Effect of Heat Exposure Time on Tensile Properties in Cold Rolled Steel

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Abstract—**This paper presents the effect of heat exposure time on tensile strength of cold rolled specimens. Welding and process annealing are applied to the specimens to investigate their implications. The two processes involve heat and time but in differential amounts. In welding the temperature raises to levels far beyond the melting point of the specimens and cools quickly. The case is different in process anneal the specimen temperature increases slowly to the subcritical level and cools slowly after a specific soaking time. Welded and process annealed in the form of tensile specimens are tested in the tensile machine until fracture. The test results showed that welding and process annealing caused a decrease in yield strength by one third and almost two thirds respectively compared with the as rolled. The fracture of the welded specimen was localized at the heat affected zone near the weld line but was random in all other specimens. Percentage elongation was lowest in the welded specimen compared with other patches of specimens.**

Index Terms: **cold work, process anneal, stress relief, welding, tensile strength, elongation.**

I. INTRODUCTION

Cold working refers to the process of strengthening a metal by changing its shape without the use of heat. This metal working technique involves subjecting a metallic material to mechanical loads to cause a permanent change to the metal's crystalline structure. When a metal is cold worked, most of energy goes into plastic deformation to change the shape and heat generation. However, a small portion of the energy, up to ~5 %, remains stored in the material. The stored energy is mainly in the form of elastic energy in the strain fields surrounding dislocations and point defects generated during the cold work. Cold worked grains are quite unstable due to the strain energy imposed by mechanical loading beyond yield strength. By heating the cold worked material to high temperatures but lower than the lower critical temperature where sufficient atomic mobility is available, the material can be softened. As a result, a new microstructure can emerge. This heat treatment is called process annealing where recovery and recrystallization take place [1-4].

During process annealing, new equiaxed, strain-free grains nucleate at high-stress regions in the cold-worked microstructure. Hence hardness and strength decrease whereas ductility increases. There are three stages of process annealing: recovery, recrystallization, and grain growth. Recovery is the first stage of annealing which takes place at low temperatures of annealing. During recovery, physical properties of the cold worked material are restored without any observable change in microstructure. There is some reduction, though not substantial, in dislocation density as well apart from formation of dislocation configurations with low strain energies. The concentration of point defects is decreased and dislocation is allowed to move to lower energy positions without gross microstructural change. Dislocations become mobile at a higher temperature, eliminate and rearrange to give polygonization [5, 6]. At first, recovery occurs in which there is a change in the stored energy without any obvious change in the optical microstructure.

Recrystallization is the formation of a new set of strain-free grains within a previously cold-worked material. It involves replacement of cold-worked structure by a new set of strain-free, approximately equi-axed grains to replace all the deformed crystals. Nucleation begins in a jumble of dislocations. The recrystallized grain will essentially be free from dislocations. The nucleation of new grains happens in regions of high dislocation density [1, 5]. After recrystallization is complete, the strain-free grains will continue to grow if the metal specimen is left at the elevated temperature. Stress relief treatment is carried out at a relatively low temperature to reduce internal mechanical stresses caused by casting or welding [7, 8].

Welding is used to join two or more pieces of metal to become one piece. However, it introduces a localized heat affected zone near the weld bead. In industry, fusion welding is widely used to produce certain shapes of metal structures. One of the widely used types of welding is the metal-inert gas arc welding (MIG) [9]. The molten zone and heat affected zone HAZ are critical areas because of their sensitivity to internal defects, inappropriate metallurgical structures and unfavorable residual stresses. The metallurgical changes that occur in weld and HAZ considerably affect the weld quality. These changes depend on several factors such as the nature of the

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material, the prior heat treatment, and the prior cold working [10, 11].

