thermal gradients from welding result in high magnitude residual stresses of the order of yield strength of the material within and around the weld region, along with significant deformation/distortion of the structures to be welded.

In other way, welding induced distortion can be defined as the change in shape and dimension of a welded assembly after welding; when it is free from any of the external forces of thermal gradients. The interaction of solidifying weld metal with the parent base metal, results in change in dimensions and shape of the weldments, generally referred to as welding distortions. Different types of distortion patterns for plate and pipe in both longitudinal and circumferential welding, the mechanism involved and the factors affecting different types of welding distortions were presented by many researchers in recent years. In circumferential welding of thin pipe, the longitudinal distortion which is transverse to the welding direction and caused by shrinking near the fusion zone resulting in a change in the shape of straight pipe. Fig. 2.1 portrays weld induced distortion in a circumferentially butt welded pipe joint.
In circumferential welding of pipe mainly there are two types of dominating distortions, the axial shrinkage and the radial deflection. In this case, it is possible that the component can have expansion and shrinkage. The shrinkage of the weld in the circumferential direction induces circumferential force, shearing force, and bending moments, to the cylinder, which are the resultants of the residual stresses in both circumferential and axial directions. Thus, the state of stress in a circumferential welded pipe may be quite different of that in the flat plate.

2.3 Residual Stress

In order to analyze the residual stresses and distortions due to welding, a thorough understanding of heat transfer, metallurgical transformations and mechanical fields and the interactions in between them are needed [1]. Of course, the welding is difficult problem to solve mathematically due to the transient temperature distributions, moving heat source design, material deposition, temperature dependent material properties, metal plasticity and elasticity, transient heat transfer and thermo-mechanical coupling etc. Despite of these considerable innovations in high temperature joining techniques, still the problems of weld induced imperfections like residual stresses and distortions are major challenges for the welding engineers due to the complex nature of the welding phenomena.
Welding residual stresses are produced in an assembly as a consequence of local plastic deformations introduced by local temperature history consisting of a rapid heating and subsequent cooling phase. During the welding process, the weld area is heated up sharply compared to the surrounding area and fused locally. The material expands as a result of being heated. This expansion is restrained by the surrounding cooler area, which gives rise to thermal stresses. The thermal stresses partly exceed the yield limit, which is lowered at elevated temperatures.

Consequently, the weld area is plastically hot-compressed. After cooling down too short, too narrow or too small compared to the surrounding area, it develops tensile residual stress, while the surrounding areas are subjected to compressive residual stresses to maintain the self-equilibrium.

In case of circumferentially welded pipe joints, there are mainly two types of residual stresses which may develop after welding, which can be classified in to axial and hoop stress. The stress normal to the direction of the weld bead is known as the axial stress. In general, compressive and tensile axial stress fields can be observed in and near the weld region on the outer and inner surfaces of the cylinders respectively. Varying shrinkage patterns through the wall thickness on the inner and outer surfaces, due to different temperature gradients results in tensile and compressive residual stress fields on inner and outer surfaces, respectively near the weld line. The stress parallel to the direction of the weld bead is known as the hoop stress. The residual hoop stresses are developed due to the radial expansion and contraction during the heating and cooling sequence of the welding process.
Although, the experimental investigations provide valuable insights into the process of arc welding, many experimental techniques are complex and expensive and some quantities, such as the transient stress/strain development during welding, cannot be measured. Furthermore, traditional trial and error approach based on costly and time consuming welding experiments encounters hindrance to sound welds due to welding process parameters optimization. In order to get an appropriate insight into the process, to extend the application of arc welding process on shop floor level with high reliability and cost effectiveness, it is mandatory to apply appropriate control techniques for both distortion and residual stresses. A synergistic approach involving both FEM and experimental work has proven very useful, which often fails to provide a complete picture of temperature and stress/strain/deformation distribution in the weldment. On the other hand, detailed experimental measurements of the residual elastic strain distributions in welded parts are typically not feasible due to significant resource (man, machine and material) consumption. Mathematical modeling for residual stress evaluation provides a resource effective method in comparison to the experimental methods. However, development of the modeling scheme again demands an experimental data.

