Tribological behaviour of line hardening of steel U13A with Nd:YAG laser(•)

R. Sagaro(*), J.S. Ceballos(*), J. Mascarell(*) y A. Blanco(*)

Abstract To diminish wear in tribological systems is frequently to harden locally the load carrying areas, which are subjected to wear. A Nd:YAG laser was used for the improvement of hardness and wear resistance of steel U13A. The friction and wear characteristics of steel U13A in sliding contact against steel 65MN4 under unlubricated conditions were evaluated for conventional treatments and after laser irradiation. In addition the transformations occurring during laser treatments and the influence of laser parameters for quenching on tribological characteristics are presented. The experimental work indicates that wear resistance of steel U13A (AISI W112) is several times higher then that for conventional heat treatments.

Keywords: **Laser line hardening. Surface treatment. Tribological behaviour**

Comportamiento tribológico del acero U13A con endurecimiento localizado mediante láser de Nd:YAG

Resumen Para disminuir el desgaste en los sistemas tribológicos frecuentemente se llevan a cabo endurecimientos localizados en aquellas áreas sometidas a esfuerzos y que están sujetas a desgaste. En el trabajo se presenta el endurecimiento y el incremento de la resistencia al desgaste del acero U13A, empleando un láser de Nd:YAG. Se evalúan las características de fricción y desgaste del acero U13A en contacto deslizante con el acero 65MN4 bajo condiciones de fricción seca para muestras con tratamientos térmicos convencionales y luego del tratamiento con láser. Se presentan además las transformaciones estructurales que tienen lugar durante el tratamiento con láser, así como la influencia de los parámetros operacionales del láser en las características tribológicas. Todo el trabajo experimental muestra un incremento de la resistencia al desgaste del acero U13A (AISI W112) con tratamiento térmico superficial con láser comparativamente con los tratamientos térmicos convencionales.

Palabras clave: **Endurecimiento con láser. Tratamiento superficial. Comportamiento tribológico.**

1. INTRODUCTION

The laser surface treatment of metallic materials has received great attention (1, 2 y 3) and presents advantages in relation to conventional treatment methods. By means of laser treatment of steels, a wide range of microstructures can be obtained. In most cases, the treatments result in considerable wear resistance improvement of the treated steel while maintaining a satisfactory bulk toughness. U13A steel is used to many handle agriculture tools like files. Cuba is using per year about one million of units and has to import the 90 % from Spain and Japan because the low wear resistance of file PM-200C/A made by U13A steel, annealing, grinding and quenching up to 61 HRC (735 HV). The present study covers the effects of laser parameters on the U13A microstructure and tribological performance.

2. MATERIALS AND METHODS

All the experimental study was performed with U13A steel that presents a perlitic matrix microstructure. Table I shows chemical composition, microstructure and hardness of samples (Fig. 1).

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TABLE I.— Chemical composition of steel U13A

TABLA I.— Composición química del acero U13A

Denomination	Composition	Microstructure	Hardness (HV)
U13A	1.25-1.35 % C, 0.15-0.35 % Mn, < 0.15 % Cr	Globular perlite	224

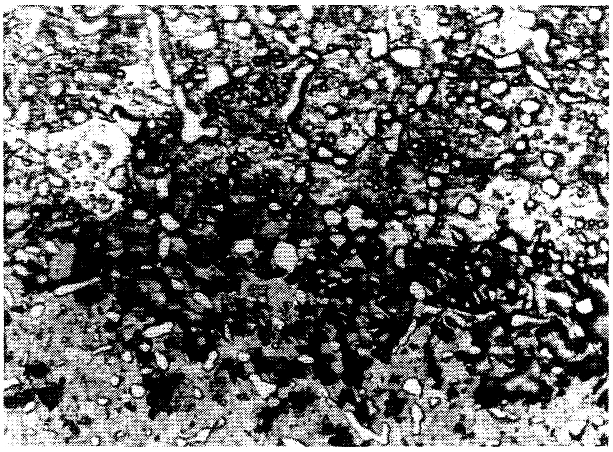

FIG. 1.— Microstructure before treatment with laser of U13A.

FIG. 1.— Microestructura del acero U13A antes del tratamiento láser.

