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Experimental assessment of hot-work tool steels performances under the creep-fatigue regime

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Abstract

In the present research an innovative testing method, specifially developed to characterize the tool steels under creep-fatigue conditions, was carried out an a TQ1 hot-work tool steel. The experimental campaign consisted of different testing conditions and part of the specimens were nitrided to account for the specific surface state of the tools. Tests were performed on a 10tons MTS fatigue machine equipped with a heating furnace. A creep-fatigue loading type was applied to the specimens, i.e. a cyclic load with a dwell-time, in order to properly reproduce the conditions acting on a hot forging or extrusion tool. Then, under a constant temperature of 520°C, the effects of four different load levels and 2 different values of dwell-times were evaluated. In addition, selected test conditions were replicated with the specimens not nitrided with the aim to evalute and quantify the influence of the superficial treatment. Final results were presented in terms of fatigue curves of the TQ1 and compared to the performances of the H11 tool steel tested in a previous research by the same authors.

Keywords: hot-work tool steels, TQ1, AISI H11, creep-fatigue, nitriding

1. Introduction

Hot work tool steels are used to manufacture molds and dies for processes marked not only by high mechanical loads but also by high operating temperatures; examples are forging dies and punches, mandrels, extrusion dies. The high mechanical loads are related to the level of pressure released on tools by the forming material (up to 300 MPa) and, in addition, they are cyclic in nature since each forged or extruded component represents, for the tool, a single loading cycle. On the other hands, the high operating thermal loads originate from both selected relevant preheating temperatures of the billet and tools, but also from the large amount of heat generated due to deformation and friction on the workpiece-tool contact surfaces[1,2]. Under these critical working conditions, tools are subjected to the detrimental effect of the creep and fatigue phenomena that can lead to a premature failure even for stress levels under the macroscopic yield point of the material[3]. Creep is defined as the time-dependent deformation under constant stress and temperature. It appears over a critical level of temperature (usually one third of the melting temperature that for steels is around 400 to 500°C) and manifests itself as a progressive accumulation of plastic deformation during the forming time of the components. Together with creep, fatigue contributes to weak the material with an additional progressive and irreversible increase of the accumulated plastic deformation caused by repeated, cyclic loads. In the last part of the tool life, creep and fatigue become also responsible of the possible appearance of material discontinuities (pores, voids, cracks). It is proved that the sum of the effects of these two phenomena is more detrimental that their single effect[3]. Thus, the service condition to be investigated is named creep-fatigue regime and it is characteristic of the low-cycle fatigue portion of the tool life in which high loads and plastic deformations are involved.

Under these critical working conditions, the main requirements for the tool material are a high temperature strength and toughness and a high tempering resistance. These characteristics ensure an extended tool life both in terms of reduced deflection under loads, thus generating in-quote components, and increased number of cycles to failure. In general, hot work steels used in a temperature range between 300 °C and 650°C, are of the medium and high-alloy type, and most of them have relatively low carbon content (0.25 to 0.6%). They typically contain additions of chromium, vanadium, tungsten and molybdenum, each element contributing to increase a specific aspect of the material depending on tools' field industrial application[4,5]. However, among number of hot work tool steels available, the super clean TQ1 represents a milestone in material development[6]. This material is able to combine the toughness of the AISI H11, the steel most widely used among all the existing hot work tool steels, and the high temperature strength properties of others. If compared to the chemical composition of the standard AISI H11, the TQ1 mainly differs in terms of the silicon content (1wt.% for the AISI H11, 0.35 wt.% for the TQ1), even if small alterations exist also in terms of the molybdenum, manganese and vanadium content[7]. The effect of silicon has been investigated in literature in terms of tempering behavior[8] and fatigue properties[9]. Specifically, it was proved that silicon has a considerable influence on the precipitation of secondary carbides shifting the secondary hardening peak towards lower tempering temperatures. Since the second tempering of a hot work tool steel used in industrial application is generally performed above the temperature of the maximum hardening peak, an over-aging for the high silicon grade steel is responsible of a lower tensile and fatigue properties. Even if a comparison in terms of fatigue performances between the AISI H11 and a lower silicon content grade tool steel have been then already performed[9], even slightest modification of composition or heat treatment are known to have a huge impact on the mechanical properties of the material due to the unstable microstructure. Thus, no previous researches directly report the performances of the TQ1 hot work tool steel under cyclic loads and high temperatures.

