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Mechanical Properties of Laser Heat Treated 6 mm Thick UHSS-Steel

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Abstract. In this work abrasion resistant (AR) steel with a sheet thickness of 6 mm was heat treated by a 4 kW Nd:YAG and a 4 kW Yb:Yag –laser, followed by self-quenching. In the delivered condition, test material blank (B27S) is water quenched from 920 °C. In this condition, fully martensitic microstructure provides excellent hardness of over 500 HB. The test material is referred to AR500 from now onwards. Laser heat treatment was carried out only on top surface of the AR500 sheet: the achieved maximum temperature in the cross-section varies as a function of the depth. Consequently, the microstructure and mechanical properties differ between the surfaces and the centre of the cross-section (layered microstructure). For better understanding, all layers were tested in tensile tests. For a wide heat treatment track, the laser beam was moved by scanning. Temperatures were measured using thermographic camera and thermocouples. Laser heat treated AR500 samples were tested in hardness tests and by air bending using a press brake machine. Microstructures were studied using a light microscope and FE-SEM/SEM-EBSD. At least three kind of microstructure layers were observed: 1) Dual-Phase ferritic/martensitic ($T = A_{C1} - A_{C3}$), 2) ferritic ($T \sim A_{C3}$) and 3) bainitic/martensitic ($T > A_{C3}$).

INTRODUCTION

Ultra-high strength steels (UHS) allow manufacturing of robust lightweight structures. A desirable combination of ultra-high strength, good wear resistance and reasonable formability allow new possibilities for applications in high performance structures and modules, for example, in booms of forest machinery. These applications, however, require good formability, but higher strength often results in reduced formability, as a consequence of decreased toughness. /5/.

By laser heat treatment, it is possible to improve the formability locally, without significant strength reduction /7, 8/. Laser heat treatment is a fast and highly localized process, where the control of the heat distribution is complicated. High heating rate and short holding time produce more likely an ultra-fine grain structure /2/. When annealing thick sheets by single laser beam, microstructure in the cross-section forms nonhomogeneous. Hence, for the sake of clarity, these structures are referred to layered structures from now onwards. In this study the main goal was to investigate how layered structures behaves under tension stress and strain. Study was carried out in two chairs: Laboratory of manufacturing technology (University of Oulu) and The chair of manufacturing technology (University of Erlangen-Nürnberg).

TEST MATERIAL

Test material used was AR500 abrasion resistant steel with sheet thickness of 6 mm. The number of the designation indicates the average Brinell hardness value [HBW]. Test material is boron based low carbon (C~0,3 %) hardened (water quenched) steel grade, with excellent hardness and strength properties. AR500 steel grade has reasonably good formability and it is resistant to abrasion and extreme surface pressure. Test material properties are shown in **table 1**.

TABLE 1. Test Material Properties.

Tensile test results									Hardness test results [HV1]									
AR500									AR500, Average (AVG) ~560 HV								AVG	Depth
Direction	Zwick				Aramis-Camera				587	575	579	575	571	573	557	561	572	Top
					Breakline		50 mm		575	579	585	573	573	555	569	569	572	0.6
	YS	TS	UE	TE	TS	TE	UE	UT	567	567	565	559	563	561	559	552	562	1.2
	[MPa]	[MPa]	[%]	[%]	[MPa]	[%]	[%]	[%]	571	569	565	563	559	573	563	563	566	1.8
45 °	1416	1688	2,9	10,9	2122	47	3,9	10	546	544	544	546	550	548	559	552	549	2.4
Longitudinal	1435	1654	2,8	10,5	2079	39	4,3	10,2	575	581	575	581	579	575	581	587	579	3
Traverse	1385	1687	2,9	10,9	2097	47,5	4	10,7	559	557	559	552	550	550	546	546	552	3.6
									561	563	555	561	561	569	559	563	562	4.2
									546	555	559	557	561	571	561	550	558	4.8
									548	552	559	565	567	563	563	561	560	5.4
									552	544	555	554	557	548	548	550	551	Bottom

EXPERIMENTAL METHODS

4.0 kW diode pumped Yb:YAG disk laser (TRUMPF HLD 4002, **Fig. 1**) with Welding head (Precitec YW50, focal length 300 mm) was used for laser annealing experiments in Finland. Similar 4.0 kW Nd:YAG disk laser was used in Germany. The tensile testing machine used was Zwick Z300 with Aramis-equipments. Microhardnesses was measured by Struers Duramin A300. Hardness profiles and tensile test results were combined with microstructure results for better understanding of the correlation between the microstructure and mechanical properties. Microstructures were analyzed using SEM-EBSD. In addition, forming tests were made using a press brake machine.

