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ELABORATION OF DUCTILE FRACTURE CRITERIA BASED ON PUNCHING FORGEABILITY TEST

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Abstract

A new approach of forgeability test, based on compression-punching state of stress was proposed. Comparison of the results of the presented research methodology with standard compression test is presented. The new forgeability test is designed to generate controllable failure location for good plasticity materials, where fractures result from high level of stresses achieved. Different shape of tools and specimens tend to show the effect of geometry on the areas of concentrations of tensile and shear stresses which favour the formation of cracks. The paper presents the methodology based on laboratory tests of compression and pseudo-punching performed on laboratory rig with 5MN hydraulic press and numerical FEM simulation of the tests on commercial code with introduction of the elaborated fracture criteria.

Key words: forgeability test, failure strain, fracture prediction, FEM

1. INTRODUCTION

In traditional compression test a cylindrical specimen is upset into a flat pancake and it is usually considered to be a standard bulk forgeability test (Suresh et al., 2014; Lisiecki et al., 2015; Semiatin, 1996). The state of stress observed in common workability is similar to that in many bulk deformation processes, without introducing the problems of necking (in tension) or material reorientation (in torsion) (Suresh et al., 2014; Lisiecki et al., 2015). Therefore, a large amount of deformation can be achieved before fracture occurs. The limit for compression without failure by radial or peripheral cracking is considered to be a measure of forgeability (Suresh et al., 2014; Semiatin, 1996).

The principle of the standard method of fracture criteria formulation is inseparably associated with accurate definition of the limiting deformation at which the facture is observed. Hence, the validity of the determined value depends on indication of the moment of fracture occurrence. Standard attitudes involve load drop criterion, Rice and Tracey (Lisiecki et al., 2015; Gouveia et al., 2000). The use of the load plotting works well in case of brittle materials, whereas ductile ones hardly indicate reliable changes in the load diagrams. Besides, overlapping of concurrent occurrences may blur the result. High resolution and high frequency photo shooting devices allow precise determination of the moment of failure initiation as long as it falls into the spotlight side. To solve the problem of insecurity as for the location of cracks formation, special design of geometry can be used, promoting concentration of stress in a desired point.

Another setback of standard compression is testing the materials which feature good workability. In such cases the fracture does not readily occur, but when it does, it is assisted by severe reduction ratio. The presented test makes it possible to reach the moment of fracture initiation at accessible hight reduction, sufficient enough to induce fracture in the

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good workability material. This method was necessary for the analysis of the reasons of cracks formation during dynamic forging processes where high levels and unfavorable concentration of stresses are achieved. In this light, initial part of the work is focused on two aspects: 1) selection of the sample shape for compression test which would control the areas of defects formation and 2) design and construction of the new set of tools used for forgeability test and dedicated to dynamic forging operations.

The integration of the proposed tasks allows the development of rules and guidelines for a new laboratory test for determining the workability limit of the material. Additional analysis based on numerical simulation made it possible to determine the process conditions favorable for fracture formation.

2. THEORETICAL AND NUMERICAL ANALYSIS

Based on literature analysis, it was found that the shape of the specimens during compression determines the occurrence of tensile stress concentration zones, which are largely responsible for the formation of cracks (Saanouni, 2008). The selection of shape is done based on the following criteria:

– concentration of stress (mostly tension) at specific areas,
– the cost of production and repeatability of the samples shape.

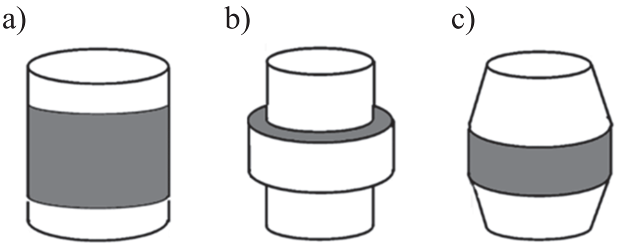

Fig. 1. Examples of the samples shapes for the compression test with zones of tension stress concentration (grey)

A few different shapes of samples used in conventional compression test were considered in the analysis (figure 1). With regard to the above requirements the rectangular geometry was selected. The selection is based on numerical simulations and laboratory tests, which took into account the analysis of stress concentration sensitivity to sample shape.

