The AISI H11 creep-fatigue behaviour: an innovative experimental design

B. Reggiani, L. Donati, L. Tomesani
DIEM-Department of Mechanical Engineering, Bologna, Italy

J. Zhou
Department of Materials Science and Engineering, Delft, The Netherlands

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Introduction

During the hot-extrusion manufacturing process, a number of damage and deformation mechanisms act simultaneously to produce cumulative damage to the tools, thus causing the increasing deviations from the original geometry or the final breaking [1-3]. Due to the severe cyclic thermo-mechanical loads, mandrel, i.e. the part of the hollow die that defines the internal shape of the profile, is the most critical component in the extrusion of an hollow profile. Indeed, the high pressure generated during the process creates severe friction conditions that results in longitudinal tensile stress and significant bending stresses can arise in the bridges of the mandrel during extrusion. In addition to the mechanical cyclic load, the total loading/unloading time for the whole batch and the temperature that the die is exposed to are great enough to necessitate the consideration on the creep behaviour of the die material, particularly for hollow dies. Hence, the combination of dynamic, heavy loading and high temperature determines a hostile working condition for the mandrel that is normally designed on the basis of static loading at elevated temperatures on hot-work tool steels that are tempered to reach an adequate balance of hot hardness and toughness. Premature failure may occur after a certain number of loading and unloading cycles as a result of creep-fatigue interaction. The new technologies developed for aluminium extrusion aim to minimize the tool system-material flow interference and optimize the mechanical performance of the die that is related both to design and tool steel.

Aim of the present work is to illustrate the steps followed to design an innovative experimental test purposely developed to investigate the deforming mechanisms of the AISI H11 tool steel in the creep-fatigue regime. The specimens replicate the geometry and the loading scheme of a mandrel on a smaller scale and are manufactured following the same working scheme. In such a way the test is able to account for realistic stress and strain distributions and superficial roughness of a real mandrel as well as to investigate different material and heat treatments.

Material & methods

In order to define the specimen design, a number of requirements and constraints were taken into account.

A first set of constraints were imposed by the testing machine used for the experimental investigation, the thermo-mechanical simulator Gleeble 1500. In this system, the specimen, that is held between two tools, is heated using Joule's effect with a close-loop feedback signal that enables precise control of the heat input throughout the test. Standard specimen for this testing machine should had a maximum of 20 mm^2 as contacting area with tools and the peak applicable load was restrained, in compression, to 80 kN. The force measurement accuracy was ± 1% of full scale. An additional requirements for the specimen was related to its workability. For a correct replication of the superficial state of an extrusion die, the design of the specimen had to be not extremely complex and workable by following the same manufacturing sequence usually adopted to produce an extrusion die (EDM cutting).

A second set of specifications was aimed to replicate as close as possible an industrial extrusion die in terms of material and loading scheme. The material chosen was the AISI H11 tool steel with a tempered martensitic structure. The chemical composition, as monitored with an X-ray fluorescence analysis (XRF), is reported in Tab. 1:

C*	Fe	Si	Mn	P	S	Al	Cr	Mo	Ni	Cu	V
---	90.95	0.90	0.48	0.059	0.0056	0.0295	5.13	1.27	0.198	0.373	0.308

Table 1: Chemical composition of the AISI H11 tool steel used in this work.

With regards to the loading scheme, a double fixed end beam loaded in the middle was used as the basic scheme to reproduce the loading conditions acting on the mandrel of a porthole die (Fig. 1)

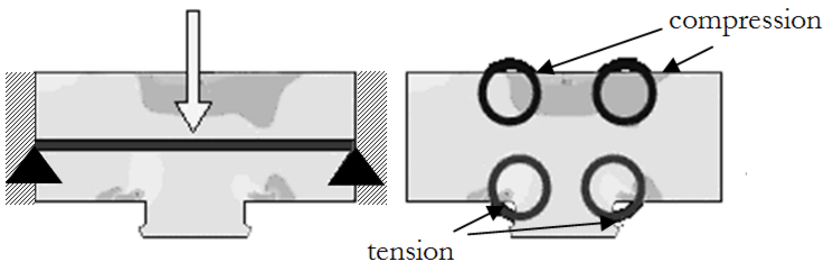


Figure 1: Loading scheme of the mandrel of a porthole die

Several specimen designs were investigated and tested by means of finite element (FE) simulations under the aforementioned constraints. In the following are reported some of these configurations:

