Mechanical and microstructural properties of AISI 4140 after flow-forming process

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Abstract. Flow-forming is a cold deformation process to form dimensionally precise and rotationally symmetrical parts. Strain hardening effect of the flow forming process, and possibility of producing cylindrical part are the advantages especially for aerospace industry. The purpose of this study is to investigate the effect of initial microstructure of an AISI 4140 steel on the microstructure and mechanical properties after being flow formed by 70% as the reduction ratio in the thickness direction. In this context, as-received steel was heat treated to standard quenched and tempered condition, and an additional annealing was also performed. Before and after the flow forming process, the microstructure was examined, hardness and tensile tests were conducted. The results revealed that the additional annealing was beneficial to obtain a crack free material after the flow forming process of a heat treated material.

Introduction

Flow forming is a cold deformation process commonly used in metal forming industry. With this process, dimensionally accurate and rotationally symmetrical parts can easily be produced [1,2]. Cold deformation during flow forming improves hardness and strength properties of the formed parts due to strain hardening mechanism, which occurs as a result of generation of the dislocations within the material and their interactions with each other [3]. In the flow forming process, a relatively short and thick starting material in tube form (preform) is formed into a longer and thinner tube by means of a rotating mandrel inside the preform, and one or more rollers outside the preform. There are basically two flow forming methods depending on the flow direction of the material. When the flow direction of the material is towards the front of the roller, it is called as forward flow forming, and when the flow direction of the material is the rear of the roller, it is called as backward flow forming. Higher dimensional accuracy, higher inner and outer surface quality, improved hardness and strength, and finer and uniform directional grain structure can be achieved by the flow forming process [4].

Flow forming is an active research area both in academic and industrial point of view. In this context, several works have been published so far focusing on Al alloys [5], Mg alloys [6], Ti alloys [7] and steels. Beside experimental works concerning the relationship between input parameters of the flow forming, and final microstructure and mechanical properties of the flow formed alloys, numerical modelling coupled with the experiments was also made. For example, Banerjee et al [8] studied efficiency of two artificial neural network architectures to estimate the final dimensions of large tubes with respect to the input parameters, by using three optimization techniques, and concluded that BFGS (Broyden–Fletcher–Goldfarb–Shanno) tuned Elman Neural Network (ENN) provided satisfactorily statistical performance with a faster computational time with respect to LM (Levenberg–Marquardt) tuned method. In another work, Roula et al [9] conducted mechanical tests and finite element analysis to model the flow forming behavior and predict the necking behavior during flow forming. On the other hand, Xu et al [10] studied fatigue crack growth rate of a 34CrMo4 steel which was flow formed after hot drawing. They reported that the hot drawn and cold flow formed steel exhibited a higher resistance to the crack growth than the base metal, fatigue crack growth rate increased with increasing stress ratio, and the sample direction had a little effect on fatigue crack growth rate. Karakaş et al [11] investigated the mechanical properties of an annealed 5140 steel tube after being flow formed in comparison to the annealed condition. They reported that after the flow forming, hardness, yield strength and tensile strength were all significantly improved by a factor of 1.2, 2.6 and 1.6 times, respectively, with a corresponding decrease in elongation at fracture by 50%. They also found that hardness through the thickness direction of the flow formed tube significantly decreased from the outer surface to the inner surface.

AISI 4140 alloy is a medium carbon low alloy steel, which is generally used in quenched and tempered condition to meet the strength and hardness specifications in industrial applications. Although the flow forming has a potentiality to modify the microstructure and mechanical properties of AISI 4140 steel, to the best of our knowledge, its mechanical properties have not been studied so far. It is therefore, in this study, it is aimed to investigate the effect of the initial microstructure of an AISI 4140 low alloyed steel on the microstructure and mechanical properties after flow forming.

