DC PLASMA JET HEATING OF A ROTATING CYLINDER : MODELING AND MEASURING

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Abstract

This paper concerns the utilization of a DC plasma torch to achieve surface transformation hardening of steel after localized heat treatment. A method was developed to determine the heat transfer of the jet. This method is based on the minimization of the difference between the measured surface temperature of a rod of steel revolving at high speed and that calculated thanks to a 2 D model. A computer code has been written to solve numerically the heat equation for the rod. In the modeling, the heat transfer was described according to Newton's law (that is to say as the product of an heat transfer coefficient by the difference between plasma temperature and surface temperature of the rod). After the measurement of plasma temperature by emission spectroscopy, the pre-cited minimization was achieved by adjusting the other parameters related to heat transfer (heat transfer coefficient, radius of the plasma impinging the material) entered as boundary conditions in the calculation. The calculation of the temperature field in the rod allowed to estimate the hardness of the steel and heat affected zones which were compared to measurements.

1. Introduction

Surface transformation hardening of ferrous materials is an established process widely used to enhance their mechanical properties [1,2]. Induction and flame heating are the main technologies used in industry, but new processes involving electron beam [3, 4, 5], laser [5, 6] or plasma jet can be used [7, 8, 9]. The potential of a DC plasma torch similar to a plasma spray torch has been established earlier on samples of 36 NiCrMo 16, 35 CrMo 4, 50 CrVa 4 steels and perlitic globular cast iron [10]. But, the control of process suppose the capability to correlate heating parameters to the resulting metallurgical structures and to be able, at least, to foresee the treatment of any hardenable steel component. So, a method was developed to characterize the heat transfer. This method was conceived to enable, not only the characterization of heat transfer and the influence of heating parameters, but also to check its outcomes by the comparison between predicted metallurgical results and measurements.

2. Characterization of heat transfer

2.1 Principle of the method

The method is based on the minimization of the difference between the measured surface temperature of steel samples and that calculated thanks to a model. A detail of the method is given in [11]. Our modeling is related to the plasma heating of a cylindrical sample of 36 NiCrMo 16 steel revolving at high speed (400 rev/s). Thus, the energetic system studied can be illustrated by *Figure* 1 below.

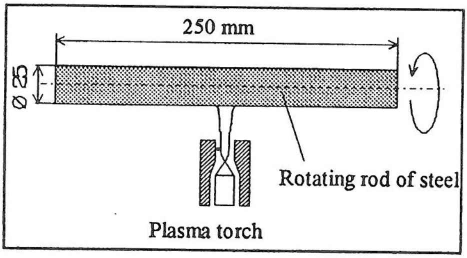

Figure 1 : Configuration of heating studied

So, the rod is submitted to radiative and convective heat transfer with the plasma jet impinging its surface and with the surrounding atmosphere. In that configuration, the temperature of the plasma near the surface can be measured above 7000 K in the laboratory by emission spectroscopy [12].

2.2 Modeling the rod

The distribution and the evolution of the temperature in a rod during a plasma heat treatment have been calculated by solving numerically, using the controlled volume method, the heat equation in transient state. Considering the high speed of revolution, the system was solved in two dimensions. In that case, an axial symmetry is to be respected, and the heat transfer from the plasma is assimilated to a ring surrounding the rod. In the calculation, we have taken into account the variable thermal properties of the steel which were issued from Dardel [13]. To simplify the problem, the shifts in temperature of the properties due to the kinetic of the phase transformations were neglected. The grid spacing was variable in order to be narrower in the zones submitted to important gradients of temperature. The heat transfer with the surrounding atmosphere has been evaluated according to semi-empirical relationships from Wong [14]. A computer code has been written in HP Basic language to achieve the calculations.

2.3 Modeling the heat flux of the plasma

Let Ψ (W/m^2) be the heat flux density transmitted by the plasma jet.

In the model, we have described, the heat transfer using a heat transfer coefficient according to Newton's law :

$$\Psi = h \cdot (T_{plasma} - T_{rod}) \quad (1)$$

Where h (W/m².K) is the heat transfer coefficient, T_{plasma} (K) the plasma temperature near the surface, T_{rod} (K) the surface temperature of the material.

