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Application of thermography to analyse the influence of the deformation speed in the forming process

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Abstract

The present work develops an experimental study which aims to establish a relationship between the temperature variations and the deformation speeds in the material and between these deformation speeds and the possible microstructural changes. With this aim, an IR thermographic camera is used to record several tensile tests with different deformation speeds.

Keywords: Thermography; tensile test; AISI 304.

1. Introduction

The thermal effects associated with the strain processes have been studied for a long time by the researchers. The first experiments in thermoelasticity were performed by Kelvin (1853) in the XIX century. Many authors have worked in the difficult problem of estimating, from the temperature levels, the heat released during the processes of strain.

Some metallurgical engineers worked in the creation of models which allow evaluating the evolution of some microstructural parameters, such as the dislocation density or the grain size. However, when the processes of strain are quasi-static or are carried out at slow deformation speed, the temperature variations are so small that these processes may be considered as isothermal.

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The study of temperature variations, which are induced by processes of strain, allows to establish complete energy balances and combine mechanical aspects with deformation energy. The thermographical analysis may perform the estimation of the distribution of heat sources, by means of a heat conduction equation, which is associated with the microstructural changes studied by Chrysochoos et al. (1996) and by Chrysochoos and Louche (2000).

The application of the thermography in these studies and the associated technological development has opened new possibilities, such as the inverse methods for the estimations of thermomechanical heat sources from the infrared temperature measures carried out by Renault et al. (2010).

The fatigue research has been other field where the thermography has been applied as a non-destructive method which can be used in real time without contact. The application of infrared thermography to detect the fatigue damage has been studied for years by estimating the relationship between the temperature increment and the damage or the failure proximity performed by Wang et al. (2010), also in weldments by Cupri et al. (2009).

As it is known, cold work can improve the mechanical behaviour of austenitic stainless steels. This phenomenon is associated with microstructural changes, such as the movement and accumulation of dislocations and the formation of strain induced martensite, which depend not only on the strain level, but also on the deformation speed.

The contribution of the present work is to use a thermographical camera for establishing the relationship among microstructural changes, temperature, strain level and deformation speed. The present work aims firstly to set an analysis system complementary to the tensile tests, by using the continuous thermographical analysis of the tensile test until fracture. A latest generation high resolution and high recording velocity IR camera is used.

The technological application of this work is the optimization of the forming process with the aim of improving the mechanical characteristics and keeping the good corrosion behaviour, which has special relevance in the most important uses of the AISI 304.

2. Experimental procedure

The tensile tests are performed in a Shimadzu AG-IS Universal Testing Machine, with the deformation speed as a critical parameter. For the thermal analysis a complete system consisting of a camera InfraTec ImageIR controlled by the software IRBIS 3 Professional is used. The system possesses a matrix of 320x256 detectors in the spectral region MWIR (2.0 – 5.0 μm). With the aim of reducing the signal noise, the detectors matrix is cooled with an internal Stirling engine. The assembly of a telephoto lens of 100 mm allows the observation of the foreground elements with high spatial resolution.

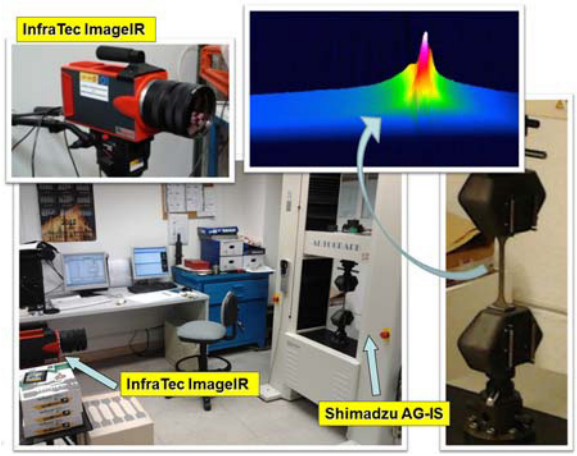

Fig. 1. Equipment used in the present work. Detail of the clamping between jaws of the tensile test specimen and detail of the local heating of the fracture zone.