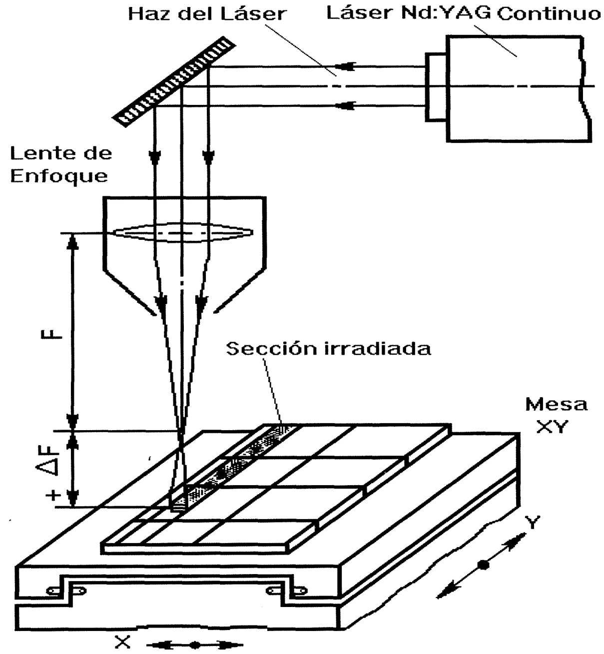

FIG. 2.— Experimental device.

FIG. 2.— Instalación experimental.

The treatment was carried out with a Nd:YAG laser. Figure 2 shows laser device LTI 702. Ranges of operations conditions are show on table II.

The method of measuring each of the variables was as follows:

- Total laser power: The output power from the laser was stable enough over extend time periods to makes measures satisfactory. Measurement was realised by an ENLING powermeter with a accuracy of 0.1 W. The output powers chosen for the experiments were 100, 80 and 60 W.
- Incident beam diameter: This parameter was found to be the most difficult to measure. Many techniques have been employed to measure the beam diameter. The technique used here is the “charring paper” (4). The values chosen for the beam diameters were: 1.6, 1.1 and 0.6 mm.
- Traverse speed: The velocity of the x-y table beneath the stationary laser was measured electronically. The accuracy of measurement of the relatively speeds used here was ± 0.5 %. The speeds chosen for the experiments were 1.5, 1.25 and 1 mm/s

TABLE II.— Laser device parameters of LTI 702

TABLA II.— Parámetros operacionales del equipo láser LTI 702.

Wave length = = 1,060 nm	Power range: $0 \div 120$ W
Diameter = 3 mm	Régimen de trabajo: continuous
Divergence = $= 2 \cdot 10^{-3}$ rad	Power beam guarantied: 120 W
Mode: TEM_{01}	

A microhardness tester SHIMADZU performed studies of microstructural examination and microhardness. Parallelepiped samples of 40 mm × 10 mm × 5 mm of U13A steel were used on microhardness and metallographics studies. The treatments were carried out with a single sweep of the laser beam along the longitudinal axis of the 45 mm × 10 mm faces which were previously spray covered with mat black paint.

In this series of experiments only the laser power, beam diameter and traverse speed were varied and correlated with the resulting depth of hardening and microstructure. It is well know that the surface hardening of certain steels is possible through a martensitic structure produced by a rapid cooling from an elevated temperature, provided by the laser power P, beam diameter D and scan speed V within certain limits, so the experiments were arranged statistically to guarantied the reproducibility of hardness traces.

To prove favourable effect on friction and wear behaviour test were performed in a block-cylinder tribometer. The load applied on the contact zone to compute friction coefficient between the two specimens caused a Hertzian effective test compression of 40, 80 and 100 MPa respectively. Wear test was carried out at contact pressure (σ_c) of 100 MPa. Wear was measured to compare the weight losses of specimens with laser treatment and heat conventional treatments. Table III shows materials of block and cylinder respectively.

The roughness measurements were performed by means of SURFTEST rugosimeter. Chemical composition of steel 65 Mn4 was as follows:

C = 0.62-0.64 %, Si = 0.307-0.318 %,
Mn = 1.02-1.03 %, P = 0.02-0.021 % and
S = 0.005-0.006 %.

3. RESULTS

3.1. Depth of hardening and microstructure examination

Table IV shows the results of experiments.

Matemathical analysis of experimental work demonstrated that the main effects of each variable have not a stronger influence by separated than the influence of the interaction between then, as is reported by Steen and Shang (5,6), so in opinion of authors (7) the parameter

$$\frac{P}{\sqrt{d \cdot V}}$$

TABLE III.— Materials for friction and wear studies

TABLA III.— Materiales para los ensayos de fricción y desgaste

Specimens	Dimensions (mm)	Materials	Surface roughness *Ra* (μm)
Cylinder	Δ 40 × 12	65MN4 steel, quenching, 54-52 HRC (593-548 HV)	6.5
Block	10 × 10 × 12	U13A steel quenching under different conditions: • Samples 1-9 treatments with laser HV = 1,379-842 • Samples 10 quenching on salts and tempering HV = 868 • Samples 11 quenching on salts HV = 1,022-941 • Samples 12 quenching by high frequency and tempering HV = 941-868 • Samples 13 quenching by high frequency HV = 941	0.8-0.9

