Analysis of fracture resistance of tool steels by means of Acoustic Emission

Eva MARTINEZ-GONZALEZ [1], Ingrid PICAS [2], Daniel CASELLAS [2], Jordi ROMEU [1]
[1] Laboratory of Mechanical and Acoustical Engineering (LEAM), Universitat Politècnica de Catalunya (UPC), EUETIB c/ Urgell 187, 08036 Barcelona, Spain; eva.martinez@leam.upc.edu
[2] Department of Material Technology, CTM-Technological Centre, Av. Bases de Manresa 1, 08242 Manresa, Spain

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Abstract

The usage of advanced high strength steels (AHSS) in structural automotive components has been broadened in the past few years to satisfy the strict specifications of the automotive industry. Besides showing excellent strength to weight rations, AHSS have several limitations due to the high loads required in cold forming and cutting tools, which decrease considerably the tooling performances. Therefore, these important forces of impact provoke unforeseen breakage of the dies.

The aim of this research is to study the micromechanical behaviour and fracture mechanisms (nucleation and crack propagation) during fracture of tool steels using the acoustic emission (EA) technique. To do that, bending testing specimens of different tool steels were monitored in order to establish a relationship between AE signals and their mechanical behavior (carbide breakage, cracks emanating from them and crack propagation through the metallic matrix).

Introduction

The automotive industry has been using conventional steel in manufacturing parts and structural components. However, in recent times, due to a demanding market, higher energy efficiency of automobiles, less contamination and higher safety standards, the use of high strength materials such as Advanced High Strength Steels (AHSS), characterised by its high yield stress of over 550 MPa, has been on the rise.

The high mechanical resistance enables manufacturing lighter parts with superior performance compared with conventional steel types, thus reducing the weight of components, which in turn reduces fuel consumption and at the same time grants high safety standards during possible collisions. The mayor advantage of AHSS turns into a challenge during the process of forming parts because of the high pressure needed, causing accelerated tool wear and premature failures [1].

In this framework, the full exploitation of the potential of AHSS requires the development of tool materials combining both high wear resistance and fracture toughness to withstand the severe mechanical solicitations acting on tools when forming AHSS. To enable this, a proper microstructural design of tool steel is needed in terms of size, shape and distribution of primary carbide as well as in their chemical composition [2].

A detailed examination of tool steels used in conventional forming processes of AHSS (cutting, drawing, stamping, bending and profile rolling) has permitted to identify fatigue as one of the most common failure mechanisms involved in such applications. The origin of fracture and fatigue cracking of cast tool steels is usually associated with the primary carbides, which break under the applied stress and act as initiation sites [3,4]. Thus, the increase in the mechanical properties of carbides is expected to also increased the fracture and fatigue resistance of tool steels. The fracture strength of carbides depends on the fracture toughness, the carbide shape and the presence of internal defects [3]. In this sense, the determination of the fracture strength for primary carbides will give valuable information to understand the global mechanical response of tool steels and forming tools.

In order to experimentally determine the stress level that induces the fracture of primary carbides, some work is being put into the application of *Acoustic Emission* (AE) [5]. AE serves as a powerful, non-destructive method of testing material degradation. It is based on real-time detection of elastic ultrasonic waves, generated in a material under tension because of the emission of micro energy which is induced as a result of diverse internal dynamic micro mechanisms, like plastic deformation, movements in edge dislocations, sliding, grain rotation, micro fractures of inclusions, appearance or propagation of cracking, etc.

In 2001, Fakaura and Ono [5] showed the applicability of the AE to determine the mechanical properties of tool steels, in which interesting results are being displayed, the relationship between the characteristic parameters of the AE waves and the progression of the damage done to the specimen that is being monitored is shown. The article indicates that there might be limitations in the results because of the use of sensors of relatively low frequencies (375 kHz). In this actual piece of work, this indication was taken into account by using sensors with a resonance frequency higher (700 kHz). Yamada [6], related the signal type and its predominant frequency, with the plastic deformation (continuous low frequency signals) and the fracture mechanisms (sudden high frequency signals) in bending tests.