Temperature measurements (**Fig. 1&5**) were made using Flir SC7600 Thermographic Camera with NA 3,99 Band pass filter, 2 infrared thermometers and 8 thermocouples (100 Hz) together with LabVIEW 8.6 software. Thermographic camera was used to measure the temperature distribution between the upper and the bottom surfaces. The results from thermographic camera measurements are depended on the emissivity of the surfaces. Emissivity value was set as 1 (black surface), in which case the temperatures measured with thermographic camera and thermocouples were similar. Thermocouples were placed on the bottom surface.

Laser Processing

The target of this study was to change the original quenched microstructure into a more ductile form, in this case to ferritic/bainitic α -phase. Complete phase transformation requires temperature of approximately 900 °C. In the laser process, temperature (heat transfer) is controlled by different parameters. Laser beam was moved by linear path, together with scanning movement (**Fig. 3B**). Spot size (20 mm) and power (4 kW) were constant. Also the scanning parameters (amplitude of 16 mm and frequency of 2 Hz) were not varied. Maximum temperature was varied via different movement speeds (linear speed 2,4 – 3,5 mm/s)

As a consequence of rapid laser austenizing ($A_{r3} + \sim 10$ °C) and short holding time (~ 1 s), the grain growth is prevented, which produces an ultra-fine grain size during self-cooling **/1, 2/**. Higher temperature results in larger austenite grain size, which ease the formation of lath like microstructure during self-cooling **/6/**. Consistently lower temperatures ($< A_{r3}$) leads to incomplete phase transformation, producing either a dual-phase or tempered microstructure. Rapid heating has also benefits to tempering process. Regarding to **/4/**, smaller carbides and more homogenous carbide distribution can be produced by increasing the heating rate. Test parameters are shown in **Table 2**.

FIGURE 1. Test Setup in the City of Nivala, Finland.

FIGURE 2. Laser Heat Treated Samples in Erlangen, Germany.

FIGURE 3. Laser Beam's Movement Paths: A = Linear, B = Scanning & C = Scanning + Maintaining.

TABLE 2. Experimental Test Parameters and Temperature Measurement (Bottom Surface measured by thermocouples) Results (n = 3).

Sample	Power [kW]	Linear speed [mm/s]	Heating rate [°C/s]	T _{max} Bottom surface [°C]
1	4	2.4	48	872
2	4	2.7	47	797
3	4	3	43	727
4	4	3.2	49	719
5	4	3.5	51	682

Material Characterizing

Samples were bent by press brake bending machine (Ursviken Optima M-4721) to estimate the formability of achieved layered microstructure. Hardness and tensile tests, as well as microstructure analysis were carried out to each heat treatment parameter group.

RESULTS AND DISCUSSION

Temperature Distribution

Heat distribution is complicated in the laser process. Laser beam heats up the upper surface very effectively and the heat is then transferred to the bottom surface. This causes a temperature difference between the surfaces. Difference is around 200-300 °C for 6 mm thick sheets, depending on used parameters (measured by thermographic camera). Heating and cooling rates vary also between surfaces. The upper surface heats up approximately twice as fast as the bottom surface. Cooling rate is higher on the upper surface at large temperatures ($T > 600$ °C).

Heat distribution is smoother in the bottom surface (**Fig. 6**) than in the upper surface (**Fig. 4**). Heating history in the upper surface has a wave like form, because of the scanning movement of the laser beam. High peak-temperature in the upper surface causes coarsened grain structure. Depth of the coarsened zone depends on process parameters and sheet thickness.

FIGURE 5. Temperature Measurements.

FIGURE 6. Temperature Profile Comparison between the Upper and Bottom Surfaces.

Microstructure & Mechanical Properties

Temperature difference between the surfaces results in nonhomogeneous phase structure in the cross-section of the heat treated zone. Different kinds of layered microstructures were produced to understand the possibilities of layered structures. Microstructure layers were analysed using SEM-EBSD. Hardnesses were measured with 0.5 mm steps from the cross-section. Microstructure images were then combined with hardness profiles (**Fig. 9 & 10, table 3**).

Tensile tests were carried with Zwick300 tensile test machine. Elongations were measured by Zwick's own motion sensor and using Aramis camera system. Aramis software was used to calculate the maximum stress and elongation in the breakline and in addition, average values from 50 mm distance around the breakline. Two types of tensile test specimens were used: 1) Samples with complete sheet thickness of 6 mm (**Fig. 8**) and 2) samples milled to separated layers (**Fig. 7**). Tensile test results are shown in **table 4**.