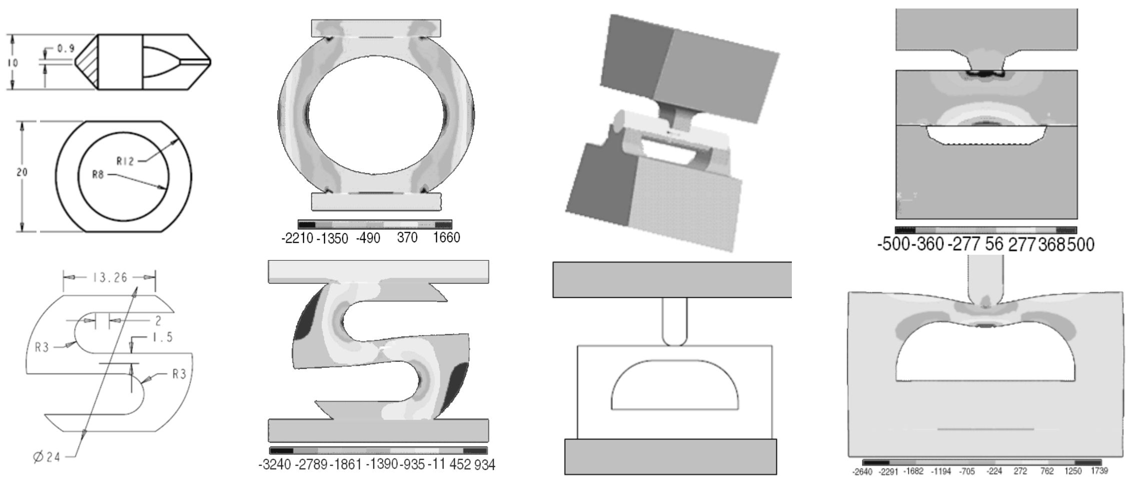


Figure 2: Some of the specimen configurations investigated. For each configuration are reported the geometric model and the Von Mises stress distribution as predicted by FE analysis.

All the illustrated configurations of the specimen violated one or more of the imposed constraints or experienced problems at the specimen-tools interfaces (e.g. reduced contact area or loss of the contact under an imposed load). The definitive shape of the specimen (Fig. 3) met all the imposed constrains, except the maximum contacting area with tools that measured 650 mm^2. However, even if the resulting shape was not a standard configuration for the Gleeble system, a good thermal distribution was guaranteed. The specimen was designed to replicate the geometry of the die mandrel on a smaller scale, thus containing a core support and two bridges. This geometry included all the characteristic elements of an hollow die, including fillet radius, the height and width of the bridges.

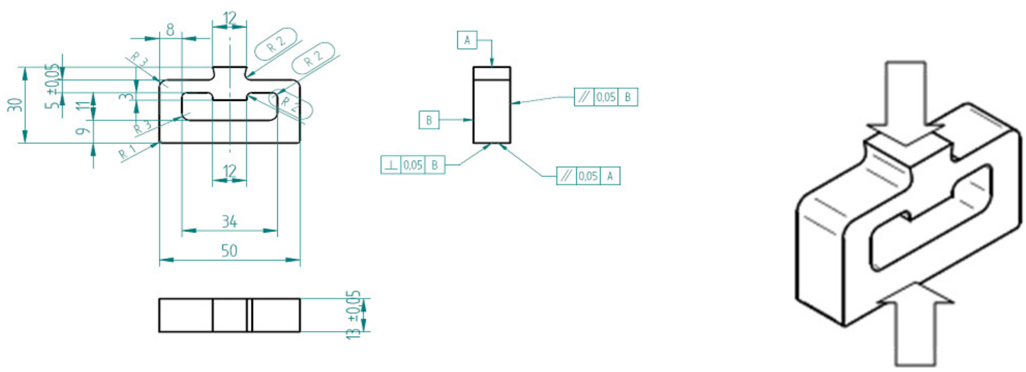


Figure 3: Final design (left) and loading (right) configuration of the specimen.