Aimed at better understanding the role of the microstructural constituents (the primary carbides and the metallic matrix) in the fracture mechanisms of tool steels, this work focuses on the application of AE to determine the stress levels at which carbides fracture in monotonic bending tests.

Experimental procedure

A. Specimens

Two commercially available tool steels were selected: a DIN 1.2379 (equivalent to AISI D2) and a tool steel named as UNIVERSAL (developed by ROVALMA). Details of the chemical composition and heat treatments of both steels can be found in reference 2. The 1.2379 tool steel , is characterised by a ledeburitic microstructure with grid precipitation of primary carbides during solidification, formed mostly by the eutectic reaction $\Rightarrow \gamma + M_7C_3$ [7]. In UNIVERSAL steel, two types of primary carbides are present, one type M_7C_3 but with higher Vanadium and Tungsten than those found in 1.2379 and a second type of primary carbide of increased hardness and toughness, rich in Vanadium of the MC type. Carbides in the 1.2379 present an elongated shape, forming carbide bands along the forging direction, meanwhile primary carbides of UNIVERSAL steels are more equiaxed and homogeneously distributed in the microstructure.

Prismatic specimens were cut from forged billets, with dimensions 50x4x3 mm with the longitudinal axis parallel to the forging direction. The obtained samples were then heat treated by quenching in oil and tempering up to a hardness of 60 - 61 HRC (heat treatments schedule can be found in reference [2]).

B. Monitorized AE flexion test.

A three point bending test was used to evaluate the mechanical behaviour of the specimens. The test was carried out in a universal testing machine. The side of the specimens under tension was ground and polished. Specimen edges were rounder in order to avoid stress concentration effects. The load rate was fixed at 1 mm/s in all the cases and carried out in air at room temperature.

Two small magnetic AE sensors are put alongside the specimens in order to detect the AE signals. The sensors are of the resonance type with a fixed resonance frequency of 700 kHz (VS700D, Vallen System Gmbh). Two pre-amplifiers with a gain 34dB of the same brand were used (EAP4). The signals were recorded and analysed using the de Vallen System Gmbh AMSY5 analyser. During the measurements, digital filters of 95-850 kHz were applied.

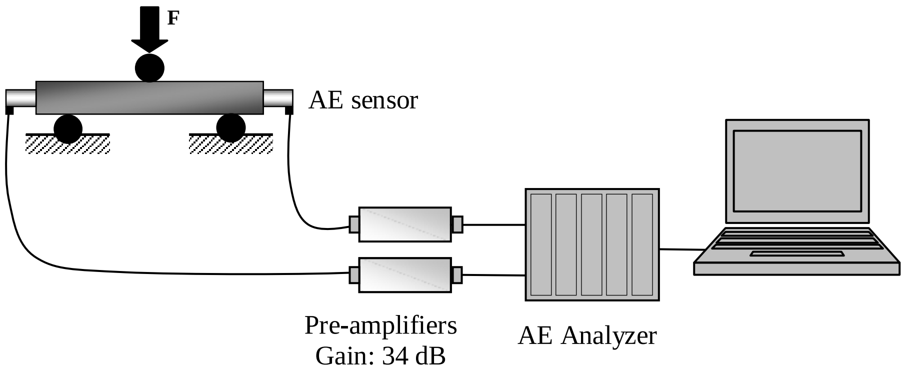

Fig 1. Diagram of the experimental setup.

C. Test procedure.

Various complete bending test runs are carried out in order to define the pattern of AE signals and to determine the specimen´s behaviour. Afterwards, the test runs were paused upon significant changes in the AE signals. After pausing the test, the surface that had been submitted to tensile loading, was examined by optical and confocal microscopy to identify the microstructural features responsible for the possible AE sources. The tests were performed at a maximum of 70% of the fracture strength (2.100 MPa for the DIN 1.2379 and 2.800 MPa for the UNIVERSAL steel) to prevent sensor damage due to a sudden sample break.

