LITERATURE REVIEW

The mechanical surface enhancement techniques are used to introduce a layer of residual compressive stress to mitigate failure mechanisms, resulting in improved life of components. Improvements in fatigue life by mechanical surface enhancement methods have been studied by many authors in the past. As explained in chapter 1, mechanical surface enhancement methods include shot peening, laser shock peening, burnishing, low plasticity burnishing and deep cold rolling. Studies on the above including theoretical, experimental and simulation using finite element methods are available in the literature. The available literature review suggests the effectiveness of the deep cold rolling process dealing mostly with microstructure, residual stress and fatigue life of aluminium and titanium alloys. Surface finish, surface hardness and fatigue life are studied in these works but only with little focus on optimization of the deep cold rolling parameters. The literature review on deep cold rolling highlighting its importance on other mechanical surface enhancement methods is presented below.

2.1 Detailed Review of previous studies on DCR

In order to assess the trend and level of research work done till date, in the area of titled work, an exhaustive literature has been reviewed. Emphasis is placed to highlight the salient findings of these research contributions. A gist of some of the most relevant research work is presented in this section under various headings: experimental approaches and analytical investigations.
2.1.1. Experimental approaches for DCR

A. Tolga Bozdana et al. [1], Volker Schulze [24] and I. Altenberger [33, 34] reviewed the most commonly used mechanical surface enhancement techniques and their applications available in aerospace industry. A brief description of each technique, as well as advantages and disadvantages over other techniques are given. The effects of those techniques on the surface characteristics and service properties of treated components are summarized. There are number of aerospace components subjected to high dynamic loads and heavy service conditions. Failure of critical components due to insufficient service properties threatens aircraft industry and greatly increases the cost of maintenance of virtually all legacy aircraft. Annual costs exceeding one billion dollars are currently incurred for inspection and maintenance by the US Air Force alone. Redesign and/or replacement of such components are generally not allowed or require considerable cost and time. So, it is reported that, surface enhancement is a practical and affordable solution for preventing failure mechanisms and also for improving the service properties of many critical components in aerospace industry.

P. Juijerm et al. [35] performed the experiment to study the effects of deep rolling on the fatigue characteristics of AA5083 in the temperature range of 20-300 °C. Residual stresses and work hardening effects near the surface of the deep rolled condition before and after fatigue tests were investigated by X-ray diffraction methods. It has been found that, after deep rolling increase in residual compressive stresses has been observed to a depth of approximately 0.5mm and maximum compressive residual stress of 240MPa were measured at a depth of 30µm. It has been also reported that, at stress amplitudes below approximately 205MPa and temperatures below 150°C, plastic strain amplitudes are decreased and fatigue lifetimes increased as compared to the untreated polished state.
P. Juijerm and I. Altenberger [36] measured the near-surface macroscopic residual compressive stresses in a deep-rolled aluminium alloy AA6110-T6 (Al-Mg-Si-Cu) during cyclic loading at elevated temperatures as a function of loading cycle. Near surface properties like residual compressive stresses, work hardening and hardness are presented in this paper. Thermal residual stress relaxation was investigated and analyzed by applying the Zener-Wert-Avrami function. The effects of stress amplitude as well as temperature on residual stress relaxation during stress-controlled cyclic loading at elevated temperatures were systematically investigated and analyzed using separate assessment of mechanical and thermal residual stress relaxation. It has been reported that the residual stress relaxation during fatigue tests at elevated temperatures after 1000 cycles was controlled by the thermal relaxation process.

David K. Matlock et al. [37] highlighted deep rolling as a process to mechanically work fillet surfaces of crank shaft to improve fatigue resistance. Three medium carbon bar steels with microstructures characteristic of forging steels of interest for crankshaft and other automotive applications were evaluated. It has been found that, surface hardness increased from 57 to 61 HRC, and compressive surface residual stresses dramatically increased from 100 to almost 1000 MPa due to deep rolling process.

N. Tsuji et al. [38] investigated the effect of deep rolling on fatigue strength and wear resistance of plasma carburized Ti-6Al-4V specimens. They used plasma surface diffusion processes such as plasma-carburizing and nitriding to improve tribological properties of titanium and its alloys. It has been found that, the maximum compressive residual stress produced just below the surface by deep-rolling is approximately 80% of the ultimate tensile strength value of this starting material and the effect of deep-rolling almost disappears at a depth greater than approximately 500µm. 20% increase in hardness is observed on the surface of the modified specimens than that on the surface of the
unmodified specimen (380HV). Similarly, 63% improvement in surface finish is observed due to deep rolling process than that of untreated specimen.

