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Influence of shallow and deep cryogenic treatment on the residual state of stress of 4140 steel

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ABSTRACT

The present research work studies the effect of cryogenic treatment on the residual stress state in 4140 steel. Two kinds of cryogenic treatment, namely shallow (SCT, $-80\,^{\circ}\mathrm{C} \times 5\,\mathrm{h}$) and deep cryogenic treatment (DCT, $-196\,^{\circ}\mathrm{C} \times 24\,\mathrm{h}$) were carried out between quenching and tempering in conventional heat treatment process. The results evidenced an increase in the compressive residual stress in steel are subjected to cryogenic treatment before tempering. X-ray diffractometry revealed that residual stresses are relieved during tempering, according to the redistribution of carbon in martensite and the precipitation of transition carbides. While conventional heat treatment (CHT) and shallow cryogenic treatment (SCT) promote a tensile state of residual stress, DCT shows a compressive residual stress.

1. Introduction

In recent years material scientists and engineers devoted their efforts in enhancing the fatigue and impact properties of metals by deliberately producing compressive residual stresses in to the surface of engineering materials. Residual stresses are the stresses that remain within a part after the original cause of the stresses (external forces, heat gradient) has been removed. Kalpakjian (1985) pointed out that the residual stresses remain along a cross-section of the component, even without the external cause. Samant and Dahotre (2008) described that these internal stresses become evenly balanced by themselves. They existed in a free body that had no external forces or constraints acting on its boundary.

Residual stresses are caused by means of load or thermal gradients or both. These stresses are developed during different processes like non uniform plastic deformation during cold working, shot peening, surface hammering, grinding, welding, phase transformations, and high thermal gradients. Over the past few years, much interest has been shown in the properties and improvement of compressive residual stress. Knowledge of residual stress in steels is important in the component design field. It not only leads to improve fatigue resistance but also improves the dimensional stability. It can also lead to improve the contemporary drop in resistance against stress corrosion cracking. In polycrystalline and/or multiphase materials, residual stresses can be classified as microstresses and macrostresses. Almer et al. (1998) stated that the microstresses are formed due to incompatibilities between grains or between phases and the macrostresses are formed by differential plastic deformation over a large scale relative to microstructure. Prevey (1996) explained that the macroscopic stresses or macrostresses are extended over large distances relative to the grain size. Macrostresses vary within the body of the component over a range larger than the grain size of the material. These stresses are of general interest in design and failure analysis. Macrostresses are tensor quantities. These stresses are determined for a given location and direction by measuring the strain in that direction at a single point. Microscopic stresses or microstresses are treated as scalar properties of the material. These microstresses are related to the degree of cold working or hardness, and the result of imperfections in the crystal lattice. Microstresses arise from variations in strain between the "crystallites" bound by dislocation tangles within the grains. They are acting over distances less than the dimensions of the crystals. Hoffmann et al. (1997) pointed out that the microstresses vary from point to point within the crystals. They are producing a range of lattice spacing and broadening of the diffraction peak. These micro-residual stresses are generated during diffusionless martensitic transformation by dislocations and by solute carbon atoms remaining in their octahedral sites without diffusion.

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During the last decade, cryogenic treatment techniques have been developed and are now broadly used by industry to improve the mechanical properties of steel components. Barron Randall (1974) and Harish et al. (2009) studied that deep cryogenic treatment of SAE 52100 bearing steel enhances wear resistance. Collins and Dormer (1997) investigated the influence of deep cryogenic treatment on D2 cold work tool steel. Dong et al. (1998) studied the effect of DCT with respect to the microstructure of T1 high speed steels. It was proved that deep cryogenic treatment can improve wear resistance by the precipitation of nano-sized eta-carbides in the primary martensite. It was also observed by Stratton (2007). Tamas Reti (2002) found that the amount of retained austenite present in steel plays a significant influence on the magnitude of the residual stresses and dimensional stability. They also pointed out that the effect of retained austenite on component performance is still a controversial issue. Some of the key factors influencing the retained austenite transformation include grain size, quenching temperature, hardening temperature, chemical composition, quenching cooling rates, and stress relieving or tempering. Retained austenite causes a decrease in tensile and yield strength in steels and reduces the maximum achievable surface compressive stresses relative to the amount of this phase. Tempering at sufficiently high temperature promotes the transformation of retained austenite, accompanied by increased hardness. The contemporary loss in hardness due to the tempering of primary martensite partially hides the positive effect of former transformation. Alexandru and Bulancea (2002) have pointed out that cryogenic treatments have been proposed as a useful method to transform retained austenite prior to tempering and to overcome the problems related to austenite stabilization. The transformation of retained austenite into martensite influences the residual stress, which will have an effect on the performance of the material. However, Preciado et al. (2006) stated that because of rather low amount of retained austenite (less than 15%) left by conventional quenching in the microstructure of alloy steels, it appears that the cryogenic cooling would not cause additional microstructure improvements compared to ordinary quenching. So, cryogenic treatments are necessary to create a molecular change in alloy steels, making the most retained austenite into martensite, a denser, refined mix, smaller and a more uniform than austenite. Besides, cryogenic treatment would induce the precipitation of very fine carbides of dimensions less than 1 μm, which occupies the microvoids so that it contributes to the increase of both coherence and density within the metal. Molinari et al. (2001) studied that carbide precipitation occurs with a higher activation energy thus leading to a higher nucleation rate which in turn leads to finer dimensions and a more homogenous distribution. A new phenomenon referred as *tempered martensite detwinning* occurred in AISI M2 steel, which showed a reduction of twins after soaking at −196 °C for 35 h. Deep cryogenic treatment reduces the wear rate of the hot work tool steel. This result was interpreted on the basis of increased toughness, because in the presence of delamination, the ability of materials to oppose crack propagation can really increase the mechanical stability on the wear surface and load bearing capacity. Therefore, even if the deep cryogenic treatment does not influence hardness, it increases both toughness and wear resistance. This is usual with no or low amount of retained austenite present in steel.