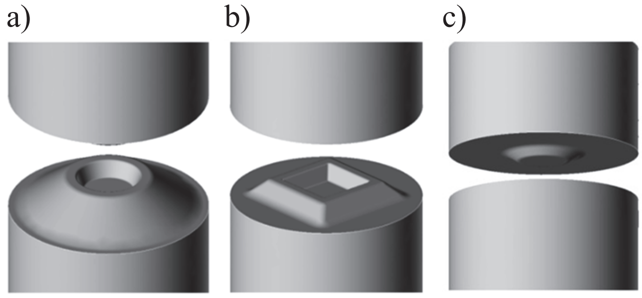

Fig. 2. Geometrical models of selected tools for workability tests

Another aspect of geometrical modification of the compression test was the change of the tools shape. It aimed at increasing the value and concentration of stresses which favor the development of cracks. The inspiration for the research was the analysis of material flow in the area of flash during forging (Sivasankarana et al., 2011; Saanouni, 2008) for the distribution of process parameters with different dynamic of deformation. Several different shapes of tools were proposed (figure 2). Their analysis was based on the following criteria:

– the possibility of compression of samples with different dimensions,
– stress concentration in a particular region of the sample during compression.
– easy, quick and accurate positioning of the sample.

After laboratory trials supported by numerical simulation, specific tools geometry was selected. It allowed simultaneous upsetting and punching, depending on dimensions of the sample. Figure 3 shows exemplary distribution results of selected parameters on the surface of the sample during test. High values of stress concentration at the center of the sidewall of the sample can be seen especially in figures 3a and 3b. On the strength of Rice and Tracey fracture criteria, higher risk of fractures occurrence is reported in this area (figure 3d). Analyzing the distribution of shear stress, two areas of concentration of their maximum values were observed: 1 - central area of the side wall (as in the case of mean stress and maximum principal stress), 2 - the upper corners of the sample in the vicinity of the upper tool. This means that the main reason of cracks initiated in the second area is mainly unfavorable distribution of shear stresses.