P. Juijerm and I. Altenberger [39] investigated and analyzed the effective boundary of deep rolling using S/N data and the stability of near-surface residual stresses and work hardening. The deep rolling treatment can enhance the fatigue lifetime of aluminum alloys although residual stresses relaxed significantly up to about 70%. It is also reported that, if FWHM values decrease by more than about 5%, deep rolling becomes ineffective. They have concluded that the near-surface work hardening state is the major factor influencing the fatigue lifetime of the deep-rolled aluminum alloys.

M. D. Richards et al. [40] studied the effects of processing temperature on the deep-rolling response of three medium carbon bar steels. In the deep rolled condition the nontraditional Bainitic steel and C38M alloys exhibit distinct hardness peaks with an increase in hardness of 65 and 50 HV, with respect to the hardness level at the core were reported at depths of 0.35 and 0.25 mm, respectively. In the deep rolled condition, the nominal stress endurance limits found were 607 MPa for the 4140 steel, 586 MPa for the NTB steel, and 524 MPa for the C38M steel.

I. Nikitin and M. Besel [41] examined the effects of different surface treatments on the low cycle fatigue behaviour of austenitic stainless steel (AISI 304) and ferritic-pearlitic steel (SAE 1045). It is found that consecutive deep rolling & annealing as well as high temperature deep rolling produce more stable near-surface stress states than conventional deep rolling at room temperature. For lifetimes over 10,000 cycles the plastic strain amplitude for the deep rolled state is higher than for the untreated condition. The high stress amplitudes in the lifetime region below 10,000 cycles generate high plastic flow with measurable sample heating. Under these conditions the residual stress and work hardening state are not stable and the positive effects of deep rolling on the
fatigue lifetime is smaller. It is stated that, for SAE 1045 the best fatigue improvement is obtained by deep rolling at 350° C followed by deep rolling & annealing (1 min at 325° C) and least improvement from conventional deep rolling.

P. Juijerm and I. Altenberger [42] developed a new mechanical surface treatment. In this a high temperature deep rolling was performed on the solution heat treated aluminium alloy AA6110 for different temperatures up to 250 °C. Macroscopic residual compressive stresses, work hardening and hardness are presented in this paper. Cyclic deformation behaviour and S-N curves of the high temperature deep rolled solution heat treated AA6110 have been investigated at room temperature and at elevated temperatures up to 250 °C and compared to conventional deep rolling. It has been found that, fatigue lifetime decreased with increasing test temperature because of relaxation phenomena. The beneficial effects of the deep rolling treatment were not only affected by thermal loading, but also by mechanical loading. The lifetime enhanced through deep rolling decreased more and more with increasing test temperature and/or applied stress amplitude until the deep rolling treatment becomes ineffective as compared to the polished condition.

Patiphan Juijerm and Igor Altenberger [43] performed high-temperature deep rolling on various metallic materials, such as austenitic stainless steel AISI 304, normalized plain carbon steel SAE 1045 and aluminium alloys. The fatigue performance of high temperature deep rolled specimens was investigated using stress controlled fatigue tests and compared with the conventionally deep rolled condition. It was found that high temperature deep rolling effectively enhanced the fatigue performance of steels. A maximum fatigue lifetime of about 1,35,000 was observed at an applied stress amplitude of 340 MPa after deep rolling at a temperature of 350°C. For aluminium alloys they found that, as-quenched AA6110 has to be aged at a temperature of 160°C for 12 h to obtain a maximum hardness.
C. M. Gill et al. [44] measured the shakedown of residual compressive stresses produced by deep cold rolling caused by low cycle fatigue of titanium alloys Ti-6Al-4V and IMI679 at room temperature and elevated temperature. It has been reported that DCR introduces compression to a depth 5 times greater than traditional mechanical impact peening techniques. It is also demonstrated that high magnitude of compression (930MPa) introduced. It is established that the residual stress relaxation is limited to a depth of 400-500 µm and thus the depth of residual stress is unaffected by shakedown.

