EVALUATION OF THE EFFECTS OF DIFFERENT MANUFACTURING METHODS ON TENSILE PROPERTIES OF S700MC STEEL

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Abstract

Manufacturing of the tensile test specimens with minimal surface defects and close tolerances are the key factors to achieve desirable and accurate mechanical properties. In addition, faster and cost-effective manufacturing methods with reliable results are also critical requirements. This study focuses on determination of the effects of various manufacturing methods on tensile properties and surface conditions produced during different machining operations. For this purpose, tensile test specimens of S700MC steel were prepared in rolling directions of 0°, 45°, and 90° using wire electro-discharge machining (WEDM), abrasive water jet cutting (AWJC), plasma cutting (PC), laser cutting (LC), and milling operations. The results were discussed in terms of specimen dimensions, surface roughness, (Ra and Rz) and tensile properties in detail.

Keywords: Tensile properties, S700MC, manufacturing methods

1. INTRODUCTION

In order to determine the mechanical properties aiming to assure the quality requirements of the materials and/or any advanced mechanical characterization studies, the basic tool is the standard (uni-axial) tensile tests. Despite of its limitation on maximum obtainable strain values due to the plastic instability (necking), standard tensile test is commonly used because of its low cost and ease of accessibility [1-2]. This testing may be needed for sheet metals or thick plates especially in defense industry applications where the thickness of the materials used are relatively higher. At present, it could be stated that, the only internationally accepted method for the manufacturing of standard sheet-type tensile test specimens is milling [3]. However, the final quality of the milled specimen is barely dependent on the amount of wear of the milling tool and the dynamic response behavior (chatter stability) of the milling machine. In other words, a wide range of surface quality grades can be obtained by a standard milling operations. Due to this fact and moreover the concerns of the cost-effectiveness, alternative specimen preparation methods exist in industrial application. For the case where the tensile testing of thick plates is performed, alternative trimming options such as LC, AWJC, PC and WEDM come to seen as powerful alternatives [4]. Therefore, relative studies exist in the literature at which the different manufacturing methods are compared with respect to the obtained mechanical properties and the surface quality results. For instance, Krahmer et al. [4] performed a study on AISI 1010 steel and Inconel 718 materials and stated a 5% difference in the mechanical results among different manufacturing processes. Similarly, Barenyi [5] studied that effect of plasma and laser welding operations for Ultra High Strength Steels (UHSS). Barenyi also showed that the operation parameters can degrade the obtained mechanical properties. This contribution has a distinguishing property with these existing literatures that our focus is given to S700MC material which is commonly-used high strength steel in defense industry. Our investigation deals with not only the rolling direction but also transverse and 45° directions. The specimen thickness is also selected as 6 mm which is out of the acceptable range of sheet metals. And furthermore, a microscopic analysis is also performed to comment of the different kerf surface characteristics of different manufacturing methods. The results in this contribution reveal that when all the directions are considered altogether for S700MC steel, LC yields the most closer (~1-6% differences) mechanical results compared to milling for the given process parameters. Definitely, in order to produce more comparative data, the dependence of the process parameters on the surface quality of the specimens should also be studied. This fact (the dominance of process parameters on surface quality) would be investigated for each manufacturing method as a future work.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

2.1. Materials

In the present investigation, tensile test specimens were prepared and tested according to ISO 6892-1 standard [6]. To determine the yield strength (Re), ultimate tensile strength (Rm) and total elongation values at failure (A), tensile tests were performed on Zwick/Roell Z300E tensile tester under test conditions at test speed of 20 mm/min, clamping pressure of 4.5 bar, preload of 1000 N, and extensometer range of 80 mm. The tests were repeated five times and their mean values were accepted as final output values of the tensile test. The specimens were manufactured by different cutting methods at three different directions of 0°, 45°, and 90° relative to the rolling direction of the test material (S700MC steel). **Figure 1** shows tensile test setup, the dimensions of a specimen, and layout of specimen preparation. The employed cutting operations and their cutting conditions were:

- WEDM (brass coated steel wire, I: 22 A, V_d: 115 V, T_{on}: 10 µs, T_{off}: 15 µs, f_r: 4 mm / min)
- AWJC (3500 bar, SiC abrassive (grit size 80), Ø 1.2 mm nozzle, 2 mm standoff, f_r: 132.3 mm / min)
- PC (N_2 assist gas, f_r: 2680 mm / min, 3 mm standoff, Ø3 mm nozzle, I: 130 A, 115 V)
- LC (O_2 assist gas, 4.8 kW, f_r: 1650 mm/min, 2 mm standoff, 0.8 bar gas pressure, Ø1 mm nozzle)
- Milling (TiAlN coated carbide end mill, Ø8 mm, Z4, V_C: 50 m / min, f_z: 0.075 mm / tooth, a_p: 0.5 mm)