In addition to what previously reported, tools for hot applications are also required to resist to abrasion and adhesion that can cause premature yielding due to wear, especially in those area marked by high contact pressure and relative workpiece-tool sliding[10,11]. In order to prevent or retard this type of failure, tools are usually superficially treated by means of CVD or PVD procedure, nitriding or duplex treatments[12,13]. Among the variety of coatings and treatments, gas nitriding is the most commonly used surface treatment for hot applications due to its effectiveness in reducing the wear rate by as much as 50%[13] and in treating narrow and deep gaps in the tools[14,15]. However, although these beneficial effects, the main drawback of nitriding is related to the decrease in the toughness of the die surface. Since no selective nitriding of the tool surface is usually performed, this shortcoming can significantly alter the global dynamic performances by reducing the load bearing capacity of the most stressed area. Previous studies demonstrate the different impact of nitriding depending on the fatigue regime (low versus high cycle) for some steels. A good review is reported in literature[16]. However, the effect of nitriding on the TQ1 tool steel, to the best authors knowledge, has never been investigated.

In order to fill the underlined literature gaps, aim of the present work was to investigate the TQ1 hot work tool steel behavior in nitrided conditions in the creep-fatigue regime. The same authors previously carried out a similar research on the performances of the AISI H11 tool steel but in not nitrided conditions[17]. In comparison to standard experimental test performed on cylindrical specimens with polished surfaces under uniaxial loading conditions, in that work a novel physical experiment, able to reproduce the geometry of a porthole extrusion die on a small scale, was presented. This allowed to account for more realistic stress and strain gradients and distributions, also in consideration of the experimental evidence that highly stresses transition radii of the tools are the mostly subjected area to cyclic plastic deformation which causes crack initiation[18,19]. The experimental set was able to properly predict the material behavior under creep-fatigue regime revealing the effect of the chemical composition of tool steel or heat treatment parameters on the die lifespan and was therefore used to investigate the TQ1 behavior under different load levels and at high temperature. Selected test conditions were replicated with the specimens not nitrided with the aim to evaluate and quantify the influence of the superficial treatment. Final results were presented in terms of fatigue curves of the TQ1 and compared to the performances of the AISI H11 tool steel.

2. The testing procedure

2.1. The selected tool steel material and specimen geometry

The material of the specimens investigated in the present study was the TQ1 hot-work tool steel with the following nominal chemical composition (by wt.%).

Table 1. chemical composition of the investigated TQ1 hot work tool steel

C	Si	Mn	P	S	Al	Cr	Mo	Ni	Cu	V
0.36	0.30	0.40	-	-	-	5.2	1.90	-	-	0.55

On the basis of geometric optimization performed by means of a Finite Element (FE) analyses, the specimen was intended to replicate the geometry, and the loading conditions, of the mandrel of a porthole die on a smaller scale. The final specimen design contained a core support (mandrel) and two bridges[17]. This geometry included all the characteristic elements of the mandrel of a typical porthole die, including fillet radius and the ratio of the height of the bridges to their width (Fig. 1a). However, different specimen geometry could have been designed and used according to the specific final tool application.

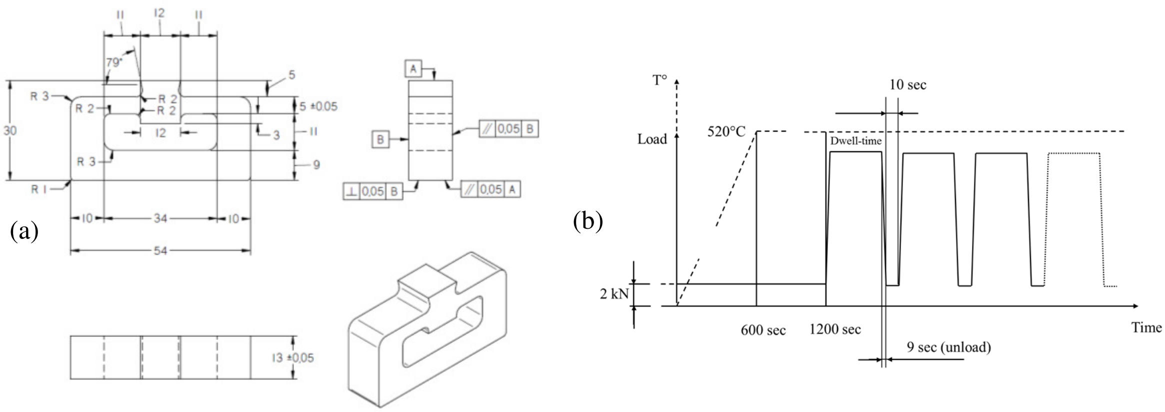

Fig. 1: (a) Geometry and dimensions of the specimen used in the present investigation, (b) loading scheme used in the present work