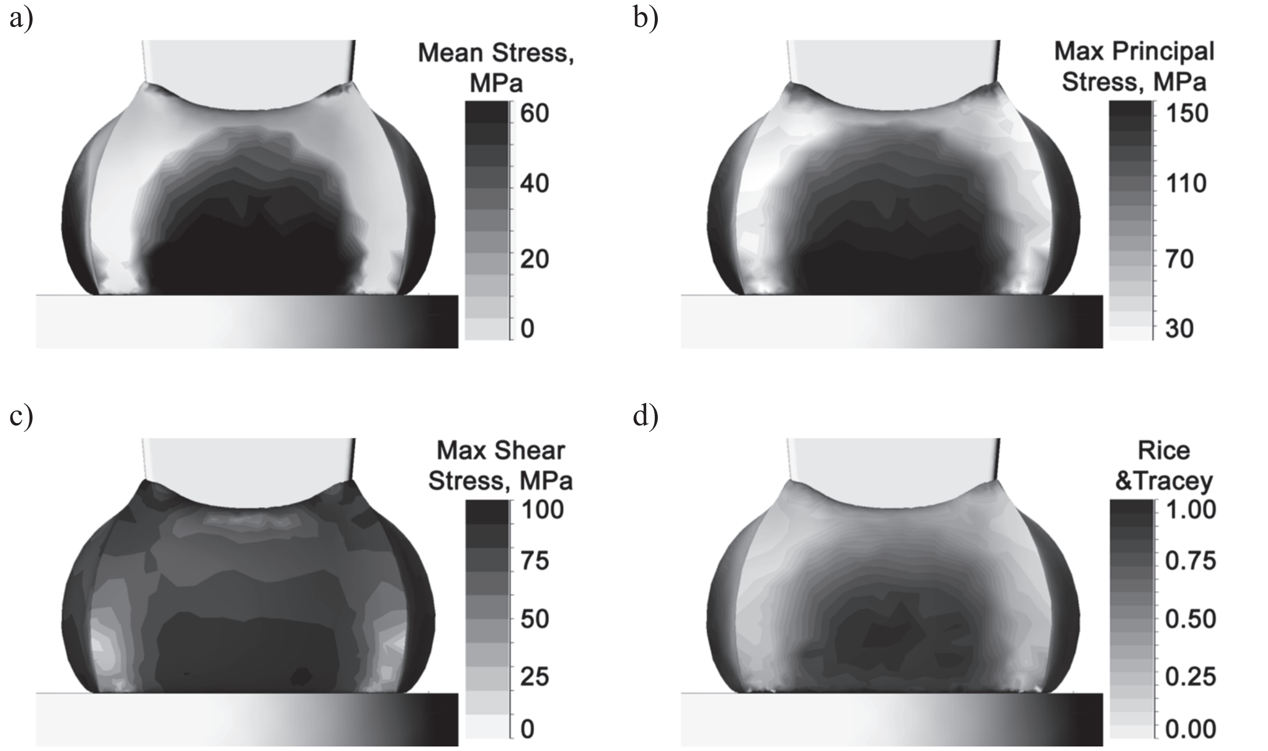

Fig. 3. *Results of numerical simulation of forgeability test in punching tools set. Distribution of: a) the maximum principal stress, b) the mean stress, c) the maximum shear stress, d) Rice and Tracey fracture criterion, on the specimen surface*

The proposed tools geometry facilitates the observation of sample areas, where the crack initiation is expected. In addition to the punch, the configuration of the lower tool includes a recess allowing for quick positioning of the sample. This is particularly important when conducting tests at elevated temperatures, where cooling time in the air during transportation from the furnace and in tools should be very short.

3. RESULTS

The obtained results of experiments and numerical modeling allowed geometrical models and technical documentation of new tools for compression tests to be made up. The new geometry makes it possible to conduct two operations (upsetting and punching) at one blow. Rectangular shape of specimens with a length of base sides 37 mm and height of 129 mm were used. Tools were made of heat treated tool steel WCLV in order to obtain the hardness of 42 - 46 HRC. The boundary conditions of the test (e.g. initial temperature of the sample, cooling

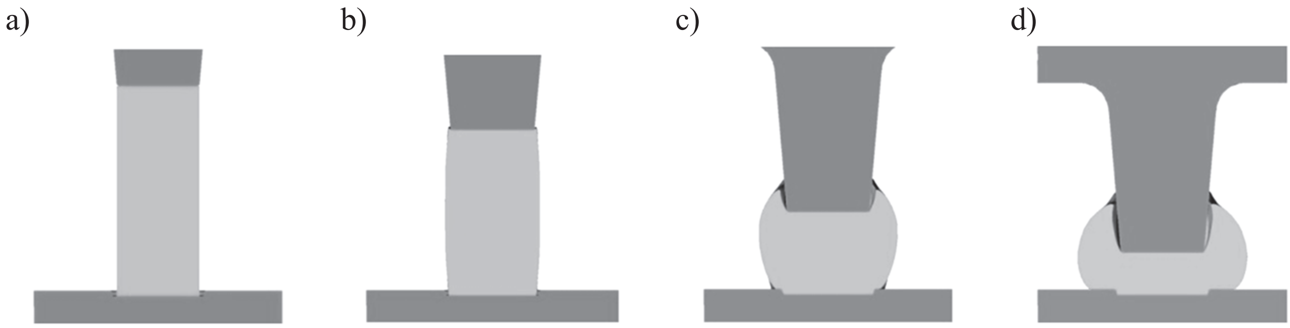

Fig. 4. *Longitudinal cross-section of the sample and tools during test: a) beginning, b) upsetting, c) punching, d) end of the process*

time in tools) are dependent on the conditions of industrial forging process.