TABLE IV.— Parameters and results of experiments

TABLA IV.— Parámetros y resultados de los experimentos

Nº	P	V	Dr	PE	HV	$V \cdot Dr$	$\sqrt{V \cdot Dr}$	$\frac{P}{\sqrt{V \cdot Dr}}$
1	60	1.00	0.60	0.11	966.0	0.6	0.77	77.46
2	100	1.00	0.60	0.26	1,379	0.6	0.77	129.10
3	60	1.50	0.60	0.07	1,449.0	0.9	0.95	63.25
4	100	1.50	0.60	0.19	1,300	0.9	0.95	105.41
5	60	1.00	1.60	0.02	959	0.9	1.26	47.43
6	100	1.00	1.60	0.07	851	1.6	1.26	79.06
7	60	1.50	1.60	0.02	1,033	1.6	1.55	38.73
8	100	1.50	1.60	0.04	926	2.4	1.55	38.73
9	80	1.25	1.10	0.06	1,072.0	1.4	1.17	68.22

has the strongest influence on depth hardening.

The fit of the average of the three replications per experiments against this parameter was examined by the least-squares method. The result was:

$$PE = 0.0029 \cdot \left(\frac{P}{\sqrt{V \cdot Dr}} \right) - 0.1136 \qquad [1]$$

The standard error on PE was ± 0.0514 and the correlation coefficient was 0.8539, a very good fit considering the results obtain by Steen.

The influence of operating laser parameters can analysed as follows. The traverse speed influence was found as negative on depth of hardening (PE), it means that an increase of speed (V), decrease PE as a consequence of a shorter interaction time (t) and thermal gradient (ΔT) is not so sufficiently higher to penetrate into substrate at depths.

The same influence is produced by incident beam diameter. An increase of Dr produce a decrease of PE as a consequence of a diminish of power density. However, an increase of laser power, increase surface power density and by this way the depth of hardening will be reach the higher depth in this kind of heat treatment.

An important result is microhardness obtain on ZAC, superior to 1,000 HV at a depth of hardening of 260 µm.

Figure 3 shows the graphical dependence between microhardness and depth of hardening for the best conditions on experiences (P = 100W, V = 1 mm/s and Dr = 0.6 mm).

The microstructure examination was carried out on Research Centre of Nuclear applied studies. This examination shown an affected area with fourth zones quite defined (Fig. 4).

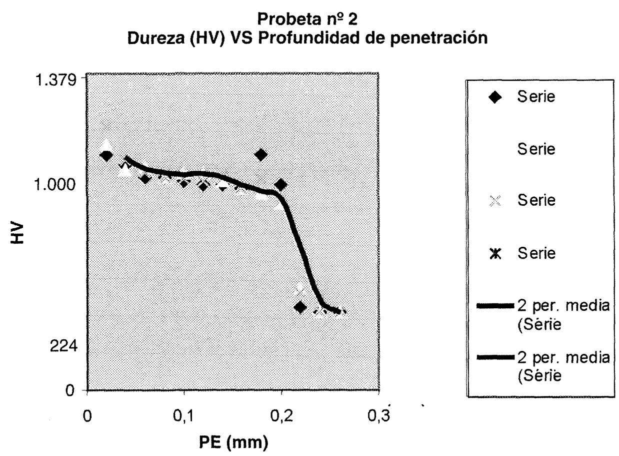

FIG. 3.— Dependence between microhardness and depth of hardening.

FIG. 3.— Variación de la microdureza con la profundidad del endurecimiento.

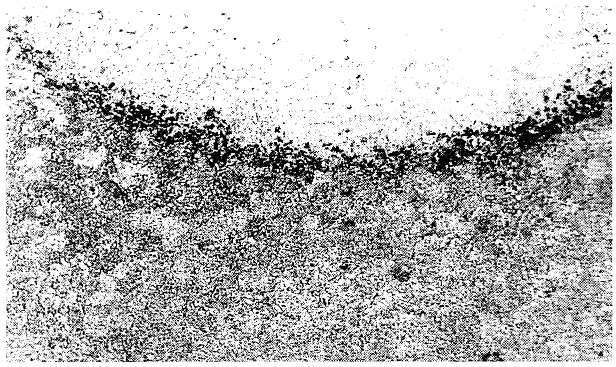

FIG. 4.— Cross section of U13A after treatment.

FIG. 4.— Sección transversal del acero U13A después del tratamiento.