Results and Discussion

The results of the complete test are displayed in the graphs in figures 1 and 2. They show the relationship between the stresses applied to the specimen and the AE signal intensity.

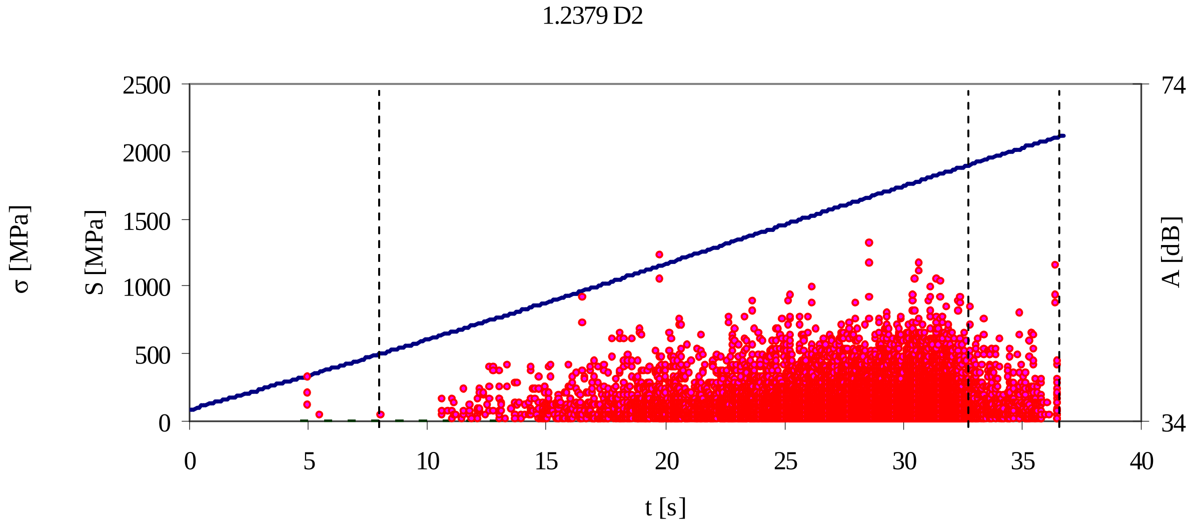

Fig. 2. Bending test results, steel DIN 1.239. Blue line, relation between stress vs time and red points EA signals vs time.