D. A. Axinte and N. Gindy [45] performed turning and deep cold rolling simultaneously. It has been found that, metallurgical analysis revealed a significant work hardening effect up to 300 µm below the surface. This was in correlation with the results from the microhardness measurements where an approximately 20% increase in microhardness could be noted within 200 µm below the TADCR surface. Similarly around 65% improvement in surface roughness noted on the TADCR surface.

P. Juijerm et al. [46] studied the influence of ageing on cyclic deformation behavior and residual stress relaxation of deep rolled as-quenched aluminium alloy AA6110. Cyclic deformation behavior, S/N curves and depth profiles of near-surface residual stresses and full width at half maximum (FWHM) values of X-ray diffraction peaks as well as hardnesses are presented as compared to the conventional mechanical surface treatment (ageing followed by deep rolling) reported by them. An increase of near-surface hardness by approximately 15 HV as compared to the bulk due to work hardening was observed after deep rolling. The hardness of the deep rolled as-quenched specimen increased significantly after the optimized ageing treatment while the residual stresses and FWHM-values decreased due to the relaxation as well as recovery processes. Residual stress and FWHM-values at the surface were reduced from -265 to -100 MPa. The maximum fatigue lifetime of the deep rolled as-quenched AA6110 can be found after
an ageing treatment at a temperature of $160^\circ$C and an ageing time of 12 h. It was found that, work as well as precipitation hardening in near-surface regions enhances the fatigue lifetime significantly.

I. Nikitin and M. Besel [47] investigated the residual stress and work hardening relaxation during thermal exposure and isothermal fatigue at elevated temperatures. It is reported that, deep rolling has led to compressive residual stresses in near-surface regions and remains in the compressive region up to a depth of at least 0.8 mm. The deep rolling induced high compressive residual stresses of about 670 MPa at the surface and 750 MPa in the subsurface maximum to a depth of approximately 40 µm. With regard to near-surface work hardening, which can be measured indirectly by FWHM values, they stated that the work hardening is highest directly at the surface and then slowly decays to a constant level in deeper regions. The compressive residual stress relaxed continuously with increasing number of cycles. In contrast, the work hardening remains stable up to about 1000 cycles, and thereafter strongly decreases as described by the authors.

A. Tolga Bozdana et al. [9] developed a new mechanical surface enhancement technique utilizing ultrasonic vibrations. They discussed surface roughness, surface microhardness and residual compressive stresses obtained after treatments of Ti-6Al-4V specimens. The principle and concept of the new process are described in this paper. The evaluation and comparison of experimental results (e.g. surface roughness, surface micro-hardness and residual compressive stresses) obtained after treatments of Ti-6Al-4V specimens are discussed. They also reported the advantages of proposed technique and its potential applications. It has been also suggested that the ultrasonic deep cold rolling could be used for treating thin components without deteriorating the component shape. It has been reported that, about 19% increase in surface micro-hardness after UDCR as compared to CDCR. The reason is that work hardening of surfaces after UDCR is higher
than those after CDCR. It was also found that, residual compressive stresses of about 900 MPa at 0.3 mm depth from the surface can be achieved by this process.

Junfeng Xie et al. [48] studied the effects of ultrasound-aided deep rolling (UADR) process on the microstructure of 30CrMnSiNi2A steel. It is found that, a compressive residual stress layer with a maximum of 1418 MPa and a depth beyond 500 lm was introduced by the UADR process. It was observed that, the UADR process produced a nano crystallized surface layer and a fine-grained subsurface layer with the grain sizes about 68 nm and 2.7 lm, respectively. The severe plastic deformation in the treated surface and subsurface resulted in strain-induced martensite transformation. The evaluated area fraction of retained austenite is 2.2% and 4.9% in the subsurface and the substrate, respectively.

You-Li Zhu et al. [49] developed an ultrasound-aided deep rolling process (UADR) for anti-fatigue applications for surface enhancement of titanium alloy specimens. It is found that, the $10^6$ cycles fatigue strength increased from 375 MPa for the untreated fatigue specimens to 612 MPa for the UADR-treated ones. An improvement of about 65% of high cycle fatigue strength of the Ti-6Al-4V smooth fatigue test specimens demonstrated the effectiveness of the UADR process for anti-fatigue applications. It is also found that, the compressive residual stress attained a maximum value of about 950 MPa in depth of about 0.3-0.4 mm beneath the surface and the penetration depth of the compressive residual stress layer is in excess of 1 mm while the compressive residual stress is about 430 MPa at the surface of the specimen. Apart from this, 95% improvement in surface finish was recorded for UADR specimens when compared to untreated specimens.