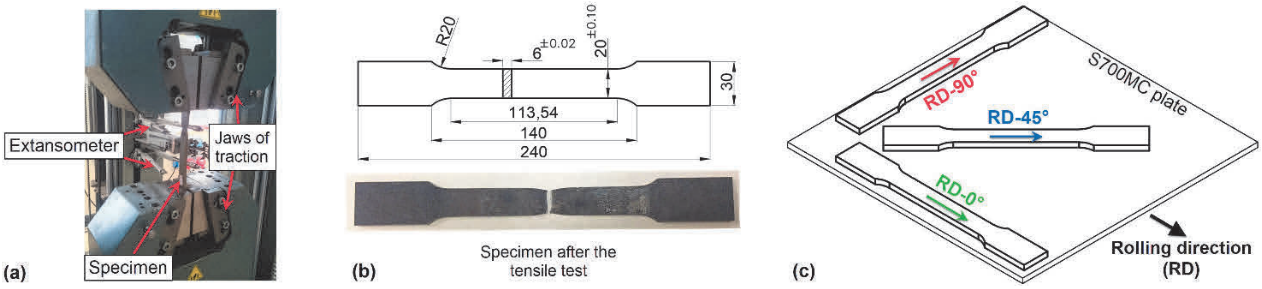

Figure 1 a) Tensile test setup, b) the dimensions of a test specimen, and c) layout of specimens at different orientations on S700MC plate.

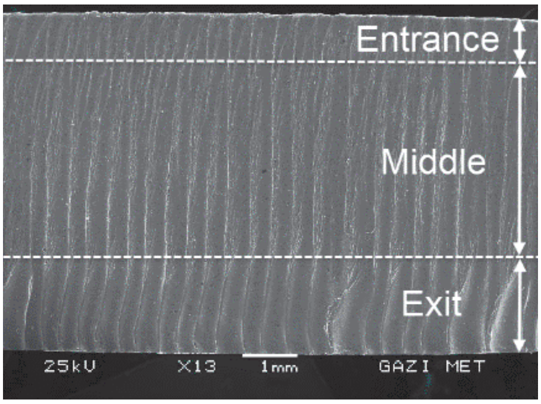

Figure 2 Three regions of a surface cut with LC

Mitutoyo Surftest SJ-301 surface roughness tester was used to determine surface roughness values (Ra and Rz) at entrance, middle, and exit regions of the kerf surfaces using a sampling length cut-off (Lc) of 0.8 mm and evaluation length (Ln) of 6 mm. Three measurements were taken from RD-0°, RD-45° and RD-90° directions and their mean values were accepted as the final surface roughness values. **Figure 2** shows the entrance, middle, and exit regions of an example surface cut using LC.

After manufacturing of the specimens, each of them was analyzed in terms of lost regions in the cross-sectional area, occurred due to natures of some cutting processes such as LC, PC and AWJC using AUTOCAD software. In **Figure 3**, measurement method of lost regions on a specimen cross-section (after PC) and burr formation conditions of the specimens for each machining condition are presented.

Cutting method	WEDM	AWJC	PC	LC	Milling
Area loss (%)	-	0.77	1.06	0.89	-
Burr formation	-	+	+	+	+

Figure 3 The representation of lost regions on specimen cross-section and area loss values and burr formation conditions of specimens cut by different methods

In this study, milling operation which is the standard method for producing the sheet metal tensile specimens [3,4], is selected as the base cutting method and the results obtained from other methods were compared to ones from milling.