Fig.1 shows the equipment used in the present work, which is placed in the metrology-UVa laboratory of the University of Valladolid, a detail of the clamping between jaws of the tensile test specimen and a detail of the local heating of the fracture zone.

The tested material is AISI 304 austenitic stainless steel whose chemical composition is shown in Table 1 The tensile test specimens are obtained, from sheets whose thickness is 1.5 mm, according to UNE-EN-ISO 6892-1 and have a gage length of 50 mm and a width of 12.5 mm.

Table 1. Chemical composition of the AISI 304 sheets (wt. %).

C	Si	Mn	P	S	Cr	Ni
0.07	0.41	1.76	0.019	0.001	18.00	8.58

The tensile test parameters are shown in Table 2.

Table 2. Experimental plan for the tensile tests.

Test equipment:	Shimadzu AG-IS	
Force transducer:	100 kN	
Mounting type:	Jaws for flat test specimens	
Controlled environmental conditions:	Temperature:	21.5 ºC ± 2 ºC
	Humidity %Hr:	25-75%
Deformation speed:	10, 20, 40, 60, 120, 240 y 480 mm/min	

An assembly of a 100 mm lens in high-speed thermographical camera allows to achieve a high resolution spatial observation, but an assembly of 500 mm lens allows to achieve a resolution of 30 μm. Considering the specimen length and with the aim of avoiding changes in the orientation of the thermographical camera, only the 100 mm lens is assembled even though the resolution is not as high as it could be. The emissivity values used are those reported in Wen (2010); the emissivity settings have been verified under environmental conditions by using a long thermal stabilization time (longer than eight hours). Additionally, high speed video cameras have filmed the tests in order to analyse the crack propagation.

Table 3. Experimental plan for the temperature measurement tests.

High- End Thermographyc System		InfraTec ImageIR
Configuration	Telephoto lens	100mm / 100mm + 500mm
	Frame size	320x256
	Frame rate	250 fps
	Calibrated range	20 ÷ 120 ºC

Fig. 2 shown, as a function of time, elongation, load and maximum and minimum temperature. The maximum temperature recorded is reached at the fracture instant, which is taken as a reference to synchronize data. However, these results do not match with others from previous studies carried out by Rodríguez-Martínez et al. (2011), where the maximum temperature and the maximum load are reached simultaneously.

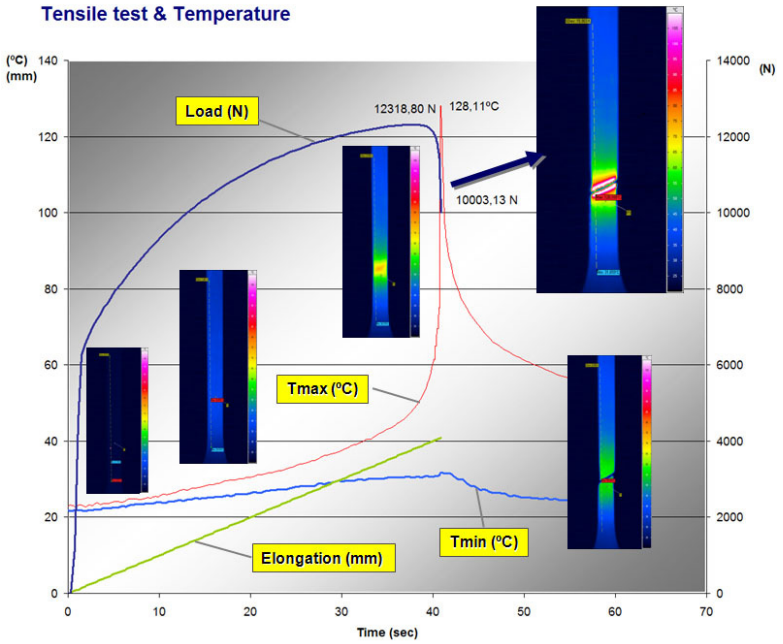

Fig. 2. Comparative between tensile test and thermographic analysis (at a deformation speed of 240mm/min).

3. Results and Discussion

Thermographic study of the specimen was the first objective in order to determine the reference parameter of the thermal analysis. The analysis was carried out considering both the temperature distribution in the area of the specimen, and a reference line (taken longitudinally, Fig. 3) collecting values in the range of variation (Tmax and Tmin) or the average temperature in the reference element (Tm) along the test duration.