Specimens have been heat treated achieving a final Rockwell hardness of 49.5 HRC (stress relieving 650 °C (3 hrs) and 850 °C (3 hrs); austenitization: 1010 °C (1 hrs); quenching in nitrogen atmosphere to 50 °C (0.5 hrs); first tempering at 550 °C for 6 hours; second tempering at 580 °C for 6 hours.

A total of 21 specimens were manufactured, 16 of which used in the present work. In order to guarantee the homogeneity of the material and heat treatment among the specimens, the initial hardness of each specimen was monitored before the trials. The original dimensions of the specimens, in terms of height and bridges thickness, were recorded as well before the tests. Then, 14 specimens were nitrided resulting in a final hardness of the nitrided layer in the range of 900 to 1200 HV.

2.2. Testing settings and design

The experimental campaign consisted of different testing conditions. Tests were performed on a 10tons MTS fatigue machine equipped with a heating furnace. A pure compressive load was applied to the upper surface of the specimens by means of a standard hot-steel tool. A creep-fatigue loading type was chosen, i.e. a cyclic load with a dwell-time during which the load is kept constant (Fig.1b). This loading scheme copies the conditions acting on an die during a continuous extrusion process, with the dwell-time representing the time required to extrude each single billet. A minimum load of 2 kN was kept in order to avoid the specimen motion and misalignment between two consecutive cycles. In detail, testing conditions were planned at different load levels and for two different dwell-times (160 sec and 300 sec) at a constant temperature of 520°C. In order to determine the load levels, the range of critical stresses (average and peak) on the connecting area between the mandrel and bridges was investigated by means of a FE analysis of an industrial hollow die that experimentally failed after around 500 cycles (extruded billets) (Fig. 2a).

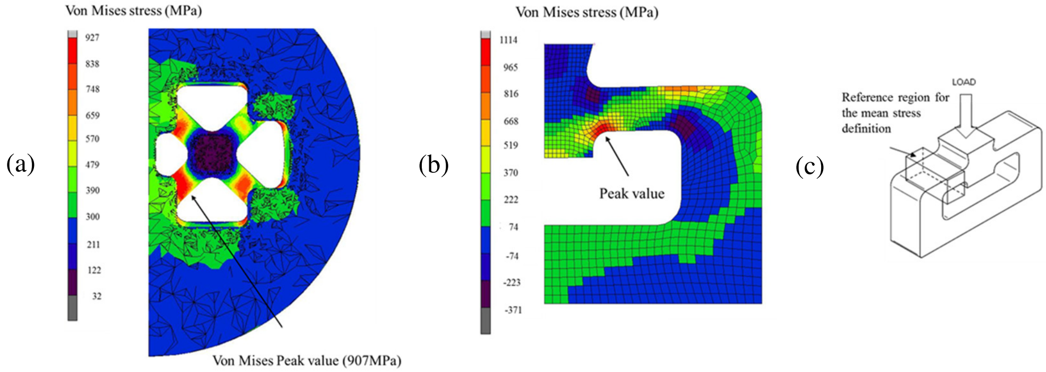

Fig. 2: Peak stress in the FE model of the industrial extrusion die (a). Definition of the peak stress in the FE model of the specimen (b) and of the region for the average stress calculation (c)

The FE model of the die was generated within the structural code Marc MSC and an elasto-plastic model was used for the material behavior. The stress-strain curves at different temperature were obtained by means of tensile tests. Temperature and pressure applied to the model of the hollow die were linearly interpolated from the process code HyperXtrude® in which a coupled thermo-structural simulation of the sole aluminum was previously performed. Hereafter, the FE model of the specimen was generated in order to define the load entity that induces the required level of stress in the bridges, the most critical for the crack nucleation and propagation (Fig. 2b). The same level of average stress in the area of the connecting radius between the bridges and the mandrel in the industrial die (907 MPa, Fig.3a) was found to be generated in the specimen by a load value of 30kN (Fig. 2c). This load was used in the first trial. Then, on the basis of the output results in terms of mandrel deflection, different load levels were applied (Tab.2).

