SURFACE LAYER ALTERATIONS IN AISI 4140 STEEL FROM TURN-ASSISTED DEEP COLD ROLLING PROCESS

P. R. Prabhu*, S. M. Kulkarni, S. S. Sharma, Jagannath K

1Associate Professor, Department of Mechanical & Manufacturing Engineering, MIT Manipal, India  
2Professor, Department of Mechanical Engineering, NITK Surathkal, India  
3, 4Professor, Department of Mechanical & Manufacturing Engineering, MIT Manipal, India

ABSTRACT

Mechanical surface enhancement (MSE) techniques have been used to modify the surface reliability properties of many materials by generating ultrafine or even nanometer-sized grains in the surface and subsurface region. These fine grained materials created by mechanical surface enhancement techniques usually have higher hardness and frequently exhibit enhanced mechanical properties. Turn-assisted deep cold rolling (TADCR) process is used to improve the surface integrity of AISI 4140 steel which is commonly used in automobile industry. Turn-assisted deep cold rolling is particularly attractive since it is possible to generate, near the surface, deep residual compressive stresses and work hardened layers while retaining a relatively smooth surface finish. Microstructure alteration to a depth of around 300µm was obtained from turn-assisted deep cold rolling process, which reflects an increase in residual compressive stress from as-turned material. Microhardness measurements indicate that the hardness in the small grained layer created by turn-assisted deep cold rolling is increased by about 36% related to the bulk value. Current results show that turn-assisted deep cold rolling could be an effective processing method to modify the surface integrity of AISI 4140 steel.

Keywords: Surface Integrity, Microstructure, Deep Cold Rolling, AISI 4140 Steel, Microhardness.

1. INTRODUCTION

It seems that it is the outer layer, lesser in volume relative to the core, which regulates major functional properties such as: friction, grindability, corrosivenes, fatigue life, load capacity. Improper physical and stereometrical properties of the outer layer cause failure damage in approximately 85% of the modern machine units [1]. Latest research results indicate that the life and the reliability of machine components or parts are affected greatly by the technological manufacturing and varieties of surface enhancement technologies applied, and also by the sequence and conditions of their application. Deep cold rolling process is an attractive mechanical surface enhancement technique which improves the surface characteristics by plastic deformation of the surface layer. The enhancement of surface characteristics mainly serves in terms of improved fatigue behaviour of work-pieces under dynamic load. Besides producing a good surface finish, it has additional advantages such as increased hardness and corrosion resistance. In addition, this process transforms tensile residual stresses, present in the surface zone after turning, into compressive residual stresses [2-4]. Residual stresses are probably the most important aspect in assessing integrity because of their direct influence on performance in service, compressive residual stresses generally improve component performance and life and inhibit crack nucleation and propagation. These advantages of deep cold rolling and, further, the efficiency, the simple construction of tooling, the economy, and the possibilities of using typical machine tools in the process and parts of
various types made of various materials, make the deep cold rolling process more attractive in comparison with other mechanical surface enhancement techniques.

The literature review shows that earlier investigations on deep cold rolling process are dealing primarily with microstructure, residual stress and fatigue life of specific materials like aluminium and titanium alloys. Many researchers have studied experimentally this process with regard to the effect of ball diameter, rolling force, feed and lubricant [5-7]. In these studies, unique and specialized deep cold rolling set-ups are used and the analysis of resulting surface roughness and surface hardness are less focused upon.

A. Tolga Bozdana et al. [7] developed a new mechanical surface enhancement technique utilizing ultrasonic vibrations. They discussed surface roughness, surface micro hardness and compressive residual stresses obtained after treatments of Ti-6Al-4V specimens. P. Juijerm et al. [8] performed the experiment to study the effects of deep rolling on the fatigue characteristics of AA5083 in the temperature range of 20-300^\circ 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. P. Juijerm and I. Altenberger [9] studied the effect of high temperature deep rolling on cyclic deformation behaviour of solution heat treated Al-Mg-Si-Cu alloy. Near surface properties like compressive residual stresses, work hardening and hardness were presented in this paper. N. Tsuji et al. [10] investigated the effect of deep rolling on fatigue strength and wear resistance of plasma carburized Ti-6Al-4V specimens. They reported that the fatigue properties and wear resistance of Ti-6Al-4V alloy modified by a combination of low temperature plasma carburizing and deep rolling were significantly improved in comparison with those of the unmodified Ti-6Al-4V alloy. C. M. Gill et al. [11] measured the shakedown of the compressive residual stresses produced by deep cold rolling caused by low cycle fatigue of the titanium alloys Ti-6Al-4V and IMI679 at room temperature and elevated temperature. G. H. Magzoobi [12] studied the effects of deep rolling and shot peening on fretting fatigue resistance of Aluminium 7075-T6. The results showed that fretting fatigue reduced the normal fatigue life.