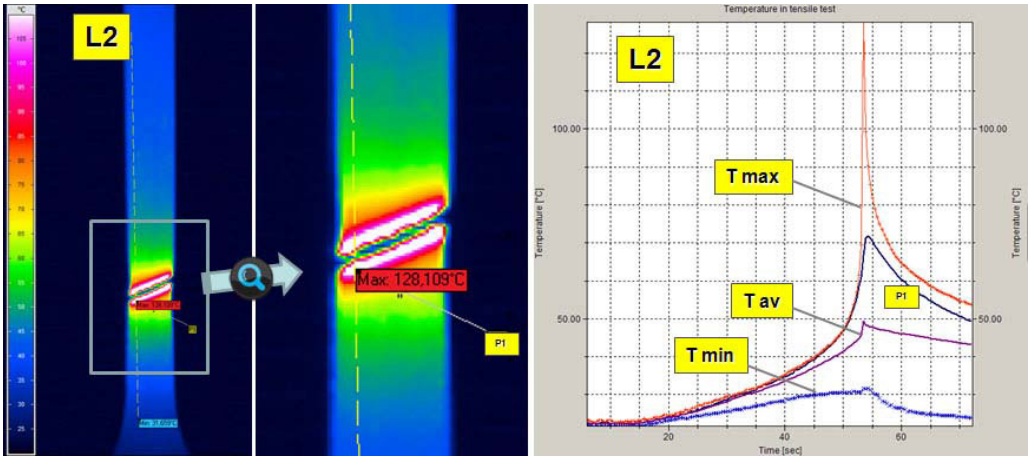

Fig. 3. Thermography of the specimen. Detail of the fracture zone & (Tmax, Tm and Tmin) vs time in longitudinal line L2.

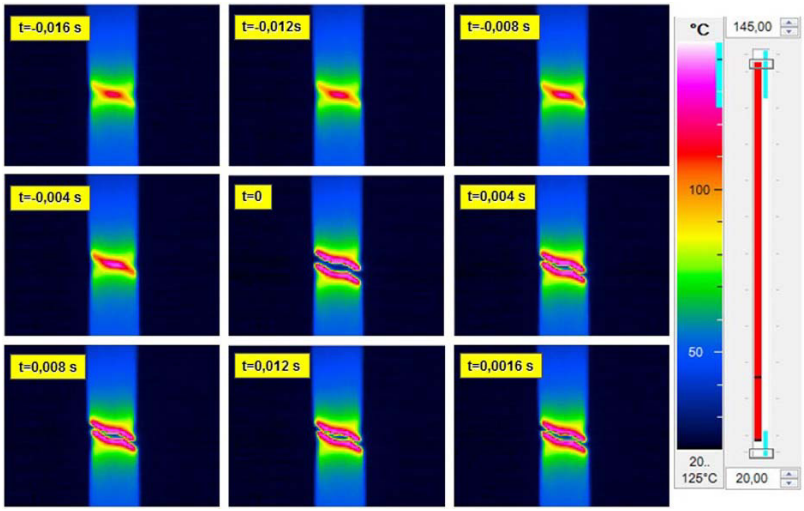

Fig. 4. Four slices before and after fracture (Δt=0.004 s).

Besides the qualitative analysis, the color map allows a quantitative interpretation of how heating is produced, especially around the fracture zone. Considering the sampling rate used, pictures can be obtained at intervals of 4 ms (Fig. 4). The strain increment is manifested by an initial progressive heating, relatively uniform in the calibrated length of the specimen, which is defined in the bibliography as a lineal increment of the temperature with the deformation. However, in the final phase of the test, the heating location is very clear, anticipating the immediacy and the location of the fracture. The maximum temperature is obtained just in the instant of fracture, when the interior of the specimen is visible.