The microstructure examination after laser treatment shown on samples with martensite transformations a fine grain of martensites on surface zone. That zone is coinciding with incident beam diameter an its approximately the 50 % of ZAC with microhardness of 1,283-927 HV. A quite defined zone is under martensite zone with martensite not so fine and perlite (thermal influence zone). The microhardness of this zone is about 857-733 HV. There is another zone (transition zone) where we find perlite, trostite and martensite with microhardness of 425 HV. Finally on substrate appears perlite with a microhardness of 224 HV.

3.2. Friction and wear tests

A conventional tribometer MEFD block-rotating wheel was used for tribological test under dry conditions. All the experiments were carried out under a sliding speed of 0.8 m/s and for 2,400 cycles (1 h). A friction experience was realised with increasing of contact pressure of 40, 80 and 100 MPa respectively. The contact line block cylinder is across sweep of laser beam. Contact pressure used in wear test was σ_{max}, as formula:

$$\sigma_{\text{máx}} = 0,564 \cdot \left[\frac{P^1}{R \cdot \left(\frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2} \right)} \right]^2 \qquad [2]$$

$$P^1 = \frac{Fn}{l} \qquad [3]$$

Where: Fn : Normal load.
E_1 y E_2 : Elasticity modules of block and cylinder.
μ_1 y μ_2 : Poisson's coefficient of each material tested.
l : Length of contact zone.
R : Outer radius of cylinder.
An : Apparent contact area An = 0.634 mm^2.

Tables V and VI show the results of wear test.

To appreciate the best condition of treatment authors introduce the coefficient

$$K = Wgc/Wgp$$

where: Wgc : Weight loss of cylinder.
Wgp : Weight loss of block.
Wh : Linear wear (mm)
1-9 : Samples with TTSL.
10-13 : Samples with conventional treatments.

Mathematical dependence between wear and operations parameters of laser of U13A steel could be express by following formula according simple analysis regression:

$$W = 0.0177\,(V.Dr) - 1.68 \cdot 10^{-4}\,(P \cdot Dr) - 0.039 \quad [4]$$

Using these arguments it can be concluded that those parameters of laser operating that cause an improvement of depth hardening and a high surface hardness produce an increase of wear resistance of U13A steel on sliding with 65MN4 steel. Because on files its necessary to guarantied a high wear resistance and to produce a abrasion on cutting tool

TABLE VI.— Gravimetric wear. Conventional heat treatment $Wg \cdot 10^{-4}$ (g)

TABLA VI.— Desgaste gravimétrico. Tratamientos térmicos convencionales $Wg \cdot 10^{-4}$ (g)

Sample	Cylinder	Block	$K = Wgc/Wgp$
	$Wgc \cdot 10^{-4}$ (g)	$Wgp \cdot 10^{-4}$ (g)	
10	108	25	4.3
11	47	7	6.7
12	124	62	2
13	103	93	1.1

for conventional heat treatments the best performance were presented by samples with quenching on salts without tempering according with coefficient K established by authors (K = 6.7), so the representative behavior of exit are presented by laser treated materials with conditions 1, 2, 3, 4 and specially case 2 with higher power beam and low traverse and spot diameter (K = 26).

Those cases with laser treatments, however, presented a poor wear resistance performance, it was caused by an insignificant depth of hardening and a rapid destruction of the hardened layer during the experiences (8). From tables IV and V, it can be seen that in cases 1, 2, 3 and 4, linear wear does not excess the depth of hardening (PE) and the effect of hardening produces an increase of wear resistance, while in samples 5, 6, 7, 8 and 9 the hardened layer was destroyed and the existence of others metallurgical microstructures with a low wear resistance in comparison with martensitic microstructure (perlite,

TABLE V.— Gravimetric wear $Wg \cdot 10^{-4}$ (g) TTSL

TABLA V.— Desgaste gravimétrico $Wg \cdot 10^{-4}$ (g) TTSL

Sample	Cylinder	Block	Block	$K = Wgc/Wgp$
	$Wgc \cdot 10^{-4}$ (g)	$Wgp \cdot 10^{-4}$ (g)	Wh (mm)	
1	63	5	0.09	11.3
2	79	3	0.06	26
3	42	2	0.04	21
4	58	7	0.14	8.2
5	21.3	100	2	0.21
6	51	21.4	0.42	3.6
7	41	293	3.8	0.15
8	78	27	0.54	2.9
9	72	46.8	0.94	1.8

trostite, etc) produce a high wear. Soft substrates are able to increase wear too. This reason justifies the proposition of some researches about pre-treatments.