In order to achieve an hardness value in the range of 46-48 HRC, typical of an extrusion die, the specimens were subjected to the same sequence of thermal treatments. In particular, a four-step heat treatment was applied consisting of austenitizing at 1000°C, quenching in nitrogen atmosphere and double tempering (Table 2).

	Austenitizing	Quenching	First tempering	Second tempering
Time		30 min(nitrogen)	5 h	4.5 h
Temperature	1000° C		550° C	585° C

Table 2: Heat treatment applied to the AISI H11 steel

Two tools made of the AISI H13 steel with an hardness of 55 HRC were used to hold the specimens during the testing time in the Gleeble system.
In order to investigate the level of stress to be induced in the specimen during the test, two porthole dies with different bridges design were analysed (Fig. 4).

Figure 4: Geometry of the porthole die: standard (left) and blade (right).

An FE code, DEFORM 3D®, was used to simulate the extrusion process and to predict the force components exerted by the deforming workpiece on the dies. Then, a subroutine was developed to transfer the load data to a code specifically dedicated to structural analyses and more suitable for the die stress analyses. The followed procedure is described in details in [4]. Within this code, the FE models of the dies consists of 561359 and 1068823 10-noded tetrahedral solid elements for the blade and the standard geometries respectively corresponding to 782339 and 1482615 nodes. A linear elastic material model was assumed (EX= 210000 MPa, ν=0.3). The results were analysed in terms of the equivalent Von Mises stress.
Once defined the level of stress to be induced in the specimens, an experimental campaign was performed accounting for three levels of stress, four levels of temperature (380°C, 490°C, 540°C and 580°C) and three type of loading conditions (pure creep, pure fatigue and creep-fatigue) [5]. Example of the output results are then presented.

RESULTS

In Fig. 5 is shown the Von Mises stress distributions in the cross-section of the two die designs analysed.

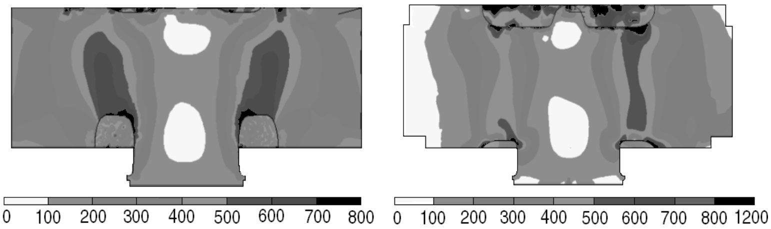
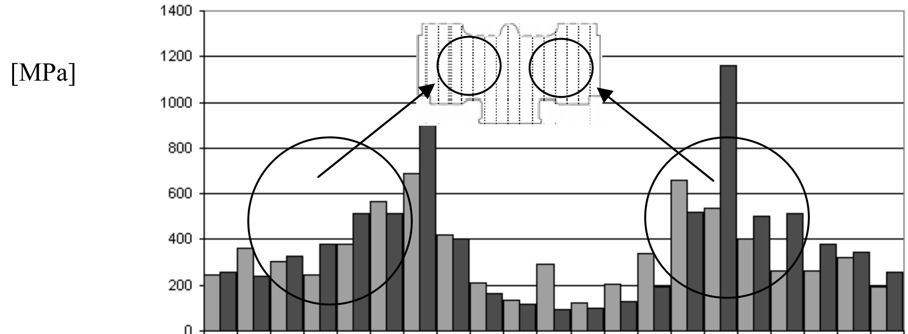


Figure 5: Von Mises stress distribution (MPa) in the cross- section of the porthole dies: (left) standard, (right) blade.