Tools dimensions are adjusted so as to:
- prevent loss of stability of specimen during the test,
- generate relatively the highest deformation,
- provide easy access of the deformation area for observation.

Reduction of the samples dimensions (length of base sides less than 37 mm) causes the time prolongation of upsetting operation (figure 4b), before punching starts (figure 4c). Depending on the material and the process conditions the minimum value of the base surface of the sample can be estimated, which lets carry out upsetting and punching operations at the same test. Above that value and under these conditions the test will consist of only one of those operations i.e. forging stage.

a) b)

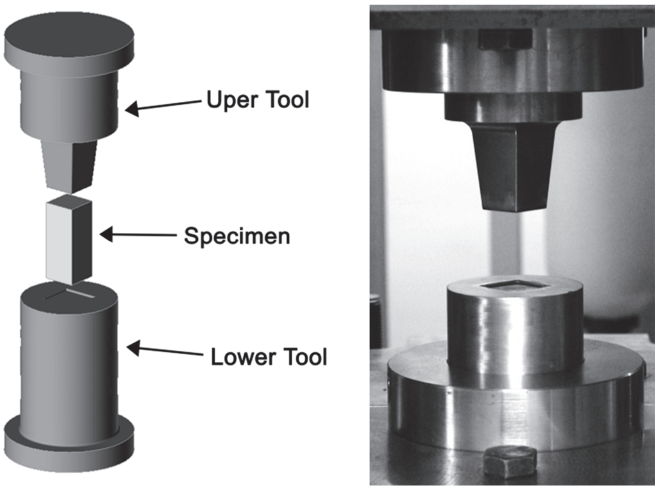

Fig. 5. *Tools for punching workability test: a) geometrical model, b) tools on the laboratory hydraulic press*

The new proposed compression test laboratory rig consists of two elements (figures 5a and 5b): the lower one (with a recess for correct positioning of samples) and upper one (in the form of a punch of square working surface). The test is conducted until the rupture of the material takes place or the final distance between tools is arrived at. At the same time, the created models (figure 5a) can be used for numerical simulations which would allow tracking the parameters in a precisely defined location.

Testing of new tools for deformation limit analysis of materials were carried out for both close and open die forging processes. Figure 6 shows the results of compression of the rectangular sample of aluminum alloy (figures 6d, 6e, 6f) including upsetting and punching operations, and the cylindrical sample of the same material in conventional compression test (figures 6a, 6b, 6c). The differences in relative deformation prior to the occurrence of fracture are the result of different initial temperatures of the material measured with the use of a pyrometer (bright spots on the surface of the samples).

Various types of cracks depending on the test conditions were observed. Failure of the structure in case of the component of higher initial temperature (rectangular specimen) occurred at the point of maximum shear stress concentration (upper corners of the sample) after substantial plastic deformation. The crack in case of the cylindrical sample is preceded by small plastic deformation and its line of propagation coincides with the direction of maximal shear stresses which may indicate a brittle type of fracture.

The next stage of verification of the new workability test solution was its comparison with the traditional method of research where the tools with a flat working surface were used. Samples of prismatic shape made of stainless steel (AISI 4140) were used in the analysis. The intention was to reflect the manufacturing conditions of large-size forgings (Skubisz et al., 2015). The investigations involved compression of samples with two different deformation ratios (defined as the ratio of absolute deformation to the height of the initial sample) 54% and 71%, using both investigated tool sets and observation of samples surfaces in order to identify the locations of cracks.

4. CONCLUSIONS

Analysis of the results showed fracture occurrence only in the case of specimen 4 (figure 7a). Cracks in the concentration area of both shear and tensile stresses were observed. In other cases, the samples were not damaged.