L. Wagner [50] studied the influence of shot peening, roller burnishing and deep rolling on magnesium, titanium and aluminum alloys. Surface roughness, fatigue life and
residual compressive stress were measured and the comparison was made. It was found that after deep rolling residual compressive stress to a depth of 0.4mm is observed, while shot peening and burnishing resulted in an increase in residual compressive stress to a depth of 0.1mm and 0.2mm respectively. This enhanced the fatigue life by an order of two than shot peening and burnishing.

G. H. Magzoobi [51] studied the effects of deep rolling and shot peening on fretting fatigue resistance of Aluminium 7075-T6. The results show that fretting fatigue reduces the normal fatigue life by about 67% at the stress of 130MPa. For low cycle fatigue, shot peening while being superior to deep rolling, increases the fretting fatigue life by about 300%. For high cycle fatigue, however the effect of deep rolling on fretting fatigue resistance is more profound than shot peening with an increase of about 700% is observed at a stress of 130MPa for deep rolling at high force. Numerical simulation of shot peening and deep rolling was also presented in their paper. From the analysis it was found that the depth and maximum of compressive residual stress profile for high force deep rolling are considerably about 25% higher than those of low force deep rolling.

I. Altenberger et al. [52] investigated the thermal stability of near-surface microstructures induced by deep rolling and laser-shock peening in AISI 304 stainless steel and Ti-6Al-4V using in situ transmission electron microscopy. The improvements in fatigue resistance at elevated temperature are related to the high-temperature stability of the work-hardened near-surface microstructure. They have reported that, the beneficial effect of deep rolling and laser shock peening on the fatigue life at temperatures as high as 550-600 °C, where almost complete relaxation of residual stresses has occurred, appears to be related to the thermal stability of the work-hardened near-surface microstructures.
I. Nikitin et al. [53] studied the effect of laser-shock peening and deep rolling on the cyclic deformation and S/N behavior of austenitic stainless steel AISI 304 at elevated temperatures (up to 600 °C). The laser shock peening treatment induced compressive residual stresses of about 300 MPa at the surface and deep rolling induced much higher compressive residual stresses of about 670 MPa at the surface and 750 MPa in the subsurface maximum in a depth of approximately 50 μm. Fatigue results of untreated, deep rolled and laser shock peened AISI 304 clearly indicated that fatigue life is significantly enhanced by both treatments, at ambient as well as at elevated temperatures as high as 600°C. For all temperatures investigated laser shock peening yielded very similar, but in general slightly lower fatigue lives than deep rolling. Between 250 and 600°C the lifetime improvement by both surface treatments stays quite constant and is not influenced significantly by the testing temperature. In contrast to high temperature fatigue, the S/N-results for 250°C show slightly higher fatigue lives for the laser shock peened condition as compared to the deep rolled material.

R. K. Nalla et al. [25] investigated the influence of deep rolling and laser shock peening process on the fatigue behaviour at ambient and elevated temperatures of Ti-6Al-4V work material. In their investigation, the effect of deep rolling on the low-cycle fatigue (LCF) and high-cycle fatigue (HCF) behavior of a Ti-6Al-4V alloy was examined, with particular emphasis on the thermal and mechanical stability of the residual stress states and the near-surface microstructures. They found that, deep rolling leads to a significant enhancement in the observed fatigue lifetime at room temperature, particularly in the high-cycle fatigue regime; indeed at stress amplitude of 500 MPa, lives are increased by roughly two orders of magnitude. In terms of the resulting improvement in fatigue performance, the deep rolling process was correspondingly found to confer the larger increases in fatigue lifetimes at a given applied stress for all test temperatures.
investigated (25°C, 250°C and 450°C). They also observed that the near surface microstructures consist of a layer of work hardened nanoscale grains which play a critical role in the enhancement of fatigue life by mechanical surface treatment.