The heat transfer coefficient mentioned above does not presuppose the nature of the phenomena and includes convective and radiative exchanges, the effect of the latter being very probably much less important in our case. We have considered the heat flux of the plasma as the integral, on the impact area of the jet, of the product of a constant heat transfer coefficient with the difference between the spatially variable plasma temperature and the surface temperature. This heat flux is represented *Figure 2.*

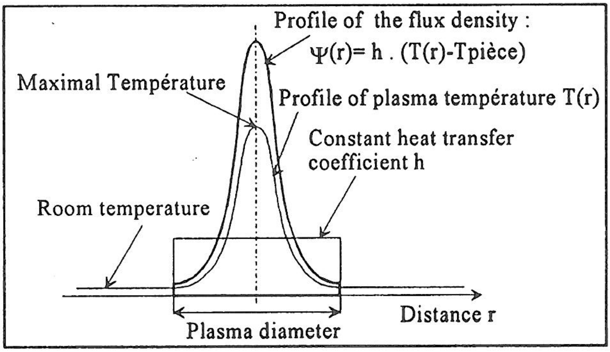

Figure 2 : Representation of the heat flux considered in the model

A plasma jet being axisymmetrical, we have defined the temperature of the jet as an analytical function depending on the distance r at the axis of the jet. So, we have set :

$$T_{plasma}(r) - T_{room} = T_{max.\ plasma} \cdot \left(1 - \left(\frac{r}{R_{plasma}}\right)^2\right)^2 \quad (2)$$

Where $T_{max.\ plasma}$ is the maximal temperature of the plasma, T_{room} the room temperature, R_{plasma} the radius of the plasma jet at the impact.

Finally, the heat flux can be written as follow :

$$\Phi = h \cdot \int_{\text{Impact area}} \left(T_{plasma} - T_{rod}\right) \cdot dS \quad (3)$$

The small dimension of the plasma plume compared to the diameter of the rod led us to neglect the curvature of the surface and we calculated the heat flux as if it impinged a plane surface. Finally, in our model, the heat flux parameters are the plasma radius at the impact, the heat transfer coefficient, and the maximal temperature of the plasma.

2.4 *Experimental study*

2.4.1 Heating parameters

In order to study the effect of different parameters, several experiments were performed by varying some parameters. The heating conditions were as follow :

- nozzle diameter = 7 mm,
- plasma gas composed of 75 % vol. of argon and 25 % vol. of hydrogen,
- total flow rate of 40, 50 and 60 Nl/min,
- arc current intensity of 130, 200 and 250 Ampere,
- distance between the nozzle and the rod of 16, 21, 26 and 31 mm

2.4.2 Measurements of temperatures

An experimental set up was designed to allow the measurements both of the plasma temperature and of the temperature of the rod. The surface temperature measurements of the rod were performed by using a bichromatic pyrometer. The operating range of this equipment is 0.8 to 1.06 µm in wavelengh for a temperature range of 700 to 1400 °C. The pyrometer was placed on the same axis of the jet but on the opposite side of the rod. The measured zone was 4 mm in diameter. The temperature measurements of the plasma jet were performed near the surface of the rod by emission spectroscopy. The apparatus used is described elsewhere [12].

2.5 *Results*

2.5.1 Determination of heat flux parameters

For every heat condition, after the measurement of the plasma temperature, the other parameters related to heat transfer (heat transfer coefficient, radius of the plasma jet impinging the material) have been determined by adjusting their values, entered as boundary conditions in the calculation. An example of calculated temperature compared with measured temperature is illustrated in *Figure 3*.

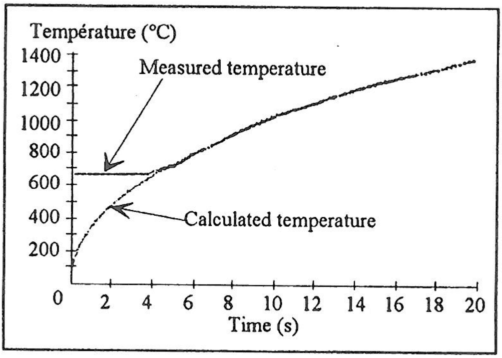

Figure 3 : Comparison between calculated and measured temperatures

So, the modeling yielded to the determination of the heat tranfer coefficient for each working condition. Thus, the influence of the different heat parameters could be established on the intensity of heating *(see for example Figure 4)* and the dimension of the impact area.

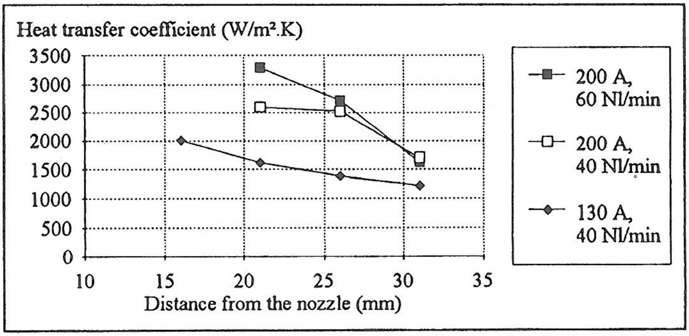

Figure 4 : influence of heating conditions on the heat transfer coefficient

2.5.2 Comparison between results obtained and predicted by the model

Thanks to the determination of the temperature field within the material, we have estimated the depth an shape of the heat affected zones, *i. e.* the zones which have reached the temperature of the beginning of the austenitic phase transformation. The estimations showed a good correspondance with metallurgical observations [11]. A good correlation was also observed between the measured and estimated hardnesses as it is shown in *Figure 5*.