Heat treatment and welding are affected greatly by a phenomenon called diffusion. Diffusion involves the movement of atoms from position to another and this movement is motivated by temperature and time [12]. Diffusion is an important aspect in explaining the effects and differences of both heat treatment and welding. Sub-critical heat treatment occurs at much lower temperatures than welding, but at much longer soaking times. Moreover, the heat-treated samples are furnace cooled, while, welded samples are air-cooled. As a result, the diffusion is substantially different between sub-critical heat treatment and welding as the time is an important factor in diffusion [12]. The objective of this study is to investigate experimentally the effect of heat exposure time on some mechanical properties of the cold-rolled steel. This steel experiences two operations, namely, heat treatment and welding.

II. EXPEREMENTAL PROCEDURE

A. Materialand Sequence of Action

Five specimens of cold-rolled low carbon steel (0.1wt % C) were cut in a special mold by impact shear. They were from stock material of a 2 mm thickness into the standard shape of the tensile test specimens.

In order to proceed with the experiment plan, specimens were classified into five categories as shown in Table 1.

Table1. The Specific Procedure on each Group of Samples.

Patch number	Procedure	Specimen code
1	Cold-Rolled	CR
2	Cold-Rolled and welded	CRW
3	Cold-Rolled and process annealed	CRH
4	Cold-Rolled, process annealed and welded	CRHW
5	Cold-Rolled, process annealed, welded and stress relieved	CRHWH

The processed specimens are shown in Figure. 1

B. Heat Treatments

Some specimens were process annealed at 650°C for 30 minutes then furnace cooled. One sample was process annealed; cut in the middle and welded then stress relieved at 600°C for 30 minutes and cooled in air.

C. Welding Processes

Specimen’s surfaces were cleaned to remove oxides and other contaminants then cut by a rotation disk at the middle with the use of a lubricant then welded by MIG method.

D. Tensile Test

The tensile test was conducted on the specimens to determine the mechanical properties which are, yield strength, tensile strengths, and percentage elongation.

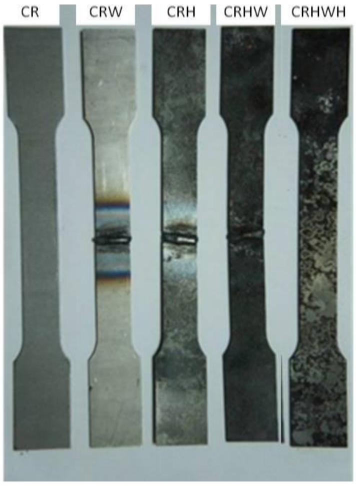

Figure 1. Tensile Test Specimens.

III. RESULTS AND DISCUSSION

The values of yield tensile stress YS, ultimate tensile stress UTS, and percentage elongation % El are indicated in Table 2 and Figure. 2. The as-rolled (CR) specimen results were considered as a reference.

Table2. Summary of the Mechanical Properties.

Specimen	% El	YS N/mm^2	UTS N/mm^2
CR	5	613	677
CRW	2	455	473
CRH	28	202	340
CRHW	26	210	350
CRHWH	28	188	326

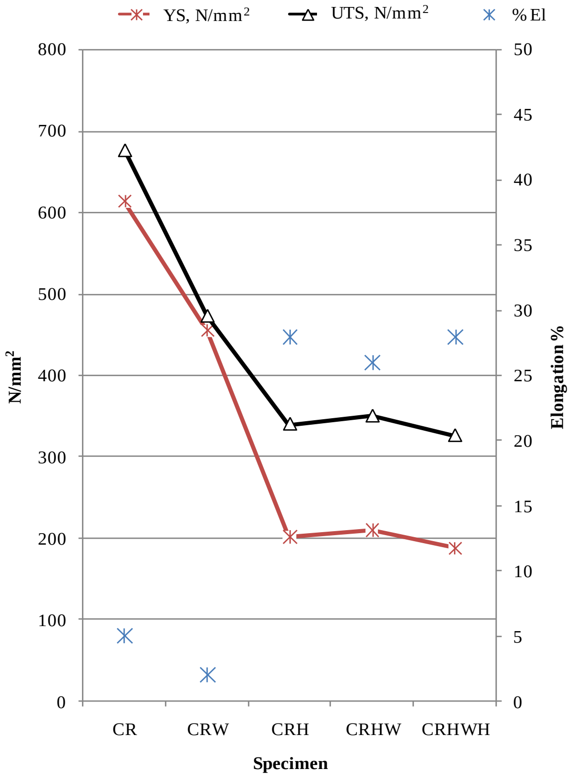

Figure 2. Values of % El, YS, and UTS of Tested Specimens.