I. Nikitin and I. Altenberger [54] compared the fatigue behavior and residual stress stability of laser-shock peened and deep rolled austenitic stainless steel AISI 304 in the temperature range of 25–600°C. It was found that, the residual stress state and work hardening induced by laser-shock peening were less stable under isothermal cyclic loading at elevated temperatures as compared to the deep rolled condition. It was also stated that, the laser-shock peening treatment produced slightly thicker (>1mm) work hardened layers as compared to the deep rolling treatment. It has been seen that surface as well as sub-surface residual stress relaxation increases with increasing temperature. Residual stress relaxation is especially pronounced at the surface due to easy diffusion paths by high dislocation densities, but also at greater distances from the surface residual stresses continue to relax with increasing temperature. At elevated test temperatures, the fatigue lifetime of the deep rolled condition is higher than of the laser-shock peened condition due to more stable near-surface microstructures.

Igor Altenberger et al. [55] investigated the thermal stability of near-surface microstructures induced by deep rolling and laser-shock peening in AISI 304 stainless steel (AISI 304) and Ti-6Al-4V using in situ transmission electron microscopy. It has been seen that, the deep rolling treatment induced a 2µm nanocrystalline layer at the surface. Additionally, in near-surface regions a layer of deformation-induced martensite, micro twins as well as high dislocation densities were observed. On the other hand, neither any nanocrystalline layers nor pronounced deformation induced martensite at the surface as well as in deeper regions were detected in laser-shock peened specimens due to the absence of martensite may hint at a local heating of the samples during the laser-
shock peening process. It is also reported that, in near-surface regions up to a depth of approximately 0.4 mm, the deep rolling induced higher dislocation densities as compared to laser-shock peening.

At the surface, the hardness of the deep rolled condition, approximately 1.3 times higher than of the laser-shock peened condition was observed. However, in a greater depth of approximately 0.4 mm, the hardness of laser shock peened specimens is higher as compared to the deep rolled specimens. X-ray diffraction measurements revealed that deep rolling as well as laser-shock peening produced compressive residual stresses at the surface and in near-surface regions up to depth of approximately 1mm. The depth profile after deep rolling showed a maximum of compressive residual stress of 750MPa while for the laser shock peened specimen significantly lower compressive residual stresses were observed. Here, the maximum of residual stress was about 300MPa directly at the surface. It has been also reported that, the laser-shock peening as well as deep rolling enhances the fatigue behavior of stainless steel AISI 304 more than 15% at elevated temperature between 25 and 600 °C.

2.1.2. Analytical and numerical investigations on DCR

Simon Ho et al. [56] used analytical technique to optimize the crankshaft rolling process to comply with a crankshaft design criterion for durability. A nonlinear finite element analysis was implemented to approximate the stress distributions induced by the crankshaft rolling process, and a crack modeling technique was developed to calculate the equivalent stress intensity factor ranges. They incorporated a nonlinear finite element analysis to simulate the residual stress due to the rolling process, a crack modeling technique to estimate the equivalent stress intensity factor range, a meta-model generation strategy based on the uniform design method, a Monte Carlo simulation technique for reliability assessment, and the Hooke-Jeeves direct pattern search method for the design
optimization. It was found that, as the bending load was increased, a negative impact was expected on the improvement of crankshaft fatigue life and as the rolling angle was increased, a positive impact was expected on the improvement of crankshaft fatigue life. It was also observed that, the optimal fillet rolling load was found to be 85-90 % of the current rolling load.

Afshin Manouchehrifar and Kianoush Alasvand [57] conducted a comprehensive 3D finite element dynamic analysis with considering spring back effect to simulate the deep rolling process. The results revealed that increase in overlap of the rolling tracks largely increases the magnitude of the residual stress filed created in target plate but 42% overlap causing a surface contraction and cause burr on the surface. It has been reported that, the increase of rolling force gives rise to the increase of the residual stress up to a specific value of rolling force, 1400 N. Further increase in force rolling gives rise to reduction of residual stress due to relaxation.

V Backer et al. [58] examined different approaches of the FEM/BEM-coupling for the simulation of deep rolling with regard to their stability and required computing time. The result comparison of the different coupling methods showed small differences between the time dependent and the matrix coupling, whereas the displacements calculated by the time independent coupling were lower by one order of magnitude. It is also stated that, the usage of the latest can already save approximately 40% of computation time achieving similar accuracy when compared to the uncoupled FE solution.