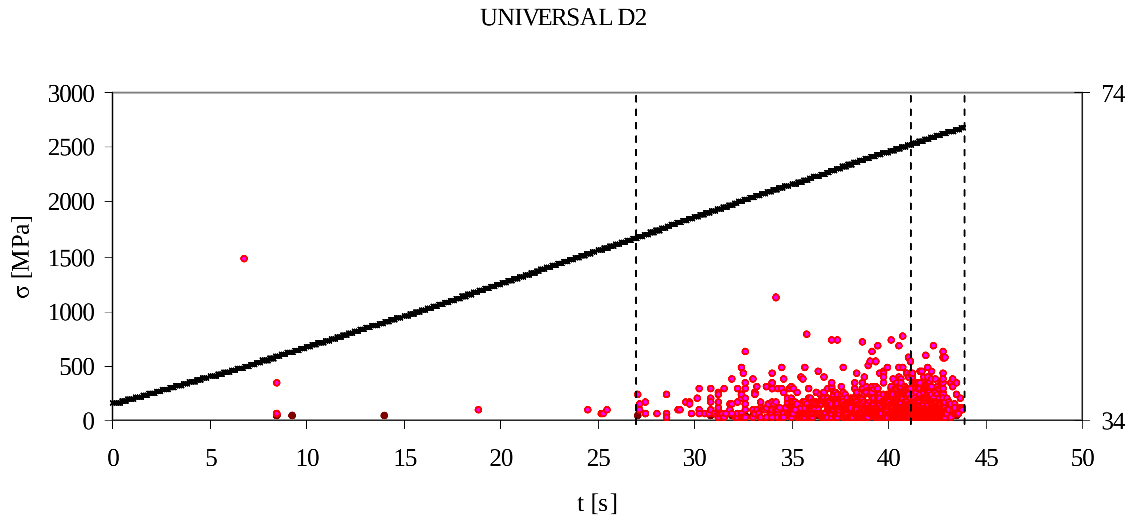

Fig 3. Bending test results, steel UNIVERSAL. Blue line, relation between stress vs time and red points EA signals vs time.

It can be observed that both materials show a similar behavioural pattern as to the captured AE signals. There are three different zones:

First zone

During the first stage of the test, AE signals are almost inexistent. The reason for this is that the material is under elastic deformation. Neither the carbides, nor the matrix show effects of fracture, propagation or plastic deformation that generate AE signals. In other words, linear behaviour of the material is associated with the absence of AE signals, once background noise is filtered out.

Some isolated AE signals appear which are suspected to be caused by premature fracture of carbides or a chip off of the material due to the polishing; however there is no certainty at this point.

Second zone

The first AE signals appear in the DIN1.2379 at approximately 11 s and in the UNIVERSAL at 27 s (that correspond to a deformation of 0,4 % and 1% respectively). The signals increase gradually in intensity and abruptly in number. During this stage in both materials in the various micrographics, broken carbides can be discerned. As shown in figure 4, the amount of broken carbides increases considerably with the rising stress. In some cases a small area of plastic deformation appears.

Third zone

Both the amounts of registered signals as well as the accumulated energy increase considerably. The intensity does not increase; moreover the average value decreases slightly. At this stress level nearly all carbides at the surface have been fractured, more areas have plastic deformation and even small matrix cracks appear. At this point, the test has been stopped to prevent the specimens from breaking down all together but it is expected that until its final breakdown, the fractures will increase until the broken carbides connect and the specimen breaks in two.