The result indicates that the yield stress of the cold worked specimen is 613 N/mm^2, the ultimate tensile strength is 677 N/mm^2, and the elongation is 5%. The fracture takes place in the gauge length of the specimen as shown in Figure. 3 (a). The fracture shape indicates that the material has undergone a plastic deformation by slip in a favorable plane favored by the tensile force according to Schmid's Law [5, 6].

A. Physical and mechanical changes in welding and process annealing

When a work-hardened metal (or alloy) is exposed to temperatures greater than approximately 0.4 T_m the deformed grains tend to nucleate new strain-free grains. This process is known as recrystallization annealing and was previously studied [13]. The driving force for recrystallization is the reduction of stored strain energy, which is reduced as the new, strain-free grains are formed. With the onset of recrystallization, mechanical properties change drastically [14]. The behavior takes place in both subcritical annealing and welding. Grain growth increases with increased temperature and time at temperature, and so is greatest very close to the fusion zone boundary and as the net linear heat input is increased in welding. This effect of welding was investigated [15, 16]. However, it is homogenous and isotropic in subcritical heat treatment. As with the subcritical heat treatment, the effect of work hardening is completely lost in the fusion zone and partially melted zone owing to melting and solidification. On the other hand, this effect is only partially lost in the heat-affected zone due to recrystallization and grain growth.

B. Tensile behavior and fracture

The yield stresses of CR and CRW specimens are 613 N/mm^2 and 455 N/mm^2 respectively. While the ultimate tensile stress of CR and CRW specimens are 677 N/mm^2 and 473 N/mm^2 respectively. Welding introduces the heat affected zone (HAZ) near the weld bead which is reflected by colors apparent near the weld bead. These colors indicate the temperature gradient in the area. Three main areas represent the stages of annealing which are grain growth, recrystallization and recovery respectively between the weld line and the base material. In the coarse-grained region, tensile strength decreases while ductility increases. The tensile test of the CRW specimen indicates that the yield stress decreases to about two thirds of the yield stress of the parent metal. However, the percentage elongation decreased from 5% to 2% after welding. The drop in tensile stress of CRW is due to the presence of localized, soft, ductile newly formed, unstressed grains in the HAZ near the weld bead. Another difference between the CR and CRW is that the fracture location of the cold rolled (CR) specimen is random. This reveals that the specimen is uniform and hence isotropic. But in the cold worked and welded (CRW) specimen failure has taken place in the HAZ right next to the weld join (Figure. 3 (b)). The CRW specimen elongation is small because of the short range, softening in the grain growth and recrystallized grains zones near the weld bead.

A comparison of the mechanical behavior in tensile mode has been made between CR specimen and CRH specimen. A cold rolled specimen is subjected to a standard process annealing treatment for 30 minutes and left to cool slowly in furnace. The resulted CRH specimen experienced a sufficient soaking time at a temperature of the annealing treatment and followed by a slow cooling rate. This gives atoms enough time to move to more stable sites in the metallic matrix. The three main stages of process annealing have taken place. In the first stage, recovery caused a release of some stored energy due to the movement of dislocations with mechanisms of slip and climb. Recrystallization is the second stage occurred at higher temperature. In this stage, hardness and strength decrease massively, ductility increases greatly and stored energy is released [8]. Once recrystallization is complete, the newly formed, strain-free grains grow in order to reduce the surface energy associated with grain boundaries [8].

Overall, after process annealing, the effect of cold working has been removed from the whole specimen and the pre-cold work properties were restored. That explains the increase in elongation from 5% of (CR) to 28% of (CRH) after process annealing because of the long-range softening through the specimen. The yield strength decreased from 613 to 202 N/mm^2 and ultimate tensile strength decreases from 677 N/mm^2 to 340 N/mm^2. A similar trend in decreasing yield and ultimate tensile strengths after process annealing was previously investigated [17].