The compression load in the case of punching tools (figure 7b) was significantly lower than in conventional compression test. During flat-tools deformation test the contact area between specimen and tool increases as a result of free flow being the cause of load increase. In case of punching tools, maximum contact area of the upper tool and the material is decreased to the working surface of the stamp. Thus the increase of force in the final phase of the test is not observed. This fact seems crucial from the point of view of maximal force of the available laboratory equipment.

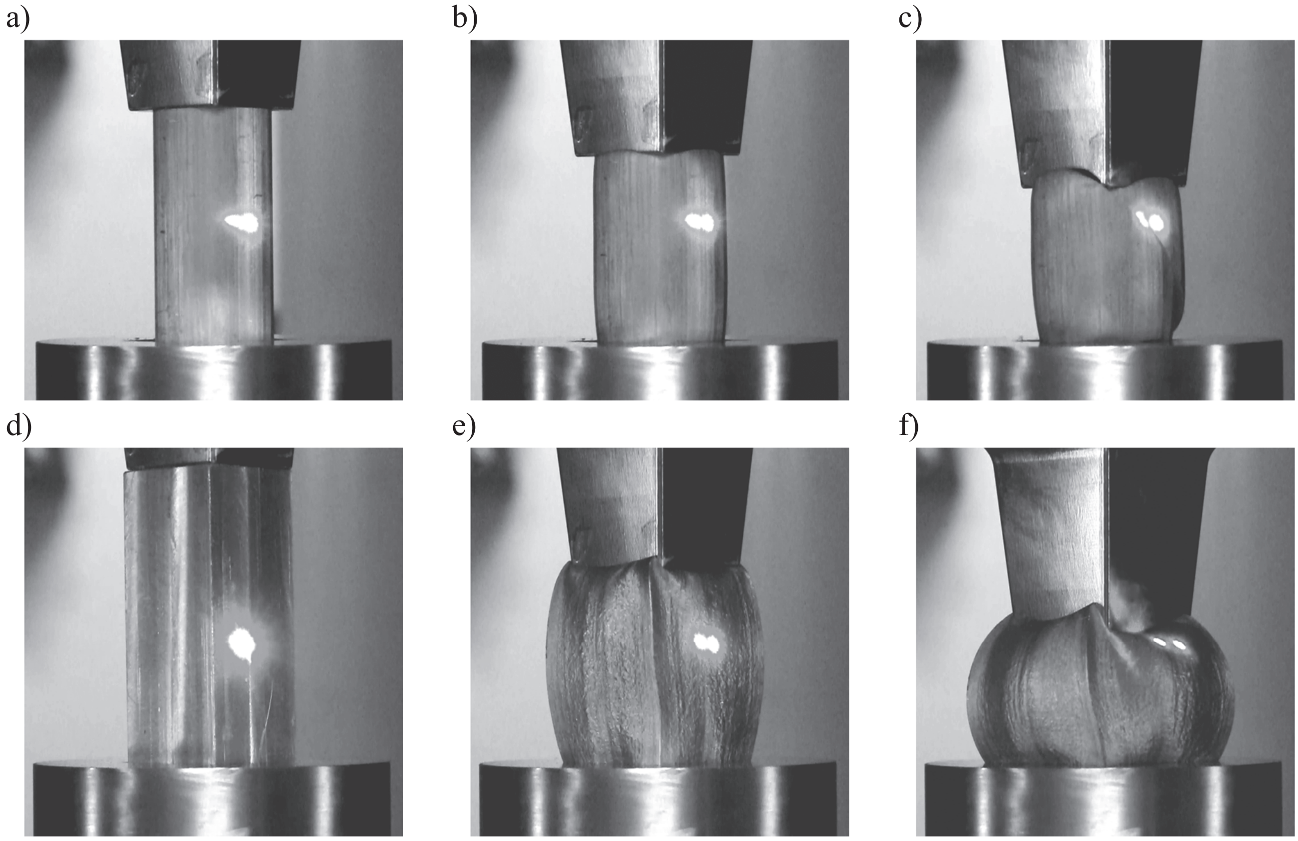

Fig. 6. Forgeability test sequences of Al alloy of the: a, b, c) cylindrical specimen (initial temperature of 20 °C), d, e, f), rectangular specimen (initial temperature of 200 °C)