Mohan Lal et al. (2001) analyzed the influence of cryogenic treatment on T1 type-high speed steel and concluded that the cryogenic treatment at 93 K, soaking for 24 h, imparts 110% improvement in tool life of T1 type high speed steel.

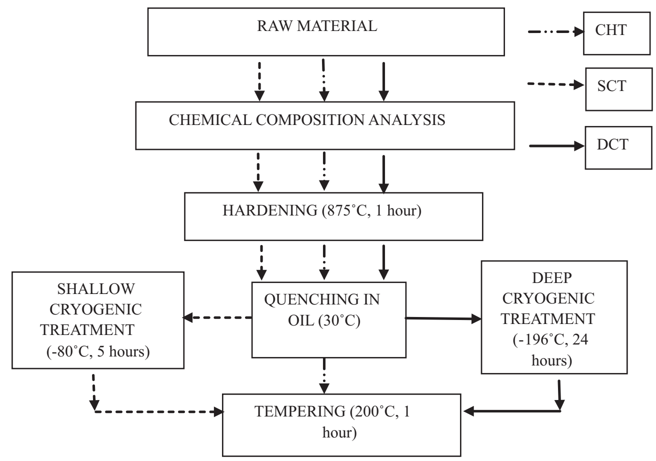

Fig. 1. Research methodology.

The main objective of the present work is to evaluate the influence of two cryogenic treatments, namely shallow cryogenic treatment (SCT, −80 °C for 5 h) and deep cryogenic treatment (DCT, −196 °C for 24 h) on surface residual stress, hardness and impact toughness of 4140 steel. It finds application in axle shafts, crankshafts, connecting rods, gears, and many other automotive components.

2. Material and experimental procedure

The material considered in study was obtained in the form of 20 mm diameter rod. The composition of the 4140 chrome molybdenum steel was obtained by optical emission spectroscopy (OES). The chemical composition of the alloy considered is reported in Table 1. The experimental procedure adopted in the present study is schematically shown in Fig. 1. Samples were subjected to conventional heat treatment (CHT) consisting of quench hardening in oil at 875 °C for 1 h. Part of samples was then subjected to shallow cryogenic treatment (SCT) and deep cryogenic treatment (DCT) as indicated in Bensely et al. (2007). By shallow cryogenic treatment the conventionally quench hardened samples were directly put in a freezer kept at −80 °C and soaked for 5 h to attain thermal equilibrium. Samples were then extracted and left to reach room temperature in air. By deep cryogenic treatment, the conventionally quench hardened samples were slowly cooled from room temperature to −196 °C in 3 h, soaked at −196 °C for 24 h and finally heated back to room temperature in 6 h. All samples were finally subjected to tempering or stress relieving at 200 °C for 60 min.

X-ray diffraction techniques exploit the fact that when a metal is under stress, applied or residual, the resulting elastic strains cause the atomic planes in the metallic crystal structure to change their spacing. When a beam of X-rays is incident on a polycrystalline material, crystographic planes diffract X-rays and Bragg's law $n\lambda = 2d_{hkl}\sin\theta$ is satisfied, which was put forward by Martinez et al. (2003). Here n is an integer indicating the order of diffraction, λ is the X-ray wave length, d_{hkl} is lattice spacing of the hkl planes, and θ is the diffraction angle on the hkl planes.

Table 1
Chemical composition of 4140 steel (wt%).

Sample description	% C	% Si	% Mn	% P	% S	% Cr	% Mo
Raw material	0.45	0.35	0.75	0.017	0.019	1.19	0.21
Uncertainty	±0.010	±0.013	±0.012	±0.003	±0.007	±0.007	±0.018