In the laser process, laser radiation heats the sheet rapidly to phase transformation temperatures. After annealing, continuing cooling takes place with moderate cooling rate. Fine grain size of austenite and continuing cooling transforms the austenite into a ferritic-bainitic or bainitic-martensitic microstructure (**Fig. 9**). Fraction of lath like bainitic-martensitic structure becomes larger, when austenizing temperature is raised due to grain growth. Due to temperature peak on the upper surface, bainite and martensite form easily to upper surface, even if the microstructure is ferritic-bainitic elsewhere in cross-section. Respectively, if ultra-fine ferritic-bainitic microstructure is produced to upper surface, incomplete transformation (**Fig. 10**) takes place on the bottom surface (depending on temperature, also in the centre of cross-section). In which case the microstructure produced is mainly tempered martensite.

TABLE 3. Color Palette used in Hardness Tests (Heat Treated Samples).

521-540	501-520	481-500	461-480	441-460	421-440	401-420	381-400	361-380	341-360	321-340	301-320	281-300	260-280

FIGURE 9. Hardness Profile and Microstructure in Different Layers (Sample 2). Layered Tensile Test Specimens are Marked with Blue Arrows (Upper, Center and Bottom).

FIGURE 10. Hardness Profile and Microstructure in Different Layers (Sample 5). Layered Tensile Test Specimens are Marked with Blue Arrows (Upper, Center and Bottom).

Hardnesses of the upper surfaces (bainitic-martensitic structure) were around 450 – 490 HV in every sample (softening 12 - 20 %-unit). In these cases, the yield strengths varied between 903 MPa (Sample 1) – 1004 MPa (Sample 3) and tensile strengths between 1265 MPa (Sample 1) – 1538 MPa (Sample 4). Finest bainitic-martensitic structure can be seen on samples 2-5, but the fine grained layer is located in different depths, depending on heat treatment parameters (temperature distribution). This kind of microstructure provided the best mechanical properties (softening 7 % [HV]). Sample 4 & 5 were made by using relatively fast laser beam movement speed. In this case, fine bainitic-martensitic layer was formed near the upper surface. With slower movement speed (Sample 2), layer was formed deeper, to the center of the cross-section. With the slowest speed (Sample 1), microstructure was coarsened through the cross-section. These microstructure observations correlate closely with tensile test results (**Table 4**).

Strongest softening (up to 47 %-unit [HV]) was observed from tempered structures (Sample 4 & 5). In this case, the lowest yield strength was 671 MPa and tensile strength 895 MPa. On the Sample 5, the tempered microstructure covered over half of the cross-section.

The microstructure and mechanical properties in Sample 2 were the most homogenous. When the laser beam movement speed was increased or decreased, the difference in hardness values and microstructure homogenous between the upper and bottom surfaces increased, because only limited zone of material reached the phase transformation temperature.

Elongation values measured from the layered tensile test specimens were lower than the ones measured from normal specimens. This may be because of the milling process or due to material flow differences. More research is needed to understand the behavior of layered steel sheets.

TABLE 4. Mechanical Properties of the Laser Heat Treated Samples.

Laser heat treated AR500 6 mm															
Zwick				Aramis				Zwick				Aramis			
				Breakline		50 mm						Breakline		50 mm	
YS	YT	UE	TE	YT	TE	UE	UT	YS	YT	UE	TE	YT	TE	UE	UT
[MPa]	[MPa]	[%]	[%]	[MPa]	[%]	[%]	[%]	[MPa]	[MPa]	[%]	[%]	[MPa]	[%]	[%]	[%]
Sample 1: Bottom surface (t = 2 mm)								Sample 3: Average values of layered samples							
983	1465	3.1	6.9	1577	27	4	6.8	894	1406	5.2	9.3	1650	24.2	6	8.7
Sample 1: Center (t = 4 mm)								Sample 3: Normal specimen (t = 6.3 mm)							
1032	1544	4	9.7	1818	35	5.1	9.1	880	1399	6.6	14.8	1782	37.2	7.5	14.3
Sample 1: Upper surface (t = 2 mm)								Sample 4: Bottom surface (t = 2 mm)							
903	1265	2.5	5.9	1396	26.6	3.5	6.1	676	948	6.7	9.8	1215	31.2	7.7	11.5
Sample 1: Average values of layered samples								Sample 4: Center (t = 4 mm)							
973	1425	3.2	7.5	1597	29.5	4.2	7.3	789	1317	6.8	11.6	1604	25.8	7.2	10.3
Sample 1: Normal specimen (t = 6.3 mm)								Sample 4: Upper surface (t = 2 mm)							
954	1420	4.3	12.3	1736	45.5	4.9	11.8	973	1538	3.9	7.8	1677	24.8	4.8	7.5
Sample 2: Bottom surface (t = 2 mm)								Sample 4: Average values of layered samples							
904	1338	4	7.7	1552	27.1	4.8	7.9	813	1268	5.8	9.7	1499	27.3	6.6	9.8
Sample 2: Center (t = 4 mm)								Sample 4: Normal specimen (t = 6.3 mm)							
973	1562	4.4	10.3	1898	34.7	5.2	9.5	859	1352	6.2	13.4	1660	31.4	7	11.8
Sample 2: Upper surface (t = 2 mm)								Sample 5: Bottom surface (t = 2 mm)							
938	1390	2.7	6	1491	28.1	3.3	5.7	775	895	5.8	9.7	1080	42.8	6.9	11.6
Sample 2: Average values of layered samples								Sample 5: Center (t = 4 mm)							
938	1430	3.7	8	1647	30.0	4.4	7.7	671	1088	7.5	11.6	1290	23.3	7.5	10.7
Sample 2: Normal specimen (t = 6.3 mm)								Sample 5: Upper surface (t = 2 mm)							
948	1471	4.8	12.8	1846	43.6	5.5	12	932	1453	4.8	8.5	1752	30.9	5.5	8.2
Sample 3: Bottom surface (t = 2 mm)								Sample 5: Average values of layered samples							
771	1265	7.1	11.1	1554	25.5	8	10.9	793	1145	6.0	9.9	1374	32.3	6.6	10.2
Sample 3: Center (t = 4 mm)								Sample 5: Normal specimen (t = 6.3 mm)							
906	1438	5.9	11.1	1699	21.6	7	10.1	695	1172	6.5	12.9	1428	27.8	7.2	11.3
Sample 3: Upper surface (t = 2 mm)															
1004	1515	2.6	5.8	1696	25.4	3	5.1								