Methodology

AISI 4140 steel is used as the starting material (the preform) for the flow forming process. Table 1 shows the chemical composition of a hot rolled and annealed AISI 4140 steel use as the preform material in the present study. Preform tubes have the dimensions of 730 mm in length and 5.5 mm in wall thickness. They were subjected to the flow forming process with a 70% reduction ratio in the thickness direction. Flow forming process parameters were as follows; feed rate was 0.5A mm/min, spindle rate was 1.95A rpm, and a cooled emulsion was used as the lubricant (A is factor of company know-how.). Final dimensions of the tubes were 1965 mm in length and 1.6 mm in wall thickness. In the present study, the preform and flow formed parts were shown in Fig. 1.

Table 1. Chemical composition of the AISI 4140 steel used as the preform in this study.

Element	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Fe
wt.%	0.41	0.23	0.68	0.008	0.013	0.97	0.19	0.12	0,012	0,18	Balance

In order to investigate the effect of initial microstructure, three samples were prepared including as-received (AR), quenched and tempered (QT), and further annealed samples (QTA) in addition to QT condition. For QT condition, the samples were first austenitized at 845°C for 30 min, quenched in oil at room temperature, and tempered at 500°C for 30 min. Additional annealing was carried out at 600°C for 3 h. The microstructures of the preform and the flow formed samples were examined on an Olympus BX53M optical microscope after being prepared by the standard manner [12] and etched with 2% Nital. The hardness was measured on the cross sections of the tubes at specified intervals along the thickness direction by an Emco Test Dura Scan – 20 hardness tester using a Vickers indenter under a load of 300 g according to ASTM E384-17 standard [13].

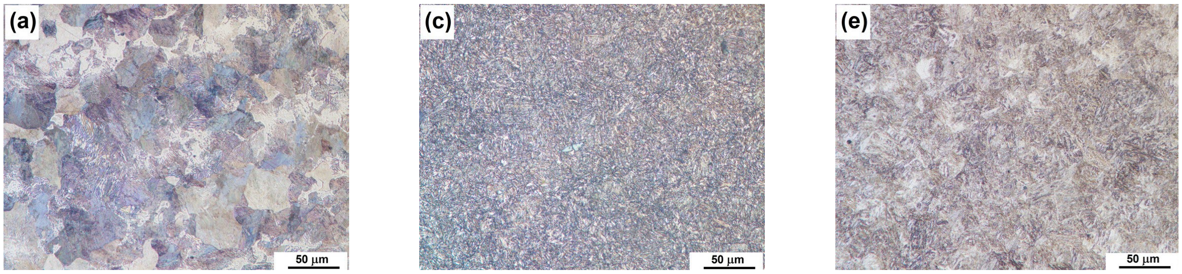
Fig. 1. Preform tube (Left) and flow formed tube (Right).

The tensile tests were conducted on an Instron 3382 model universal testing machine by using longitudinal samples prepared along the forming direction according to ASTM E8M standard [14]. Three tensile specimens were tested for each condition.

Result and Discussion

Microstructural examinations.

Fig. 2 shows the optical micrographs of the preforms and the flow formed samples representing each condition of the AISI 4140 steel. The microstructure of AR sample preforms has an equiaxed grain structure composed of ferrite and pearlite (Fig. 2a). The flow forming strongly affected this microstructure resulting in severely elongated grains along the forming direction, as expected (Fig. 2b). QT sample has a tempered martensite structure before the flow forming (Fig. 2c), and exhibited a cold worked structure after the flow forming (Fig. 2d). Additional annealing led to a tempered martensite structure (Fig. 2e), which was coarser with respect to that of QT sample. The flow forming of QTA sample resulted in elongated grains (Fig. 2f) as in the case of the previous conditions. The microstructures of all flow formed samples were similar to each other, which are characterized by severely deformed grains along the forming direction without any remarkable discontinuities in the microstructure.