The average Von Mises stress was then computed in a number of spatial intervals in which the cross-section of the bridge was divided (Fig. 6). Observing the mean stress values on the bridges, the range between 400 and 800 MPa was chosen to be induced in the specimens. Then, an FE analysis of the tools-specimen contact and specimen deformation was performed to optimize the specimen geometry and dimensions and to select the load intensities in order to achieve the selected average values of stress on the specimen bridges, 400, 600 and 800 MPa. As a results, a load of 19.3, 29 and 38.4 kN respectively was applied to the specimen faces (Fig. 3). In Fig. 7 are shown three examples of the output results, in terms of time-displacement of the mandrel, that were obtained with the presented innovative technological test for the three tested loading type: pure fatigue, pure creep and creep-fatigue All the results can be found [5].



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
BLADE	246	362	302	246	380	564	690	419	212	136	293	123	206	339	659	534	404	264	262	318	193
STANDARD	256	237	325	380	513	515	1150	404	165	118	92	97	129	193	520	1160	501	513	380	345	258

Figure 6: Average Von Mises values (MPa) in the spatial interval cross- section of the porthole dies: (left) standard, (right) blade.

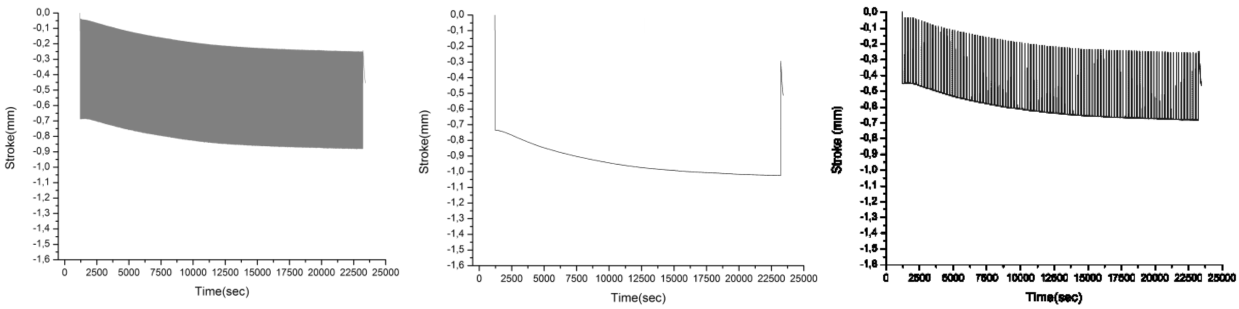


Figure 7: From left to right: time-displacement curves of the specimen's mandrel as obtained under pure fatigue, pure creep and creep-fatigue loading (400MPa, 490°C).

CONCLUSION

Accounting for the proved influence of both creep and fatigue in the lifetime of extrusion dies, the present research was performed to investigate the performance of a hot-work tool steel H11 under the normal working conditions as applied to hollow extrusion dies in industrial practice. A great work was done to define the design of the specimens as well as the testing conditions and presented in this work. The purposely designed specimens were tested under pure fatigue, pure creep and creep-fatigue loading at different levels of stress and at different temperatures and examples of the achieved results were shown. The results of this research confirmed the capabilities of the testing method to evaluate the effects of both the design (stress) and process (temperature) parameters in extrusion on the deformation and lifetime of the mandrel in the hollow die. The geometry of the specimen designed on the basis of FE analysis allowed the dedicated analysis of the regions affected by creep and fatigue. This made the test a powerful tool for the die designer.

REFERENCES

[1] L. Donati, L. Tomesani, Journal of Material Processing and Technology, 164-165 (2005) 1025.
[2] W. A. Assaad, H.J.M. Geijselaers, J. Huetink, In: Proceeding of ET '08, Gaylord Palms Orlando, Florida USA (2008).
[3] M. H. Sabour, R. B. Bhat, Materials Science-Poland, 26(3) (2008).
[4] B. Reggiani, L. Donati, L. Tomesani, In: Proc. 13th Int. ESAFORM Conf., Brescia, Italy, (2010).
[5] B. Reggiani, L. Donati, J. Zhou, L. Tomesani, "The role of creep and fatigue in determining the high-temperature behaviour of AISI H11 tempered steel for aluminium extrusion dies". In Press to the J. Mater. Proc. Technol.