Tab. 2: Peak principal stresses induced in the specimen by the corresponding applied loads used in the experimental campaign

Load level [kN]	Peak principal stress in the connecting radii [MPa]
26.0	796
30.0	850
40	1002
45	1100

Concerning the temperature in the specimen, this was set equal to 520°C in all the performed trials. During the experimental trials, different types of temperature control were adopted due to its considerable influence on the outcomes and in order to check the thermal homogenization of the specimen. Firstly, two thermocouples were inserted in the heating furnace nearby the specimen (Fig.3a). However, this measure, if taken as the reference temperature of the specimen, has been considered to be affected by the uncertainty on the quote related to the direct irradiation of the thermocouples tip itself. Then, an additional thermocouple was spot welded on the lower specimen surface (undeforming region) in order to get a more reliable measure avoiding any contamination of irradiation effects (Fig. 3b). A triple monitoring of the furnace temperature was achieved by means of a pierced block of steel having a comparable volume with that of specimen and equipped with a thermocouple placed inside the hole. This block was positioned in the oven together with the specimen and its was temperature recorded. A total of 17 minutes were used to achieve the temperature set of 520°C in the whole specimen.

The device used for the specimen loading and placement inside the furnace consisted of an upper moving tool with a flat face and a lower fixed tool with a spherical groove used to house a steel sphere used to keep the load aligned in the testing direction (Fig. 3c).

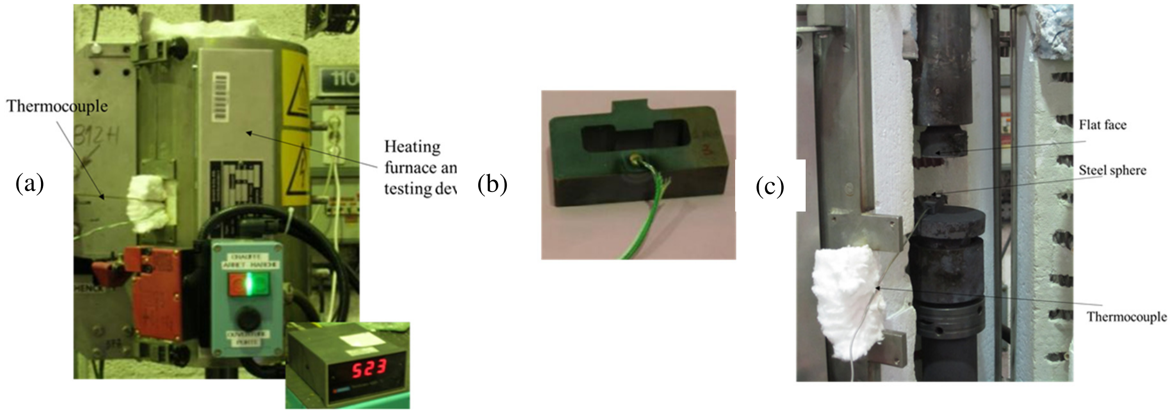

Fig. 3. Temperature controls: (a) thermocouples insertion within the heating furnace, (b) thermocouple spot welded on the specimen surface. (c) device for the specimen placement

The data acquired during each test were the stroke of the upper moving tool (displacement of the mandrel of the specimen), the load applied during the testing time and the temperature of the two thermocouples placed nearby the specimen and spot welded on it. The yielding of the testing machine system, jointly with the backlash recovery, was acquired for different load levels with the aim to depurate from the data of the specimens the deformation of the press and of the holding equipment. The experimental plan is summarized in Tab.3.