3. RESULTS AND DISCUSSIONS

3.1. Tensile test

Figure 4 shows Re (**Figure 4a**), Rm (**Figure 4b**), and A (**Figure 4c**) values at rolling directions of 0°, 45°, and 90° for different cutting methods. In **Table 1**, the percentage differences of mechanical properties of the specimens cut by other methods relative to those of the specimen cut by milling are given. Minus sign means a decrease in average mechanical properties. Except for A values obtained with WEDM and AWJC methods, the maximum variation of mechanical properties is only about 6%. In general, when compared the cutting methods, the closest results to milling were obtained with LC. However, WEDM and AWJC results are also very close to obtained Re and Rm values with milling method. It can be said that minus A values are related to strain hardening effects of milling method [4]. On the other hand, the highest differences were observed with PC method. This can be associated with irregular cross-sectional area, surface, and possible subsurface defects (for example, HAZ). Test results showed that anisotropy affected the tensile test results significantly. When compared to RD-0°, Re values increased for all cutting methods in the range of 0.40 - 8.25 % and 7.45 - 14.52 % for RD-45° and RD-90°, respectively. On the other hand, anisotropic behavior affected the Rm and A values in a different way. In case of RD-45°, Rm decreased between 0.09 - 4.32 %, whereas for RD-90°, these values increased in the range of 0.90 - 6.46 % in comparison to RD-0°. In comparison to A-values at RD-0°, although RD-45° leads to reduction averagely by 5.17 % for some methods (WEDM and AWJC), an increase between 12.43 - 31.00 % were obtained. For RD-90°, A-values decreased in the range of 3.85 - 31.57 % with respect to RD-0° for all cutting methods. During rolling process, grains of material become oriented in a specific crystallographic direction and plane. Therefore, mechanical properties of rolled sheet depend on the direction. The strengthening that takes place by the development of anisotropy is called as texture strengthening [7]. For S700MC plate, it was found that tensile strength is highest in vertical orientation to the rolling direction (RD-90°). However, ductility is highest at RD-45° in general. Similar ductility behavior can be also seen for a cold worked aluminum-lithium alloy [7], AISI 304 austenitic stainless steel [8], and API-X80 steel [9]. It can be said that different cutting methods and rolling directions affected the A values of S700MC steel significantly rather than Re and Rm values.

Table 1 Comparison of tensile test results for different cutting methods relative to milling

Machining method	Re (%)			Rm (%)			A (%)		
	RD-0°	*RD-45°*	*RD-90°*	*RD-0°*	*RD-45°*	*RD-90°*	*RD-0°*	*RD-45°*	*RD-90°*
WEDM	0.46	1.94	4.76	-0.99	0.79	3.02	14.75	-5.34	-18.33
AWJ	1.46	-1.47	2.57	-1.88	-1.2	0.14	18.58	-3.44	-3.80
PC	6.43	0.17	4.14	2.33	-0.26	1.87	-8.00	4.21	-6.16
LC	-0.27	-1.59	0.32	-0.30	-0.85	-1.68	-3.44	-6.17	-1.96