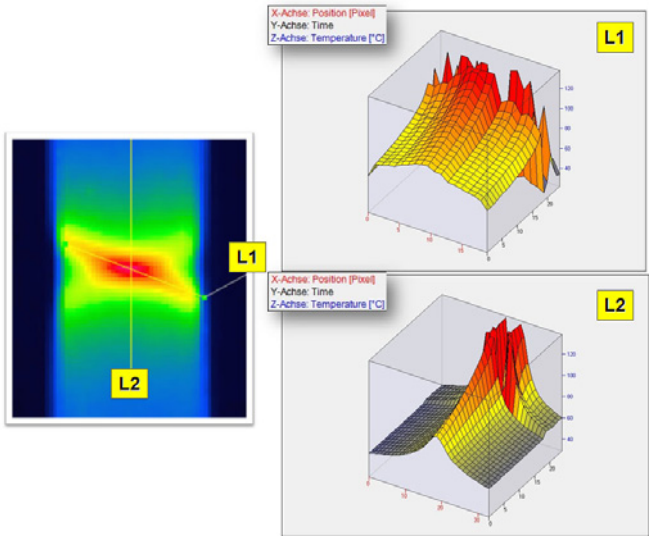

Fig. 5. Distribution of temperature around the fracture. Line L1: in the fracture zone; L2: longitudinal line.

In order to describe the analysis of the rupture zone in detail, a temporal and spatial zoom has been applied, using a reference line on the rupture zone that allows to appreciate temporal changes of the superficial temperature around the fracture point. The detail of the temporal evolution of the temperature in the references lines L1 (rupture zone) and L2 (longitudinal line) is shown in Fig. 5. The high temperature reached inside the specimen

shows how the crack is generated in the center and then it grows towards the edges. As it is shown in Fig.4, this crack develops in some milliseconds.

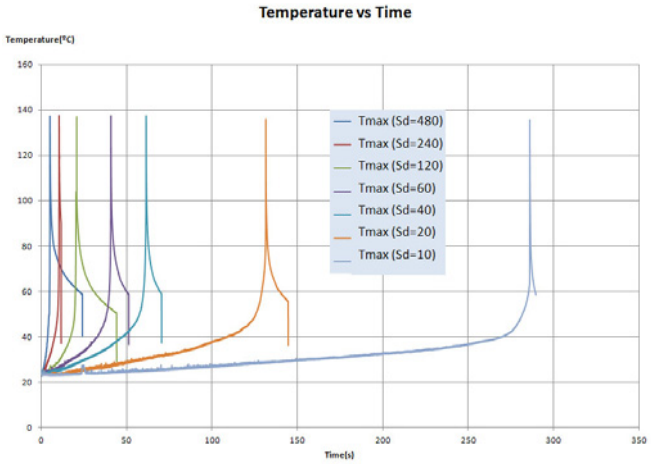

Fig. 6. Tmax vs Time for different deformation speeds (Sd= 10, 20, 40, 60, 120, 240 & 480 mm/min).

With the aim of looking for the consistency of the reference parameter, the maximum temperature value reached on the specimen surface is used in the analysis. Considering the deformation speed variable, Fig. 6 shows the evolution of this parameter versus time for the range of speeds from 10 to 480 mm/min. In all cases, it is possible to appreciate an initial phase with a linear variation versus time, with higher slopes when the deformation speed is higher, growing exponentially until fracture occurs. As it is shown in Fig.2, this final period appears just before the maximum strain is reached, although gradients are higher when resistance begins to decrease, reaching the maximum at the fracture instant. After the fracture instant, the subsequent cooling-off process can be studied, though it is not significant in terms of material behaviour.

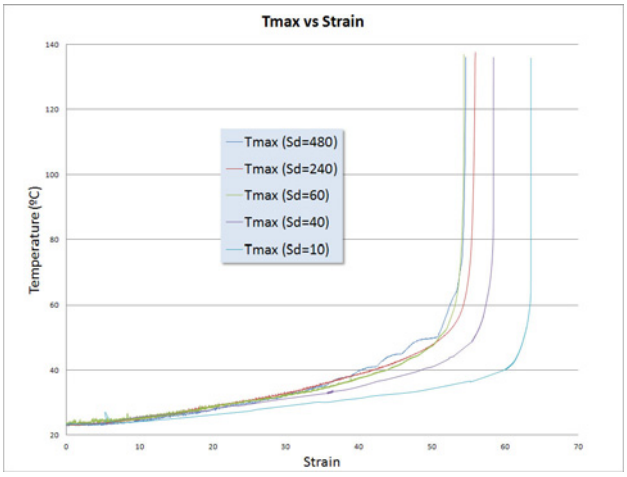

Fig. 7. Tmax vs Strain for different speeds (Sd=V= 20, 40, 60, 240 & 480 mm/min).