The next stage of the experiment is to mix the previous modifications, i.e. process annealing and welding in the same specimen. The cold rolled, process annealed specimen has been cut in the middle and welded (CRHW). Obviously the pre-cold work properties have been completely restored and the effect of strain hardening has been removed. The purpose of this experiment is to check the effect of introducing a localized heat of fusion of welding on properties. These are tensile strength and elongation in the cold worked and process annealed specimen (CRH) to become CRHW.

The yield strength values are: 455, 202 and 210 N/mm^2 for the CRW, CRH and CRHW specimens respectively. The ultimate tensile strength values are: 473, 340 and 350 N/mm^2. The amount of drop of strength is attributed to the reset of mechanical status pre-cold work. The result shows also that the percentage elongation of CRHW is 26% which approximately equals to that of the CRH specimen. That implies there is no effect of welding on the mechanical properties of a process annealed specimen. Moreover, there is no indication of a HAZ near the weld bead because the fracture took place in the parent metal away from the weld bead. This behavior is shown in Figure. 3 (d).

The fracture shape of CRW specimen is brittle and located at the weakest area which is the HAZ. On the other hand, it is close to ductile in CRH specimen and randomly located through the gauge of the specimen. In CRHW specimen the fracture was close to ductile and random within the base metal but not in HAZ. This is a

Solid indication that the failure is due to process anneal not welding.

A stress relief treatment has been done following process annealing and welding to produce a specimen coded by CRHWH. The tensile yield strength and the ultimate tensile strength are 188, 326 N/mm^2 respectively. The percentage elongation is 28%. The fracture is randomly located within the gauge of the specimen without any indication of anisotropy in the mechanical characteristics of the gauge material of the specimen (Figure 3 (e)). For stress-relieving steel, the most common temperature is about 600°C. This is high enough to drop the yield residual stresses by 80 percent, yet low enough to prevent any metallurgical changes in most steels. 90% stress relief can be obtained by heating the metal to just under the critical temperature, but some steels can become brittle after thermal stress relief at these temperatures [8]. The result shows that the drop in tensile strength is minor indicating no substantial change due to stress relief after welding of a process annealed specimen.

The difference between the effect of welding and process annealing on mechanical behavior and properties is mainly attributed to the time available for both processes during treatment. Previous work showed a huge effect of time on mechanical properties during annealing [18]. The time at a temperature of process annealing is much higher than the time available in welding. The heat level has only a supporting effect to treatment time. That means higher temperature for a short time has a less effect compared with low temperature for a longer period of time.

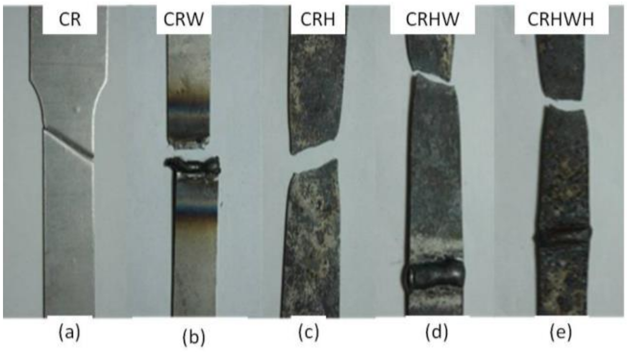

Figure 3. Fracture Location in Tested Specimens.

IV. CONCLUSIONS

1. Welding results in a loss of mechanical strength of the cold worked specimen by about 30% and due to a localized heat affected zone, which results in an anisotropic fracture.
2. Process annealing caused a drop in mechanical strength of the cold worked specimen by about 70% and an isotropic fracture.
3. Welding a cold worked and process annealed specimen did not affect the specimen material in any way. Stress relief after welding the cold rolled, process annealed and welded specimen has no considerable influence on mechanical properties.
4. Long time period at a temperature in the subcritical range in process annealing is much more influential than temperature level up to the fusion level for short time in welding.

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