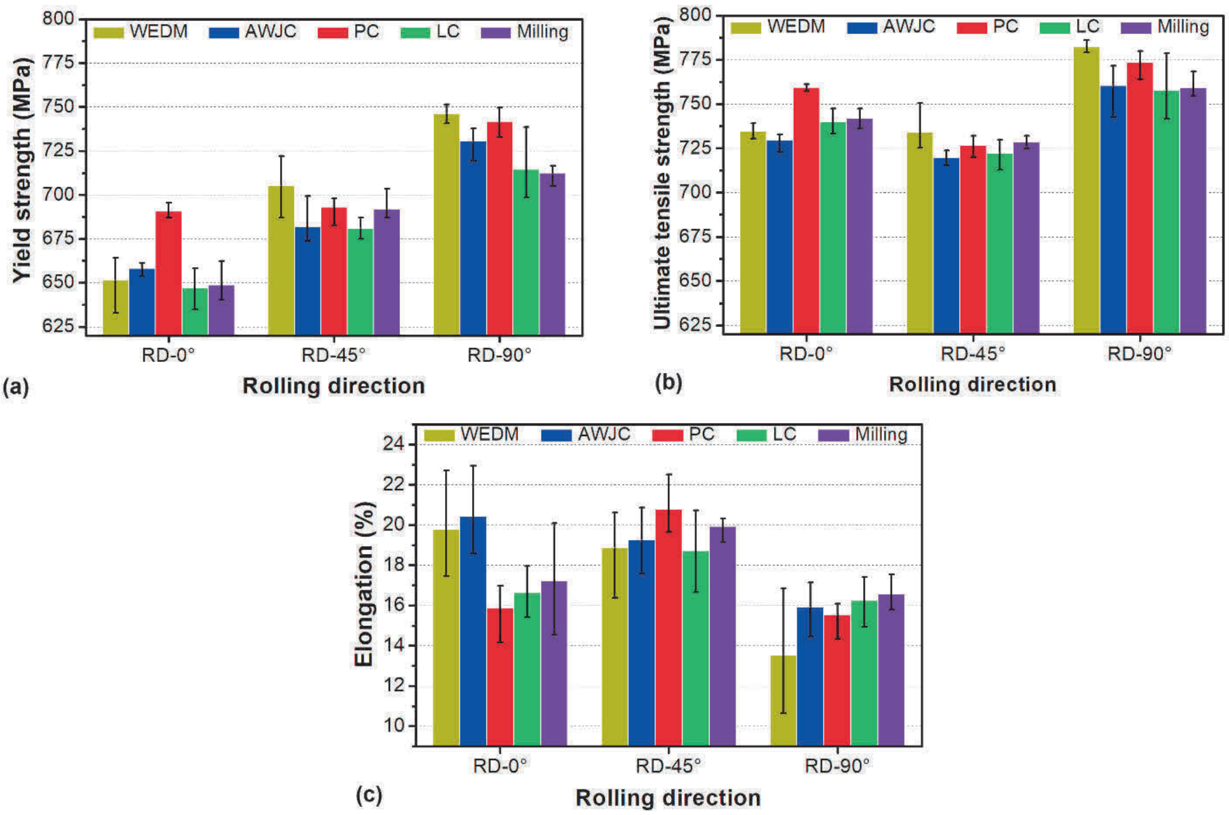

Figure 4 a) Re, b) Rm, and c) A values at rolling directions of 0°, 45°, and 90° for different cutting methods

3.2. Surface roughness

Figure 5 indicates SEM images of kerf surfaces of specimens cut by five cutting methods. As can be clearly seen, the milled surfaces have a good surface quality with small adhesions and short burrs. On the other hand, thermal effect in WEDM, PC, and LC methods, and influence of abrasive particles in AWJC [4] lead to some surface defects. In LC, some striations can be observed on kerf surface (**Figure 3**). In this case, the convection cooling effect of the high-pressure assistant gas causes to the rapid solidification of liquid metal at the kerf surface and result in formation of cast layer [10]. This, in turn, leads to formation of micro cracks at the machined surface (**Figure 5**). Similarly, in PC, some craters and micro cracks are visible due to rapid cooling of molten material. In WEDM, some adhesions were observed. They occurred during pulse off period in the cutting process and some micro cracks and voids can be seen.

Figure 6 shows Ra (**Figure 6a**), and Rz (**Figure 6b**) values at rolling directions of 0°, 45°, and 90° for different cutting methods. In **Table 2**, the percentage differences of surface roughness values of kerf surfaces of the specimens cut by different cutting methods relative to those of the specimen cut by milling are given. Ra and Rz values support the SEM analysis of kerf surfaces (**Figure 5**). The smoothest surface was obtained with milling operation. On the other hand, formation of striations in LC leads to the roughest surface. However, this case did not affect significantly the mechanical properties of the specimen. As shown in **Figure 6**, the closest surface roughness values to milling were obtained with PC. Although Ra and Rz values do not vary at entrance, middle and exit regions of the kerf surfaces for WEDM, PC, and milling, these values increase from the entrance to the exit for LC and AWJC. In AWJC, the intensity of plastic deformation increases through the thickness of specimen. Because as the abrasive particles penetrate into the part, with increasing depth the abrasive jet stream deflected, thus lead to formation of striations on kerf surface [11]. This situation results in a rougher region at the exit of the machined surface (**Figure 6**). In LC, formation of increasing deep striations from entrance to exit edges (**Figure 3**) resulted in rougher surface conditions.