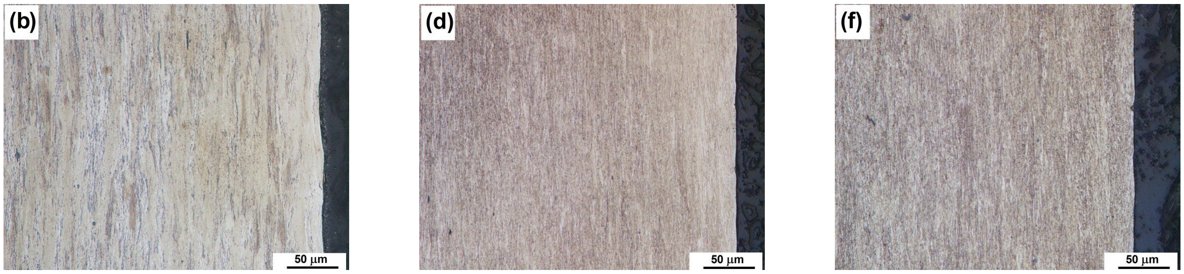


Fig. 2. Optical micrographs of the preform samples (Fig. 2a, c and e) and the flow formed samples (Fig. 2b, d and f). AR samples (Fig. 2a and b), QT samples (Fig. 2c and d), and QTA samples (Fig. 2e and f).

Hardness test results.

Hardness of the samples before and after the flow forming process was listed in Table 2. Among the preform samples, hardness increased with an increasing order for AR, QTA and QT samples. QT samples had the highest hardness, additional annealing slightly reduced hardness, as a result of a higher tempering temperature. Depending on the measurement location, the hardness slightly reduce from the outer surface to the inner surface for AR sample preforms, suggesting that the outer rollers are more effective for hardness increment. However, there was no systematic correlation depending on the measurement locations for QT and QTA samples. After being flow formed, the hardness of all samples increased due to strain hardening. The highest increment (approximately 50%) was observed for AR sample. QT and QTA samples had almost the same hardness, exhibiting a hardness increment by approximately 10-15% after the flow forming process. This indicates that strain hardening mechanism is less effective for heat treated samples than AR sample. No significant variation is observed among the hardness values of the samples from the outer and the inner surface of the flow formed samples.

Table 2. Hardness of the preforms and the flow formed samples.

Distance from the outer surface, [mm]	Hardness, [HV0.3]					
	Preform			Flow formed		
	AR	QT	QTA	AR	QT	QTA
0.15	204	396	354	312	422	435
0.30	212	374	366	305	431	419
0.44	203	388	357	308	417	424
0.60	189	389	379	310	419	413
Average	202	387	364	309	422	423

Tensile test results.

Tensile test results were listed in Table 3, and stress – strain graphs were given in Fig. 3. Among the preform samples, QT samples have the highest strength values with an elongation at fracture of 11.2% as a measure of ductility. Additional annealing reduced strength and ductility. This is a result of the coarser microstructure of QTA sample with respect to QT sample. When the samples were flow formed, regardless of their initial conditions, their strength values were improved with a corresponding decrease in ductility. This shows that hardness and strength values generally varied similar to each other, except for strength decrement in QTA sample. Although its hardness was equivalent with that of QT sample after the flow forming, strength values of QTA sample were significantly lower than those of QT samples after the flow forming, with slightly higher ductility. On the other hand, for both preform and the flow formed samples, AR samples exhibited lower strength and higher ductility. Similar to the hardness increment upon the flow forming, the strength values increased more in AR samples (approximately 110% for yield strength, and 50% for ultimate tensile strength). On the other hand, for the heat treated samples (QT and QTA samples), this increment was significantly lower (approximately 10-25%). It is also interesting to note that mechanical properties of QTA sample before the flow forming were almost similar to those of AR sample after the flow forming. The tensile test results revealed that initial microstructures of AISI 4140 steel was highly effective in determining the final properties after the flow forming.

Table 3. Tensile test results of the preforms and the flow formed samples.

Properties	Preform			Flow formed		
	AR	QT	QTA	AR	QT	QTA
Yield strength, [MPa]	345	1118	962	738	1342	1059
Ultimate tensile strength, [MPa]	692	1209	1074	1057	1483	1363
Elongation of fracture, %	16.2	11.2	9.3	8.8	5.1	6.6