One of the most contradictory aspects is related to overcastting bands (9, 10). The experiences of the authors at this point is to consider a negative influence by the tempering effect that produce microstructural changes not to able with wear resistance. Figure 5 shows microhardness on treated bands with and without overcastting.

From table VII it can be seem the friction coefficient behavior for laser treated materials and conventional heat treatments used under contact pressure of 40, 80 and 100 MPa.

Where: 1-9 : Samples with TTSL.
10-13 : Samples with conventional treatments

It can be seen from table VII that in both cases (with and without laser treatment) the friction coefficient have a similar behavior. It shown tentatively a tendency to increase its value with contact pressure and finally falls for Pc = 100 MPa. However there is a difference between laser treated materials and conventional heats because in all range of contact pressure the lowest values of friction coefficient were presented by samples with laser processing.

The variation between maximum and minimum dry friction coefficient of the U13A / 65MN4 steel was very large and indicating in our opinion the existence of stick-slip phenomenon.

4. CONCLUSIONS

An experimental and a mathematical models of surface hardening have been derived and compared with a factorial set of experiments with the following results:

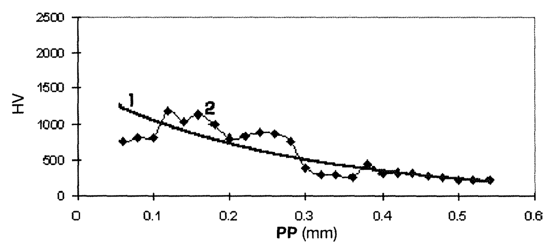

FIG. 5.— Microhardness vs. depth of hardening for a single sweep of laser beam (1) and a overcastting band (2).

FIG. 5.— Relación microdureza vs profundidad del endurecimiento para una simple pasada (1) y un cordón solapado (2).

TABLE VII.— Coefficient of friction (f) variation with contact pressure

TABLA VII.— Variación del coeficiente de fricción con la presión de contacto

Sample	*f*		
	Contact pressure Pc (MPa)		
	40	80	100
1	0.28	3	1.58
2	0.41	2.1	1.07
3	0.62	3	1.37
4	0.76	2.8	1.33
5	0.69	2	1.16
6	0.56	2.3	1.27
7	1.01	2.2	1.87
8	0.73	2.6	1.26
9	0.89	2.5	1.38
10	1	2.67	2
11	0.76	3.3	2.13
12	0.92	3.4	2.13
13	1.06	3.42	2.7

- The depth of hardening was found to be linearly related to the parameters $\frac{P}{\sqrt{D \cdot V}}$, as suggested by Steen and Courtney. Influence of power beam was favourable to produce the highest depth of hardening. An increase of speed run and incident beam diameter has a negative influence in this aspect.
- Metallurgical studies suggested four zones quite defined: a total martensite zone with fine grains, a martensite + perlite area, a martensite + trostite + perlite and finally the microstructural base material with a perlite zone. All of these metallurgical structures have different aptitude in wear conditions.
- Mathematical model obtained shown that those parameters that conditioned the higher depth of hardening bands presented low wear. Coefficient K gave the most favourable wear resistance to laser treated materials (conditions of laser operations 1, 2, 3 and 4) comparatively with conventional heat treatments.
- The overcasting bands produce a non-desirable microstructures and a diminish of hardness that do not improves wear resistance.

– Friction coefficient behaviour have the tendency to increase its value with contact pressure and later falls for all treatments tested. In all contact pressure ranges, laser treated materials shown a lower friction coefficient than conventional treatments.

REFERENCES

(1) AMENDE, W. *Laser surface treatment, transfer of scientific result to practical: Laser treatment of material.* Edited by Barry, L.M., 1986:

(2) ECKERSLEY, J. *Laser applications in metal surface hardening: Advanced surface treatments.* Pergamon Press, 1984:

(3) DAMBORENEA, J.J. DE *Rev. Metal. Madrid*, 26 (4), 1990: 247-253.

(4) STEEN, W. *Laser Processing Material.* Springer-Verlag. London, 1991:

(5) STEEN, W. *Met. Technol. N. Y.*, December 1979: 456.

(6) SHANG, H. *J. Mater. Processing Technol.* 23, 1990: 119.

(7) SAGARO et al. *Rev. Metal. Madrid* 34 (2),1998: 140-143.

(8) RUIZ, J. et al. *Materials & Design*, 17(5/6), 1996: 267.

(9) GNANAMUTHU, D. *Laser –solid interactions and laser processing-1978.* American Institute of Physics, 1979.

(10) VISCHER, H. *The influence of laser line hardening of carbon steel AISI 1045 on lubricated wear against steel AISI 52100.* Proceeding of Wear of Materials Conference, EU.1995.