The aim of the present study is to investigate the effect of deep cold rolling process on the surface integrity changes (roughness, hardness, microstructure and residual compressive stress) of AISI 4140 steel. A further aim of this study is to establish relationships among deep cold rolling conditions and surface integrity properties of this AISI 4140 steel.

2. EXPERIMENTAL WORK

2.1 WORK MATERIAL

The material used in the present investigation was AISI 4140 steel in the form of round bars with 12mm diameter as shown in Fig. 1 (ASTM standard E466). The chemical composition of AISI 4140 steel in mass% is as follows: 0.40C, 0.27Si, 0.66Mn, 0.055P, 0.046S, 1.20Cr, 0.25Mo, 0.16Ni. This steel is especially recommended for the manufacture of transmission shaft, gear shaft, crank shaft and also for a wide variety of automotive type applications [13]. The hardness of as-received material is measured to be 225HV in average.

2.2 TURN-ASSISTED DEEP COLD ROLLING PROCESS

Turn-assisted deep cold rolling experiments were conducted on a conventional lathe. The specially designed and fabricated deep cold rolling tool and experimental setup is shown in Fig. 2 and Fig. 3 respectively. The generated forces were collected by a KISTLER 4-component tool dynamometer. The forces acting only in Y direction were taken into consideration as these forces are causing the plastic deformation. The process parameters for deep cold rolling process are shown in Table 1.
2.3 MATERIAL CHARACTERIZATION

Measurements of the materials' roughness, microhardness and microstructure in the surface region were conducted before and after the processing. Microhardness measurements of the AISI 4140 specimens were made by using a Vickers indenter on a MATZUAWA Micro Vickers hardness tester with 4.905N applied load. Microstructure analysis was conducted by using an optical microscope. Surface roughness measurements were made by using a Surtronic Taylor Hobson Talsurf roughness tester and residual stress measurements were made by using a Rigaku X-ray diffractometer. At least five readings of surface roughness and surface micro-hardness were taken of each specimen in order to hinder inaccurate results.
3. RESULTS AND DISCUSSION

3.1 SURFACE ROUGHNESS

Surface roughness measurements were made before and after mechanical surface treatment and are shown in Table 2. Turn-assisted deep cold rolling result in significant alteration of the surface topography, led to a marked decrease (by more than 95%) in the measured surface roughness. Specifically, compared with a surface roughness of 4.84µm in the turned sample, the surface roughness of the turn-assisted deep cold rolled sample was 0.242µm. Such smoother surfaces associated with turn-assisted deep cold rolling can lead to significant improvements in resistance to fatigue crack initiation and hence contribute to the beneficial effect that this surface treatment can have in prolonging fatigue lifetimes.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Average surface roughness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As turned</td>
<td>4.84</td>
</tr>
<tr>
<td>DCR at 250N force</td>
<td>0.69</td>
</tr>
<tr>
<td>DCR at 500N force</td>
<td>0.486</td>
</tr>
<tr>
<td>DCR at 750N force</td>
<td>0.242</td>
</tr>
</tbody>
</table>