Bendability

Test plate dimensions were 150 mm x 300 mm. Laser heat treated samples were bent by using various punch radii (dependent on bendability) and lower die with 45 mm V-gap. The criterion for bending radius was to achieve undamaged bent. Final bending tests were made by a single punch radius per material, repeating the test 5 times to each surface. Bending direction was perpendicular to rolling direction in every test and the final bending angle was 90 degrees. The test materials were bent into both sides of the plate, so that both sides of the sheet were tested as an inner and outer

bend. All the bends were checked visually for cracks on the outer bend and edges. Bending test results are shown in **table 5**.

Best bendability was observed, when the material was completely austenized (Sample 2). Sample 2 was the hardest and strongest and had best bendability with superior minimum bending radius of 10 mm. In this case, the ratio between bending radius and sheet thickness is 1.5. When comparing this value with the ratio of the base material (1.5/9), laser heat treatment provided 500 %-unit better bendability without significant strength loss. Strain hardening during bending process compensates the strength loss even more. No significant differences were observed between the upper and bottom surfaces. It can be pointed out, that upper surface had slightly better bendability (Sample 2).

Laser austenizing and moderate cooling rate produced very fine grained ferritic-bainitic microstructure. Bendability did not correlate with the measured elongation values. The effect of the microstructure seems to be the most significant. It is well known, that the phase structure, microhardness deviation, grain size and shape, have a great influence to the bendability [3].

TABLE 5. Minimum Achieved Bending Radii.

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Base material
Min. Bending radius	R16	R10	R14	R14	R18	R60

CONCLUSIONS AND OUTLOOK

In this study, 6 mm thick boron steel was heat treated with excellent results. When heating up 6 mm thick sheet to phase transformation temperatures with single laser radiation source, temperature difference between the surfaces is around 200 – 300 °C. Due to temperature difference, the microstructure in the cross-section of the heat treated zone becomes nonhomogenous. Rapid heating up produced ultra fine grain size during cooling. After laser heat treatment (Sample 2), bendability increased 500 %-unit, when the softening was only 12 - 13 %-unit (tensile strength / hardness). The amount of softening is almost completely compensated after forming, due to strain hardening. Elongations measured using tensile tests, where not significantly increased ($A_g = 38 - 60$ %-unit and $A_t = 16 - 20$ %). Results indicate, that the ultra fine layered microstructure behaves extremely well under bending process.

Future research is focused to vehicle industry applications. The lack of formability has been limiting the use of ultra high strength steels in such applications, where good formability is needed (bending, deep drawing etc.). Tailored ultra high strength steel with yield strength of 950 MPa, tensile strength 1470 MPa and excellent bendability opens up new possibilities to achieve robust, lightweight constructions. In addition excellent strain hardening properties allows use in safety parts due to high impact absorption. First aim is to produce a beam for example for a forest harvesting machine with presented method. Later, heat treatments are carried to out to thinner boron steel sheets (~2 mm), looking out for light vehicle applications.

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