### 2.2 Summary of the literature available on DCR

From the above literature review it is evident that a focus on deep cold rolling and process parameters is yet to be built. It could be seen that, the tools and set-up used for deep cold rolling are very sophisticated and expensive and studies envisaged are limited to alloys of aluminum and titanium. Since deep cold rolling is driven by numerous
parameters which themselves depend on other variables, then the normal approach is insufficient. The mathematical modelling techniques like finite element method are used but very few attempts are available for deep cold rolling. A few of the earlier works discuss the application of modern analytical and computational techniques to deep cold rolling but not leading to cost effective process for small/medium industries. Thus, most of studies on the deep cold rolling process are experimental where effects of only few process parameters are considered. In the entire available literature, very less emphasis is given to optimization, and validation of results for development of a simple deep cold rolling process.

2.3 Objectives and scope of the proposed work

Deep cold rolling is generally done in special purpose machines which call for addition of investment. DCR tools are less affordable by most of small & medium scale manufacturing industries. Importing these machines, which is presently done in India adds to the cost of manufacturing. Majority of the automobile and aerospace industries in India sub-contract their jobs to small and medium scale industries which cannot afford to invest large amounts on machines performing secondary operations like deep cold rolling. As discussed earlier, investigations on deep cold rolling process are primarily involving unique and expensive deep cold rolling set-ups and are limited to analysis of fatigue strength enhancement of very few materials like aluminium and titanium alloys with hardly any emphasis on optimization of the process for good surface finish and surface hardness along with fatigue life. Literature review also indicates that deep cold rolling of AISI 4140 steel has not received due attention despite its wide usage in automotive parts. As explained earlier, deep cold rolling involves many parameters crucial in obtaining the desired enhancement in fatigue life. In earlier works, only a few parameters have been studied; a systematic holistic study involving development of a simple DCR process and
its optimization is far from being reported. Thus, need for such a study in the deep cold rolling of AISI 4140 steel exists. Development of an economical turn-assisted deep cold rolling and its optimization to obtain enhanced fatigue life coupled with good surface finish and hardness is the crux of present research work with the following clearly defined objectives.

• To develop & fabricate a simple turn-assisted deep cold rolling (TADCR) tool and set-up.
• To identify parameters that significantly affect the outputs of deep cold rolling such as surface compressive stress, surface hardness and surface finish using screening experimental design.
• To model the turn-assisted deep cold rolling process through finite element modeling technique and estimate the induced compressive residual stress. Compare the same with stress obtained from experimental approach.
• To investigate the effect of process parameters on the fatigue life enhancement through induced surface compressive stress using a detailed experimental study.
• To determine optimum process parameters for fatigue life improvement coupled with suitable surface finish and hardness using response surface methodology and desirability function approach.
• To confirm the optimal processing parameter combination by conducting validation experiments.

This work focusses on developing and evaluating a simple turn-assisted deep cold rolling (TADCR) process to enhance the fatigue life and surface integrity of engineering parts made from AISI 4140 steel. In the pilot study, two different deep cold rolling tools are developed, fabricated and tested, the better of them is considered for further detailed study. This developed tool could be retrofitted on a conventional lathe with a
dynamometer for monitoring of force during turn-assisted deep cold rolling. The set-up is improvised by incorporating a back rest with rolling contact elements for better process control. Initially, study is conducted to investigate the effect of process parameters of TADCR on residual compressive stress, surface hardness and surface finish with ‘screening experiments’. Here, seven process parameters, namely rolling force, ball diameter, ball material, initial roughness of the workpiece, feed rate of the tool, lubricant and number of tool passes are considered at two levels each. A finite element model is also developed to simulate the turn-assisted deep cold rolling with ANSYS and LS-DYNA. The variation of residual compressive stress with depth obtained from simulation is to be compared with the experimentally obtained data. Based on the results of the study, significant process parameters are identified and are studied further in detail by central composite design and response surface methodology. An attempt is made to develop empirical models for fatigue life, surface hardness and surface finish. The response surface obtained based on this model is used to determine the optimum process parameters for better responses individually. Desirability function approach is a sought for optimizing process parameters for multiple responses. Confirmation experiments are conducted to validate the optimal parameter settings.

The brief literature survey on deep cold rolling is provided in the beginning of this chapter followed by objectives and scope identified for the present work. The following chapter discusses methodology of developing a simple tool and set-up, different response measurement methods, the design of experiments along with the finite element modeling for proposed deep cold rolling process.