However, from the engineering point of view, the representation of temperature versus strain allows for a better interpretation of the effects. The graphic shows the linear behaviour of temperature versus strain in the early phase, being, in general terms, faster when the test speed is higher. The curves end at the fracture instant, achieving higher

strains when the speed is lower. The fact that temperature is lower at low speeds could be due to the lower deformation work as well as the cooling-off process (longer times).

Considering the microstructural changes which may occur as a result of the deformation, the maximum temperatures, as a function of strain for each test speed, are showed in Table 4. If at low speeds tests the deformation is related to the martensite appearance, the superficial temperature with higher deformation speeds could be used to locate the zones where the microstructural changes occur.

Table 4. Tmax (ºC) vs % strain for different deformation speeds.

		Strain					
		10	**20**	**30**	**40**	**50**	**60**
	Sd=480	24,80	27,85	32,10	39,78	49,76	
	Sd=240	25,01	28,91	32,95	38,79	47,63	
Sd	**Sd=60**	25,41	28,50	32,13	37,42	47,35	
	Sd=40	24,72	28,02	31,21	34,79	40,85	
	Sd=10	24,40	26,26	29,04	31,21	34,35	40,04

As a summary, Fig. 8 shows the data collected in Table 4. From a strain of 30%, it can be appreciated the difference among behaviours for different speeds, reaching a strain of 60% only with the lowest speed.

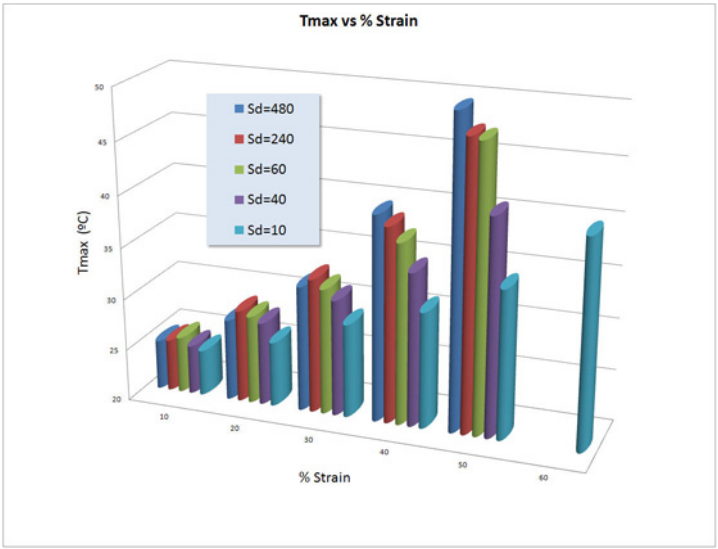

Fig. 8. Tmax vs % Strain for different speed-test.

4. Conclusions

It has been possible to tune the thermographical analysis system and check the consistency of the data obtained with the aim of studying the influence of deformation speed on AISI 304 steel.

The study of the surface temperature can have both qualitative and quantitative approach to understand how the strain occurs from the heating associated. If the surface temperature is associated with a stress state of a specific deformation speed, the possibility of discriminate qualitatively the degree of strain using only isotherms can be considered. Nonetheless from a quantitative point of view, the maximum temperature may be used as a significant parameter and it can be related with the deformation speed and with the strain hardening.

As it can be observed, the initial relation between temperature and strain is linear with a marked increase at the instant of fracture. Although the initial temperature of the specimen is relatively uniform, the local temperature

increase allows predicting where the necking appears. The crack grows from the center of the specimen to its edges.

The temperature and deformation curves as a function of the speed allow to observe several significant aspects. It could be remarked that the same temperature can be reached at lower strain levels by increasing deformation speed.

Since the importance of the microstructure in the final behaviour, the results show the possibility of using IR thermography to study the microstructural changes associates with the plastic deformation processes, considering variables such as deformation speed.

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