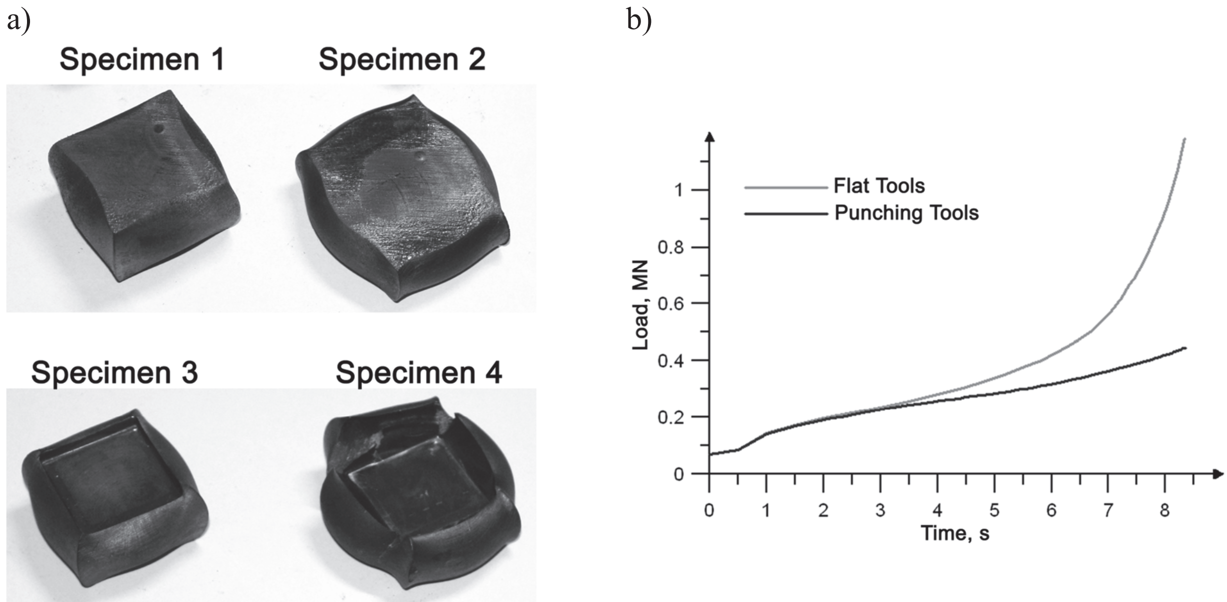

Fig. 7. Comparison of conventional compression test with the new solution: a) deformed samples b) compression load

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OPRACOWANIE KRYTERIÓW PĘKANIA CIĄGLIWEGO W OPARCI O TEST ODKSZTAŁCALNOŚCI BAZUJĄCY NA OPERACJI DZIUROWANIA

Streszczenie

W artykule przedstawiono nową koncepcję laboratoryjnego testu ściskania. Wyniki standardowego testu porównano z rezultatami osiągniętymi podczas badań z użyciem narzędzi wykonujących wgłębienia w próbkach. Nowa propozycja wyznaczania odkształcalności granicznej jest dedykowana materiałom o dobrej plastyczności, gdzie pęknięcia są powodowane osiągnięciem wysokiego poziomu naprężeń. Zmiana kształtu odkształcanych próbek oraz narzędzi wywołały wymaganą koncentrację naprężeń rozciągających oraz stycznych sprzyjającą powstawaniu wad. Badania stanowią połączenie testów laboratoryjnych z wykorzystaniem prasy hydraulicznej o maksymalnej sile nacisku 5MN oraz symulacji numerycznej MES.

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