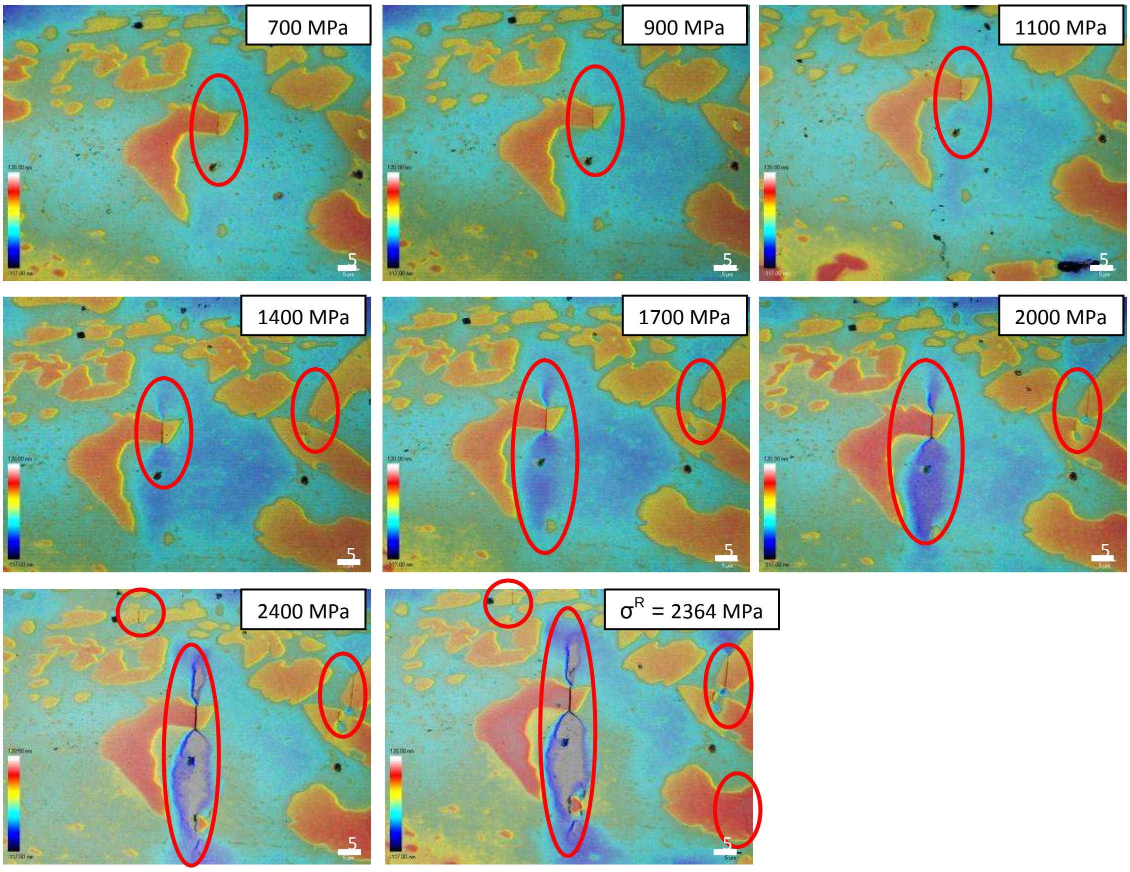

Fig 4. Tensile surfaces of DIN 1.2379 during the loading and unloading bending test. In this case, the first broken carbides apperas at 700 MPa; plastic deformation in the matrix around the carbide crack from 900-1000 MPa, it is increasing the deformed area and its depth. From 2000 MPa, the crack is generated in the the deformed matrix and propagates up to the final break of the specimen. Also it is possible to see like as it increases the load, they are breaking the carbides of around. The values of load associated with every phenomenon are stadistics since they depend on every carbide and its distribution with regard to the rest.