3. Results & discussion

3.1. Output of the experimental tests on the TQ1 hot-work tool steel

The typical output of each experimental trial was in the form of the mandrel lowering down in the load direction reported over the testing time (Fig. 4a), the fulfilled area containing all the performed cycles (Fig. 4b). For a clearest comparison of the results at the different testing conditions, two continuous curves were extrapolated by connecting the lowest and the upper peak values of each cycles. In details, the lowest curve (dashed line in Fig. 4c) represents the mandrel displacement with the load kept at 2 kN, the upper one with the load applied to the specimen (continuous line in Fig. 4c). As clearly marked in Fig. 4d, the time-displacement history evolved according to three softening stages. Specifically, in the first stage a strong softening occurred during the first few hundreds of cycles without any form of damage (crack appearance). Then, the second stage was marked by a slow steady-state softening and also for this second stage no damage appeared. Finally, in the third stage, a drastic softening occurred related to the nucleation and propagation of one or more cracks in the specimen leading to the final failure. These results are in accordance to what reported in literature for similar hot-work tool steels and are due to an unstable microstructure with a high density of tangled dislocation and to the cyclic softening under non-null mean value that involves progressive increase of plastic deformation without saturation[9,20,21]. The number of cycles corresponding to the slope change from the second to the third stages was then assumed as the number of cycles to failure (Tab. 3).

In addition to the mandrel deflection over time and to the number of cycles to failure, the displacement occurring during the dwell-time at 1%, 50% and 90% of the total cycles were recorded for each specimen with the aim to highlight the creep behavior. In Figure 5 are reported the time-displacement histories for specimens 7 and 11 tested at the same load level (40 kN) but with a dwell-time of 160 sec and 300 sec respectively. The achieved results confirmed that the presence of a dwell-time introduced a time-dependent effect on the specimen deformation[3]. The path of the displacement over the dwell-time suggested that a primary as well as a secondary creep phase took place during this time, thus contributing to the viscoplastic strain increment developed by the alternating load.

Tab.3: Summary of the experimental plan and results carried out in the present investigation

Specimen	Load	Dwell-time	Nitrided	Calibration curve	Nr. of cycles to failure
1	26 KN	300 s	YES	1	
2		300 s	YES	2	
3	30 KN	300 s	YES	3	
4		300 s	YES	4	1250
5		300 s	YES	5	
6		300 s	NO	5	1540
7	40 KN	160 s	YES	4	307
8		160 s	YES	4	296
9		160 s	YES	4	213
10		300 s	YES	5	432
11		300 s	YES	5	395
12		300 s	NO	5	
13	45 KN	300 s	YES	5	279
14		300 s	YES	5	225
15		300 s	YES	5	312
16		300 s	YES	5	396

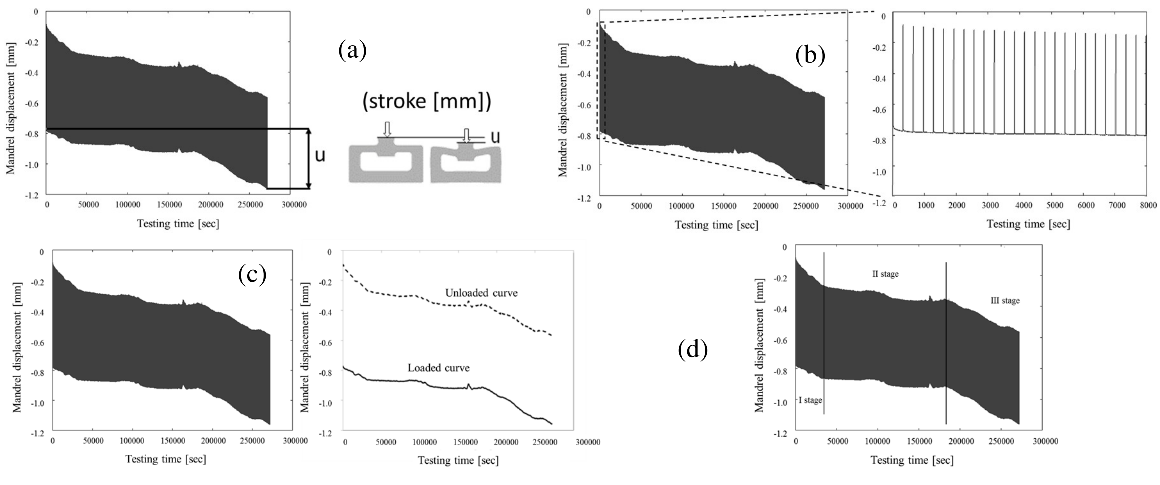

Fig. 4. (a) Main output of the experimental trials, (b) magnification of the mandrel displacement-time curve, (c) extrapolation of the two continuous curves from the original acquired data, (d) three-stages of softening of the mandrel displacement-time history