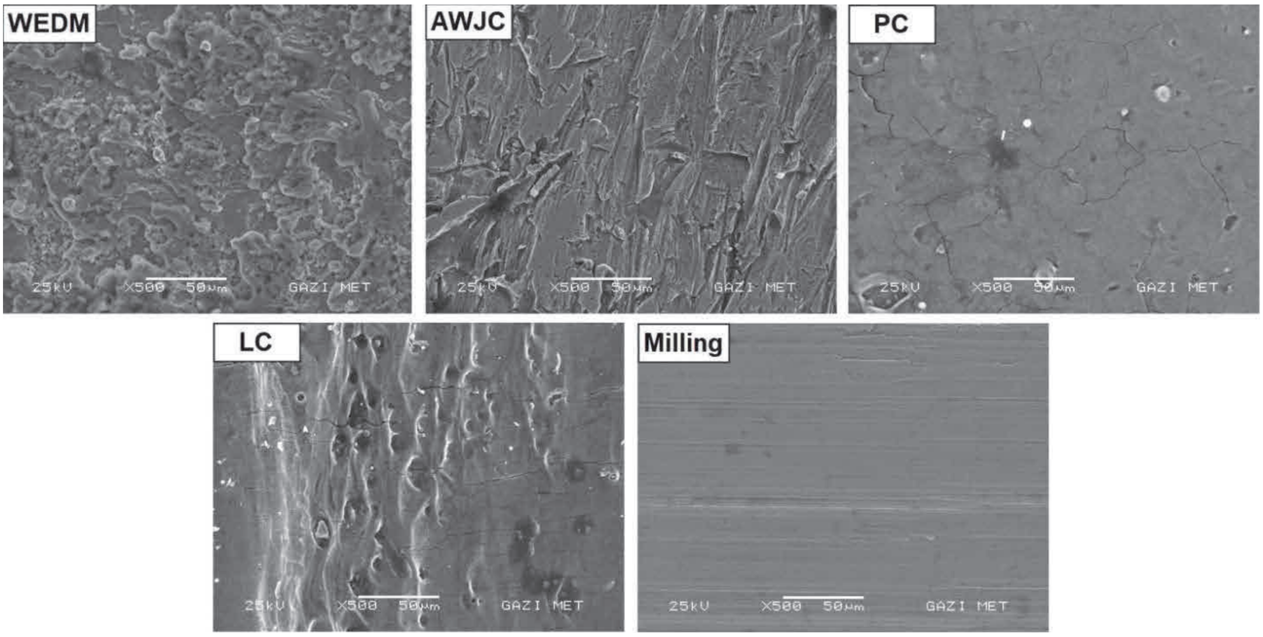

Figure 5 SEM images of machined surfaces for different machining methods

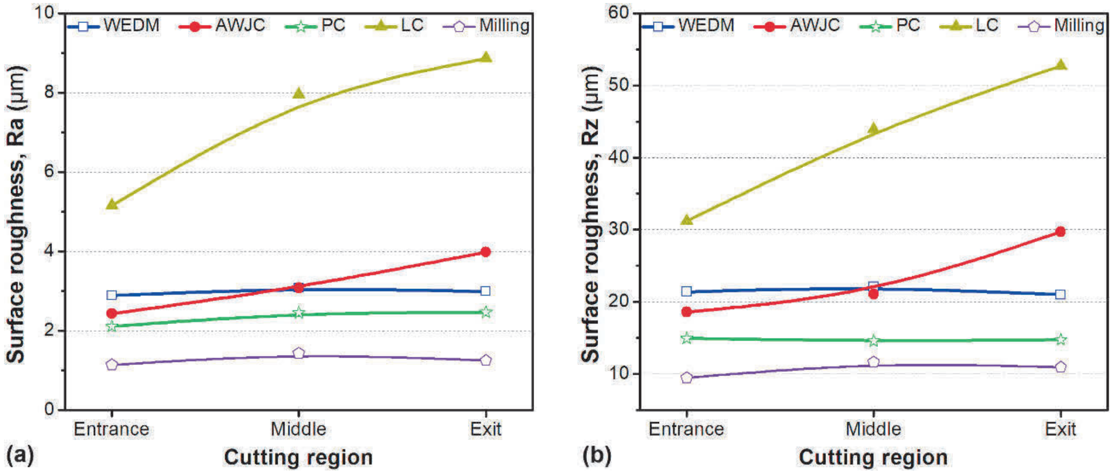

Figure 6 a) Ra and b) Rz values for different cutting methods at entrance, middle, and exit regions of kerf surfaces

Table 2 Comparison of surface roughness for different cutting methods relative to milling.

Machining method	**Ra (%)**			**Rz (%)**		
	Entrance	***Middle***	***Exit***	***Entrance***	***Middle***	***Exit***
WEDM	153.96	115.15	139.84	126.02	90.16	127.17
AWJ	113.78	115.39	219.25	96.41	81.16	221.50
PC	85.63	71.33	97.33	57.71	25.51	59.56
LC	353.08	455.71	610.70	229.54	277.85	470.53

4. CONCLUSION

In this study, it was aimed to contribute to industry and academy for determination of a time-saving and cost-efficient preparation methods of tensile test specimens in comparison to specimen preparation with standard milling method. For this purpose, test performance of different cutting methods in terms of mechanical properties and surface roughness of S700MC was investigated. Milling process was selected as base cutting method and obtained results were compared to WEDM, AWJC, PC, and LC methods. It was found that LC which is a low-cost and less time-consuming process could be an alternative process to milling due to close tensile test results. On the other hand, compatible Re and Rm values were also obtained with WEDM and AWJC methods. Therefore, it can be said that it is possible to lower the cutting time (except WEDM) and complexity for specimen preparation of S700MC with minimal differences on tensile properties using different trimming methods other than milling. In addition, the test results showed that anisotropy has a significant effect on tensile properties of S700MC.

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