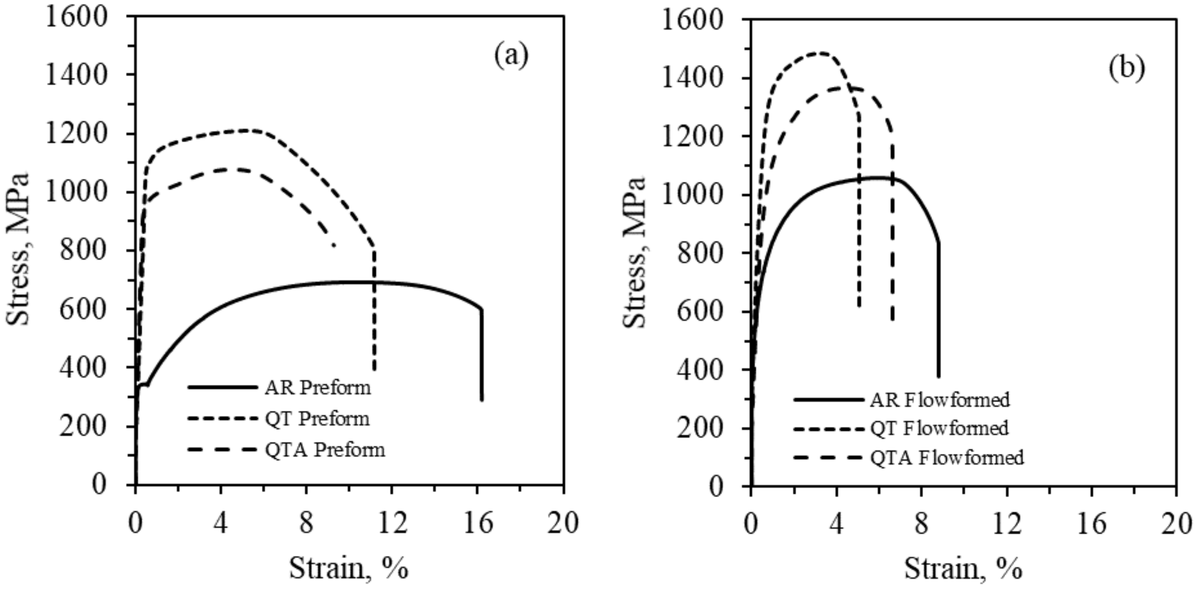


Fig. 3. Stress – strain graphs of (a) the preform and (b) flow formed parts.

Visual examination.

Visual examination of the samples after the flow forming process revealed that AR and QTA samples exhibited no visible defect inside or outside the formed tubes. However, there was a small surface crack inside QT sample as seen in Fig. 4, despite that QT sample preform has slightly higher ductility than QTA sample. The observed crack on QT sample was possibly resulted from its tempered martensite microstructure exhibiting the highest hardness and yield strength. This suggests that additional annealing after quenching and tempering is beneficial to avoid crack formation during the flow forming, and might be attributed to a coarser tempered martensite microstructure with a lower hardness and yield strength of QTA sample.

Fig. 4. Small surface crack formed inside QT sample.

Summary

In this study, the effect of various initial microstructures of AISI 4140 steel preforms on the microstructure and mechanical properties, and surface quality after being flow formed was investigated. Heat treatments significantly affected the microstructure and mechanical properties of AISI 4140 steel after the flow forming Comparative study of three initial microstructures, namely, as-received (AR), quenched and tempered (QT), additionally tempered after quenching and tempering (QTA) leads to following conclusions:

1. The initial microstructure of AISI 4140 steel significantly affects the microstructure and mechanical properties of the flow formed parts. In this context, AR microstructure exhibited higher increment (approximately 50%) in strength values after the flow forming with a corresponding decrease (approximately 45%) in ductility. On the other hand, the strength increment after the flow forming of QT and QTA samples was lower (10-25%) when compared to that of AR sample.
2. Ductility of all samples in terms of elongation at fracture decreased by the flow forming. However, the highest decrement was observed in QT samples (approximately 55%), while QTA sample exhibited the lowest decrement in ductility (approximately 30%).
3. The highest hardness (387 HV) and strength (1483 MPa) were obtained from QT sample. However, this condition leads to a crack formation on the surface during the flow forming, Additional annealing after quenching and tempering avoided the crack formation during the flow forming. This suggest that a coarser tempered microstructure developed by the additional annealing is beneficial to produce crack free parts for the investigated AISI 4140 steel.

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