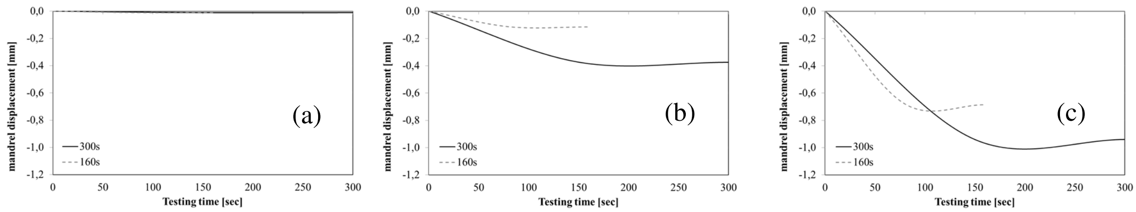

Fig. 5. Displacement occurring during the dwell-time at (a) 1/100 of cycles (4 cycles), (b) 50/100 of cycles (183 for specimen 7 tested at 160s and 199 for specimen 11 tested at 300s) and (c) 90/100 of cycles (329 for specimen 7 tested at 160s and 357 for specimen 11 tested at 300 s)

Results were then compared at the same load level in terms of continuous curve of the time-displacement history. In order to evaluate the effect of the dwell-time, specimens tested at 40 kN and 45 kN were compared (Fig. 6). The curves were normalized to zero displacement for a read clarity.

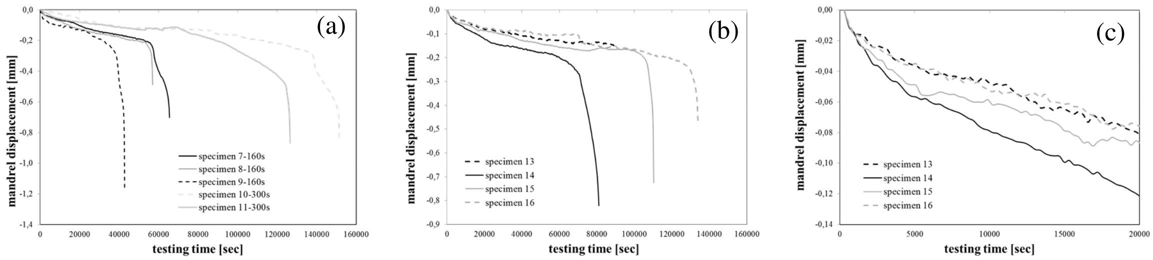

Fig. 6. Continuous curves normalized to zero displacement (a) for specimens 7,8, 9 tested at 40 kN at a dwell-time of 160s and 10,11 tested at a dwell-time of 300 s, (b) for specimens 13, 14, 15 and 16 tested at 45 kN, complete data set and (c) magnification of the original data.

As can be observed, the test showed a good repeatability in terms of time-displacement history for both load levels and, then, of lifetime prediction. In details, the time to crack propagation of specimens 7, 8 and 9, representative of the condition 160 sec of dwell-time, were all within 1 standard deviation (±48700 sec). Likewise, specimen 10 and 11, representative of the condition 300 sec of dwell-time, showed an 8% of difference in the time to crack propagation. The peak error with respect to the average value for specimens tested at 45 kN was a bit higher and equal to 25% for specimen 14.

It is interesting to note that, in a previous study of the same authors on the AISI H11[17], a reduced dwell-time under creep-fatigue loading at high temperature was proved to be beneficial in terms of the amount of softening and lifetime for not nitrided specimens. This was related to the reduced time during which the creep deformation mechanism can act as the responsible of an increasing in the developed viscoplastic strain. The detrimental effect of a reduced dwell-time in case of nitrided specimens, as for the TQ1 tool steel (Fig. 6a), can be explained with the fact that the effect of the nitriding is to produce a superficial layer that is harder but also less tough than the base material. So, while for the not nitrided specimens the ductile behavior was mostly negatively affected by the creep phenomenon (increasing dwell-time), for nitrided specimens the brittle behavior was primarily influenced by the fatigue effect (reduced dwell-time). The main effect of a reduced dwell-time was therefore to reduce the number of bearable loading cycles for specimens 7,8 and 9 promoting a premature failure if compared to specimens 10 and 11.