Fig.2.2 shows the residual stress distribution of a single pass weld made automatically with no intermediate stops and starts. Measurements of the residual stress in real welds show that this model is quite accurate in predicting the residual stress in single pass welds.
A little significant contribution for the welding residual stress distribution and its effects on the performance and structural integrity of circumferentially welded thin-walled cylinders is reported and further investigation is yet to be explored. Therefore, it demands immediate attention and focus of the researchers to ensure the structural integrity of those structures for better product quality and reliability. It is anticipated that the design optimization due to the appropriate weld parameters for thin cylindrical welded shell structures can be the major contributions from this research. It is known that one of the main contributing factors for slow-growing cracking in parts exposed to radioactive environments is the presence of residual tensile stresses near the surface.
Teng and Chang [46] presented sequentially coupled thermal stress analysis for the determination of residual stresses. They presented parametric studies based on axis-symmetric FE models to demonstrate the effects of pipe diameter and wall thickness on residual stresses. Temperature dependant material properties were used for elastic-perfectly plastic material model without solid state phase transformations. Their results exhibited self balancing behavior of residual stresses. Both the axial and hoop stresses were tensile on the inner surface near the weld centerline and stress reversal occurred in the regions away from the centerline as shown in Fig.2.3 & 2.4. They used three-dimensional shell element models and analyze welding residual stresses on the same sized pipes to investigate the effect of pipe wall thickness.
The FE simulations of welding being highly non-linear transient phenomenon is a highly computational power intensive, therefore the use of three dimensional models is limited to the single pass weld only.

Many authors have focused their investigations on weld induced distortion patterns, the influence of various process and geometric parameters on weld induced residual stresses. Few researchers envisaged the effects of tack weld orientation and identifying the optimum welding process sequence and the effects of different clamping conditions on residual stress generation and distortion patterns.

Deng et. al.[66] employed both the experiments and the FEMs to investigate the welding temperature field and the residual stress distribution for a typical medium thick-walled pipe in multi pass welding. Axial and hoop residual stresses distribution contours are shown in Fig. 2.3 and Fig.2.4 respectively.

Further, the study of both in process and post-weld stress mitigation techniques are also important in welding of thin sections. Mainly the above investigations include the geometric parameters comprising of the pipe diameter and wall thickness and process parameters include the variation of heat input. Parametric studies for implementation of best suitable numerical techniques that takes phase changes in to account mainly to analyze the effects of tack weld orientations and selection of feasible structural boundary conditions are the interest of recent investigators.

Efforts were also made to cover the significant contributions focusing on experimental measurement / prediction of residual stresses and distortions in welded structures. Mostly, significant contributions in the field of welding simulations before 2001 are critically reviewed
and discussed by Lindgren L. E et al [67-69]. Mainly their focus is on application of the FE method to predict the thermal, material and mechanical effects of welding by describing appropriate models for heat input and material behavior. Further, Yaghi et al. [70] discussed in detail the thin and thick-walled stainless steel pipe welds including pipe diameter effects as well. They have incorporated the effects of solid phase transformations in the simulation of welds. Their investigations include parametric studies and characterization of residual stresses, the effect of material properties on residual stresses, three-dimensional geometric influences etc.

The present study is mainly focused on a three-dimensional transient, non-linear thermo-mechanical simulation of welding of CE rotating bowl assembly followed by the control and mitigation of circumferentially, butt welded thin-walled cylinders. CE which can be classified under thin walled equipment is used in the nuclear spent fuel reprocessing plants of FBR to recover U and Pu leaving highly radioactive fission products [71]. There are three circumferential welds proposed for integration of the CE bowl as a single unit. Therefore adopting proper welding process parameters is extremely important in deciding the dimensions of the final bowl.

Raj et al. [72] presented the operational experience and design challenges associated with various equipments / vessels such as fuel dissolvers, evaporators, CE and single pin chopper etc., used in fast reactor fuel reprocessing plants. Natarajan, et al.,[73-74] addressed a comprehensive review on the operational experiences in the area of nuclear fuel reprocessing and a brief description of various R&D activities currently being pursued in the CORAL.

The welding process can be modeled using a coupled thermo-mechanical process. However, due to the weak structural to thermal field couplings, sequentially coupled analysis is therefore used
in modeling of welding. In general, welding analysis is carried out by performing a nonlinear transient thermal analysis first, and then applying those results as thermal loads in the nonlinear structural analysis in order to compute distortions and residual stresses.

In this regard, as a first step, the transient temperature history associated with the heat flow during welding can be solved from the thermal analysis. It is generally based on the heat conduction formulation with the moving heat source. The resulting output i.e., temperature history is applied as a thermal load for the stress evolution in the subsequent mechanical analysis. Thermal strains and stresses can be calculated at each time increment by considering the temperature dependent material properties. Also, a plastic yield criterion needs to be followed in evaluating residual stresses that will be accumulated by the thermal strains and stresses induced during welding.

In summary, review of literature shows that there is a wide scope for the future development in the area of thin walled components welding. Generally these thin walled structures are comprising of number of longitudinal and circumferential joints which are the mandatorily integrated by welding. It is evident that a lot of work pertaining to numerical simulation of welding for simplified geometries using two-dimensional analysis by employing symmetry conditions is carried out with certain assumptions due to limited computational cost. To enhance the accuracy of those numerical simulations and closely approach the shop floor welding, the present study aims at developing a fully three-dimensional modeling and simulation technique for material stainless steel (AISI-304) which is being used for manufacturing centrifugal extractors. In this research work, different cases have been verified by varying the weld process parameters to the extent possible validations as well.