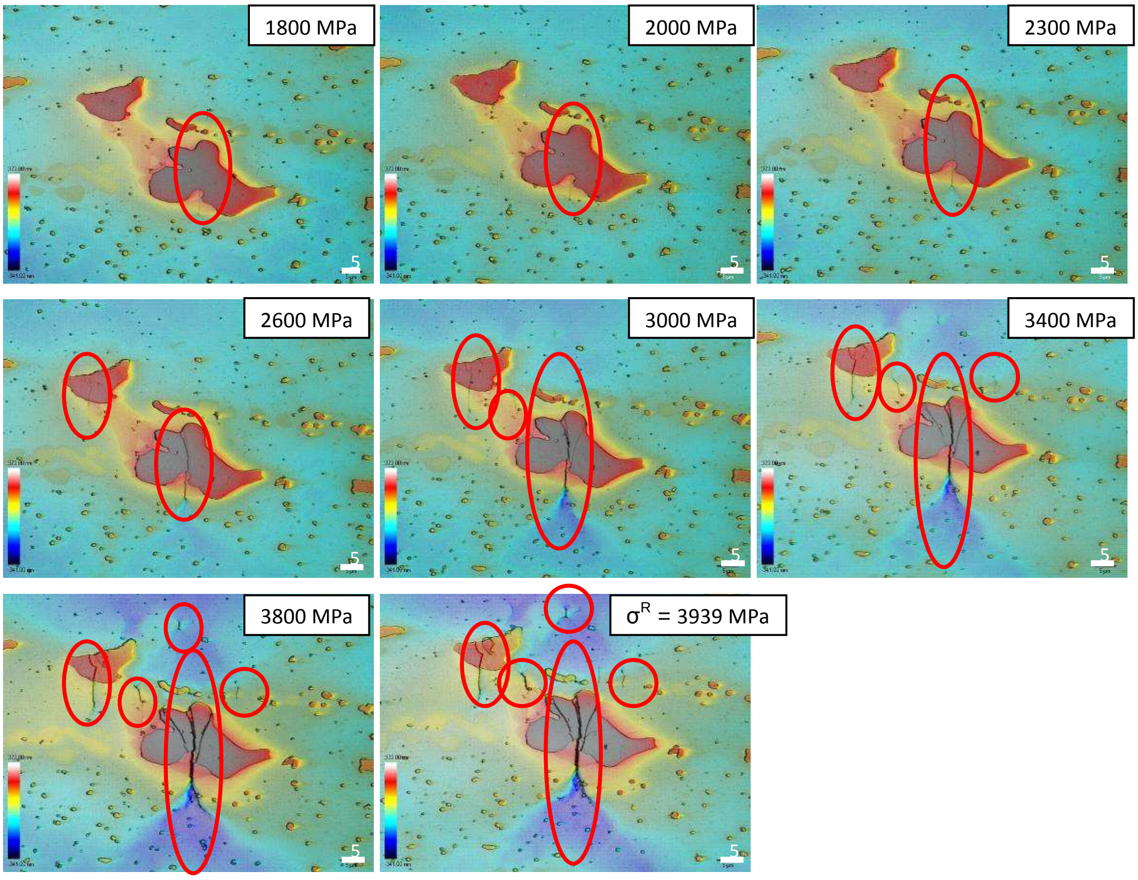

Fig 5. Tensile surfaces of UNIVERSAL during the loading and unloading bending test. In this case, the first broken carbides apperas at 1800 MPa; plastic deformation in the matrix around the carbide crack from 2000-2300 MPa, it is increasing the deformed area and its depth. From 3000 MPa, the crack is generated in the the deformed matrix and propagates up to the final break of the specimen. Also it is possible to see like as it increases the load, they are breaking the carbides of around. The values of load associated with every phenomenon are stadistics since they depend on every carbide and its distribution with regard to the rest.

The stress level at which carbides start breaking in the DIN 1.23679 steel is 640 MPa, which is 20% of the fracture strength of this material. In the case of the UNIVERSAL steel, signals that point out the breaking of carbides start appearing at 1700 MPa which corresponds to approximately 45% of the fracture strength. Such results can be explained by the lower fracture toughness of primary carbides in the 1.2379, as has been previously evaluated by nanoindentation [2]

Currently, other AE parameters concerning the physical phenomena that occur are being studied in order to obtain an efficient system of diagnose. The study of waveforms to identify the source, using their frequencies, is of special interest. The results obtained in this field have not yet been studied in depth although they are similar to those presented by Yamaha [6] concerning ceramic steel types. Basically, two types of AE signals were identified: a high frequency burst-type signal and a continuous type with lower frequency. It is possible that the first type is due to the carbide micro-cracks and the continuous type is related with plastic deformation. This is consistent with the results observed in the microscope but additional studies are needed to confirm this.

Conclusions

This work covers the description of tests that are carried out on tool steel specimens Subjected to bending tests. It basically consists of the instrumentallisation of a three point bending test using appropriate AE equipment in order to evaluate if AE is a suitable technique to discern fracture events in tool steels. Two microstructurally different tool steels have been tested. The conclusions that can be drawn are as follows:

1. AE is an appropriate tool to detect carbide cracking, plastic deformation, initiation and propagation of cracks in the metallic matrix of tool steels for tooling, according to previous works [5].

2. An experimental relationship was established between the initiation of carbide fracture and the obtained AE signal. The stress levels that give fracture of primary carbides detected by AE were experimentally confirmed by microstructural inspection.

3. The tool steel with the highest carbide content induces the highest quantity of AE signals with more temporal dispersion.

The results of this work cover the first phase of a project that will be laid out and the authors are working on establishing threshold relations that will permit to study the behaviour of steel for tooling with an increased precision. The following research project is to develop, increase and quantify the exposed conclusions.

Acknowledgments

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