The ultimate goal of this work was the identification of a fatigue curve for the lifetime prediction of the TQ1 hot-work tool steel with a low silicon content. Thus, the load level applied to the specimens was plotted against the number of cycles to failure in logarithmic scale for the specimens tested at a dwell-time of 300 sec and a temperature of 520°C (Fig. 7a).

3.2. Evaluation of the nitriding effect on the specimen's lifetime

In the previous section, the influence of the nitriding on the effect of a reduced dwell-time has been highlighted pointing out a negative impact due to the decreasing toughness of the superficial layer. In order to evaluate the effect of the nitriding at the same dwell-time for the TQ1 tool steel, the lifetime of two not nitrided specimens at 30 and 40 kN were tested and compared with two nitrided specimens tested at the same load levels. In Figure 7b is reported the comparison, in terms of continuous curve, for the load level of 40 kN.

The perturbations on the mandrel displacement history for specimen 12 was related to temperature variations occurred during trials in a range of 5°C with respect to the set value if 520°C. This experimental evidence, even if not affects the achieved results, proves the requirement for an accurate measurement and acquisition, thus justifying the adopted multiple temperature monitoring.

From Figure 7b it emerges how the not nitrided specimen 12 had a longer life with respect to the nitrided one 10. In addition, specimen 12 showed a more marked secondary softening before the final crack, while the increased superficial hardness induced by the nitriding led to an almost steady-state secondary softening. The same was for the specimens tested at 30 kN; in details, not nitrided specimen 6 failed after 1540 cycles against 1250 cycles of the nitrided specimen 4 with a 19% increment of the lifetime.

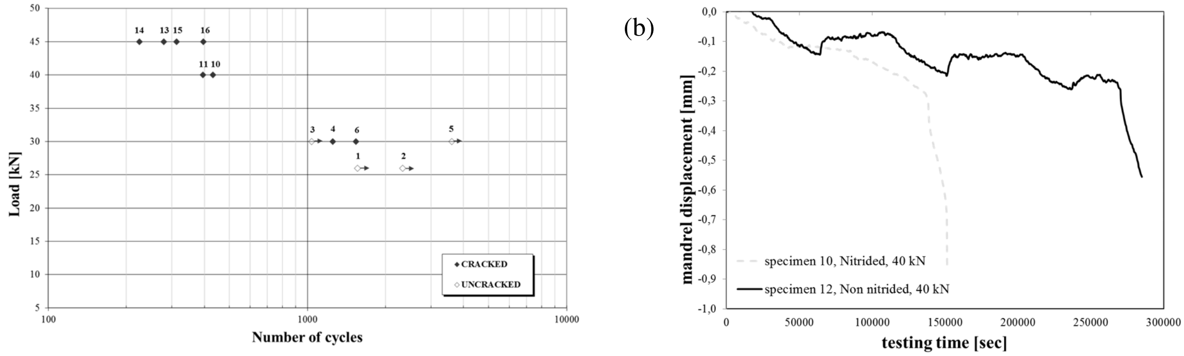

Fig. 7. (a) Load level versus the number of cycles to failure for the tested nitrided specimens at 300 sec of dwell-time and 520°C, (b) Comparison of nitrided versus not nitrided specimens in terms of time-displacement history at 40 kN

3.3. Comparison of the TQ1 and the AISI H11 hot –work tool steels

In the introduction section the influence of the silicon content of the AISI H11 tool steel has been reported based on previous studies[9]. The comparison of the TQ1, low silicon, tool steel fatigue properties against the high silicon content AISI H11 was performed also by the authors on the basis of the small die specimens test here presented. The AISI H11 was tested at little higher temperatures levels (540°C and 580°C, among others) with respect to the set value of 520°C used for testing the TQ1[17]. Results in terms of number of cycles to failure were reported in the fatigue curve of the TQ1 tool steel (Fig. 8). Specimen in AISI H11, tested at 29 kN and 19.3 kN at 540°C, did not failed within the testing time.