3.2 MICROHARDNESS

Hardness profiles, taken perpendicular to the surface of the as-turned and turn-assisted deep cold rolled microstructures, revealed the existence of a work hardened layer in the surface treated samples. Table 3 shows the microhardness values measured on as-turned and turn-assisted deep cold rolled surfaces. The subsurface microhardness obtained at different depths of the sample is plotted in Figure 4. The nature of plot obtained for both 250 N and 750 N force are similar with higher hardness at the surface and progressively decreases due to the differential amount of cold work experienced by the material. The average microhardness of the as turned specimen on the surface is about 225 HV. Highest hardness of about 306 HV is recorded on surface for TADC with a force of 750 N and the hardness is found to decrease with depth from the surface and eventually settle at hardness of turned sample at a depth of about 300 µm. From the same figure it could be observed that, surface microhardness settles at depth of 175 µm and 100 µm for TADC with 500 N and 250 N force respectively. Based on the well-known Hall-Petch relationship between yield stress and grain size as well as the close interrelations among hardness, yield stress and residual stresses, high hardness values often indicate fine grain size and large residual stresses. It is reasonable to state that the variations in microhardness were likely due to the different residual stresses being generated during processing.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Average surface micro-hardness (HV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As turned</td>
<td>225</td>
</tr>
<tr>
<td>DCR at 250N force</td>
<td>241</td>
</tr>
<tr>
<td>DCR at 500N force</td>
<td>270</td>
</tr>
<tr>
<td>DCR at 750N force</td>
<td>305</td>
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</tbody>
</table>

![Fig. 4: Depth profiles of Vickers hardness for untreated and deep cold rolled samples](image-url)
3.3 MICROSTRUCTURE
Microstructure analysis under as-turned and turned assisted with deep cold rolled surfaces was carried out after polishing and etching (97% water + 3% nitric acid) using optical microscopy. The initial microstructure prior to deep cold rolling is shown in Fig. 5(a). A representative microstructure beneath the turn-assisted with deep cold rolled surface is presented in Fig. 5(b), where grain deformations along the rolling direction can be noted. As the depth from the surface increases, the amount of ultrafine grain decreases. Since the strain induced by deep cold rolling decreases with distance from the surface to the bulk material, it is expected that the amount of ultrafine grains decreases with increasing depth. As under the turn-assisted deep cold rolled surface the material is heavily strained, a darker area than the base material could be seen for approximately 300µm from the top surface due to selective etching. This was in correlation with the results from the microhardness measurements.

![Microstructures of (a) Turned and (b) deep cold rolled sample at 750N force](image)

Fig. 5: Microstructures of (a) Turned and (b) deep cold rolled sample at 750N force

3.4 RESIDUAL COMPRESSIVE STRESS MEASUREMENT BY X-RAY DIFFRACTION (XRD) METHOD
To evaluate the magnitude of the residual stress states and the extent of work hardening induced in the near surface layers by the mechanical surface treatments. X-ray diffraction measurements were performed on the as-turned and turn-assisted deep cold rolled specimens. It is observed that turn-assisted deep cold rolling process introduced significant levels of compressive residual stresses at the specimen surface and in the near surface regions. It is apparent that after deep cold rolling, maximum compressive residual stresses as high as 569MPa was measured immediately below the surface. Table 4 shows the results of residual compressive stress of turn-assisted deep cold rolled and as-turned samples; the residual compressive stress of turn-assisted deep cold rolled samples was much larger than that of the turned sample. It is reported that the peak broadening is contributed by decreasing grain size and increasing dislocation density, which is consistent with the microstructure observations.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Residual stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As turned</td>
<td>+93.83</td>
</tr>
<tr>
<td>TADCR at 250N force</td>
<td>-292.93</td>
</tr>
<tr>
<td>TADCR at 750N force</td>
<td>-568.74</td>
</tr>
</tbody>
</table>

Table 4: Residual compressive stress results of as-turned and turn-assisted deep cold rolled samples

4. CONCLUSION
The AISI 4140 steel sample was turned and subsequently deep cold rolled. The effects of deep cold rolling on the surface microstructure, surface roughness, micro-hardness and compressive residual stress of AISI 4140 steel were examined and the following conclusions are obtained. Experimental results showed that the microstructure can be significantly improved by increasing deep cold rolling force. Grain refinement in the surface region was achieved through deep cold rolling process. Micro-hardness measurements indicated that the hardness was increased up to 36% relative to the bulk value. Turn-assisted deep cold rolling resulted in significant alteration of the surface topography, led to a decrease by more than 95% in the measured surface roughness. These physical effects lead to improvement of fatigue strength of components as well as increase in resistance to corrosion and foreign objects. Turn-assisted deep cold rolling can be done with any conventional or CNC machine tool without requiring expensive and complicated equipment.
5. REFERENCES