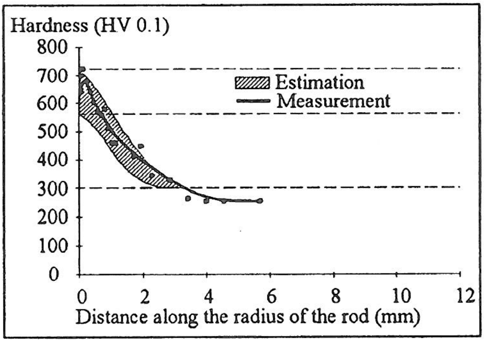

Figure 5 : comparison between estimated and measured hardnesses

3. Conclusion

A method was developed to characterize the heat transfer between a DC plasma jet and a rotating rod of steel. The principle of the method is to minimize the difference between the measured surface temperature of the rod and that calculated thanks to a numerical 2 D model. For different experimental conditions, after the measurement of plasma temperature by emission spectroscopy, the minimization led to the determination of the heat transfer coefficient and the radius of the plasma jet at the impact by adjusting their values, entered as boundary conditions in the calculation. The influence of several working parameters on the heat transfer was studied. The modeling also allowed the prediction of heat affected zones and the determination of the corresponding hardnesses of samples, which were in good agreement with measurements. It appears that the data of the heat transfer established by our method are representative and can be used to foresee surface hardening treatments with a plasma torch on various steel components.

References

[1] Metals Handbook, 9th edition, volume 4 : "Heat treating", American Society for Metals, Metals Park, Ohio, USA.

[2] J.P. Peyre et C. Tournier, *"Choix des traitements thermiques superficiels"*, Collection "Matériaux en Mécanique" du CETIM, Revue Pratique des Métallurgistes, Paris (1985).

[3] S. Schiller, S. Panzer, *"le durcissement par trempe à l'aide d'un faisceau d'électrons"*, Traitement Thermique, n°245, pp 39-44 (1991).

[4] R. Zenker, *"Electron beam surface modification state of the art"*, Materials Science Forum, Vols. 102-104, pp 459-476 (1992).

[5] A. Mulot et J.P. Badeau, *"Influence de la structure initiale et de la composition chimique sur les caractéristiques des couches durcies obtenues par trempe superficielle, bombardement électronique et laser"*, Traitement Thermique, n° 136, pp 47-62 (1979)

[6] M. Jeandin, *"Traitements thermiques superficiels de matériaux par faisceaux lasers"* , Revue Générale de Thermique, n° 372, pp 713-725 (déc. 1992).

[7] Rolf Roggen, *"Durcissement superficiel par plasma des aciers et des fontes"*, Traitement Thermique, n°136, pp 90-95 (1979).

[8] T. Kimura, T. Miyazaki, "Surface hardening of carbon steel by plasma arc", Bull. Japan Soc. of Prec. Engg., Vol. 24, n° 4 (Dec. 1990).

[9] F.W. Giacobbe, *"Selective hardening of high-carbon steel using an argon thermal plasma jet"*, High Temperature Technology, Vol. 8, n° 1, pp 3-8 (Feb. 1990).

[10] J.M. Sobrino, D. Dublanche, A. Grimaud, J.F. Coudert, P. Fauchais, D. Duchateau, J. Mongis, J.P. Peyre, R. Brunet, *"Les torches à plasma d'arc dans le durcissement par trempe superficielle des aciers et des fontes"* Traitement Thermique, n° 258, pp 83-92 (1992).

[11] D. Dublanche, Thèse de 3ème cycle, *"contribution à l'étude d'un procédé de durcissement d'acier par jet de plasma d'arc"*, Université de Limoges (1993).

[12] J.F. Coudert, C. Delalondre, P. Roumilhac, O. Simonin, P. Fauchais, *"Modelling and experimental study of transferred arc stabilized with argon and flowing in a controlled-atmosphere chamber filled with argon at atmopheric pressure"*, Plasma Chemistry and plasma Processings, Vol. 13, p. 399 (1993).

[13] Y. Dardel, *"La transmission de la chaleur au cours de la solidification, du réchauffage et de la trempe de l'acier"*, Editions de la Revue de Métallurgie, Paris (1964).

[14] H.Y. Wong, *"Heat transfer for engineers"*, Longman Group Limited, London (1977).