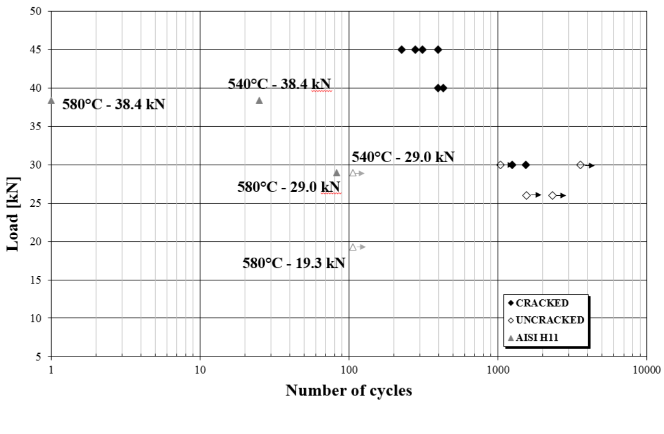

Fig. 8. Fatigue curves for the TQ1 and the AISI H11[17] hot-work tool steels tested by means of the small scale die specimens.

According to the achieved outcomes, and accounting for the fact that the specimens made of AISI H11 were not nitrided, it is reasonable to suppose a fatigue curve of the AISI H11 at 520°C still placed at the left side of that of the TQ1 tool steel, thus confirming the detrimental effect of a high silicon content in the lifetime of such type of tool steels used for hot forming applications. Moreover, the results seem also to confirm an increment amount of the TQ1 (low silicon) lifetime near to five times than that of the AISI H11 (high silicon)[9].

CONCLUSIONS

In the present research, an investigation on the TQ1 tool steel performances under the creep-fatigue regime was carried out by means of a small scale die specimens at a temperature level of 520°C. Different testing conditions, in terms of load levels (26, 30, 40 and 45 kN), superficial treatment (nitrided and not nitrided) and dwell-time (160 sec and 300 sec) have been taken into account and compared in terms of lifetime. In addition, the fatigue lifetime of the TQ1 was compared with that of the AISI H11 previously tested by the authors with the same innovative testing method.

The main outcomes of this work can be summarized as follow:

- For all the tested configurations, the time-displacement history of the specimen mandrel evolved according to three softening stages: an initial strong softening in the first few hundreds of cycles without any form of damage, a second stage of a slow steady-state softening without any damage and a third stage of a drastic softening related to the nucleation and propagation of one or more cracks in the specimen.
- The three-softening stages are in accordance to what reported in literature and previously proved by the authors for similar hot-work tool steels (AISI H11) and are reasonable due to an unstable microstructure with a high dislocations density and to the cyclic softening under not-null mean value that involve progressive increase of plastic deformation without saturation.
- The performed tests showed a good repeatability in terms of time-displacement history and, then, of lifetime prediction.
- The dwell-time introduced a time-dependent effect on the specimen deformation occurring at a constant load during which primary as well as a secondary creep phase took place contributing to the viscoplastic strain increment still developed by the alternating load.
- In case of nitrided specimen made of TQ1, a decrease of the dwell-time led a corresponding drop of lifetime. The opposite was found for the AISI H11 in not nitrided specimens for which a decrease of the dwell-time was found beneficial for the lifetime.
- The detrimental effect of a reduced dwell-time for nitrided specimens was explained with the fact that the superficial treated layer was harder but also less tough than the base material. So, while for the not nitrided specimens the ductile behavior was mostly negatively affected by the creep phenomenon induced by an icreased dwell-time, for nitrided specimens the brittle behavior was primarily influenced by the fatigue effect induced by a reduced dwell-time.
- The innvoating testing method based on small scale die specimens was found able to generate results in the form of fatigue curves (load level versus the number of cycles to failure) to be used in pratical applications.
- The compariosn of not nitrided and nitrided specimens at the same dwell-time (300 sec) showed a prolonged lifetime of the not nitrided one. In addition, the not nitrided specimen showed a more marked secondary

softening before the final crack, while the increased superficial hardness induced by the nitriding led to an almost steady-state secondary softening.

- The comparison of the TQ1 (low silicon) and the AISI H11 (high silicon) hot-work tool steels performed on the base of the small scale die specimens confirmed the detrimental effect of an high slicon content to the lifetime.

In conclusion, the innovative testing method was found able to evaluate the effects of the different loading and superficial conditions on the lifetime of the small scale components made of the TQ1, low silicon, hot-work tool steel. The designed experimental tests, accounting for the main deformation and damage mechanisms and being a down-scaled model of the most critical area of a hollow die, could therefore be used to properly design forming tools providing information on the highest level of stress bearable by the tool at a given temperature for a given material. Different tool steels or the same tool steel after different heat treatments can be rapidly and economically tested with such specimen configurations, thus providing an efficient support for the die design.

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