

FEM SIMULATION OF THE NEW RADIAL FORGING DEVICE PROCESS AT SIDENOR

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1. SUMMARY

To satisfy demands for improving the quality of forged bars and shorten the production times a new device was installed in a conventional hydraulic open-die forging press (SIDENOR Reinosa Works).

The configuration of this radial forging device (RFD) was developed by Viktor Lazorkin, Ph.D. (Ukraine). The asymmetric ram speed configuration (cinematic) of the device produces the effect of material twisting resulting in a better macrostructure of forged pieces as will be demonstrated on this paper.

This paper summarizes the finite element modelling (FEM) simulations, developed within the framework of the commercial code DEFORM, and the experimental trials that were carried out to improve die design and the development of process parameter optimisation.

On the basis of the simulations and the experimental trials it can be stated that the use of the RFD has a favourable effect in terms of improving the strain distribution over the cross section of forged bars, as well as in terms of the removal of defects of metallurgical origin (e.g. voids, shrinkage cavities).

2. THE FOUR-DIE FORGING DEVICE

Compared to other forging methods, radial forging is relatively new. It started to be commercialized in the late twentieth century. Radial forging may be characterized as a multi-hammer, open die forging process for producing solid and hollow, rotational and non-rotational, axisymmetric parts.

The configuration of our RFD was developed by Viktor Lazorkin, Ph.D. (Ukraine). The four dies are radially arranged in a plane perpendicular to the main forging axis of the piece. The top die moves attached to the ram and the two lateral dies move relative to the movement of the upper ram according to the edge guide design. The main difference with other radial forging machines is that the bottom die is fixed to the press bed and the speed of the lateral dies is half the speed of the upper die.

The four-die forging device presently works at Reinosa in the open-die forging press of 20 MN to forge ingots of 5 to 7 tons of carbon, alloyed structural and tool steels.

3. FINITE ELEMENT MODELLING OF THE RADIAL FORGING PROCESS

This paper details Sidenor's R&D experience in the use of DEFORM for radial forging device process simulation and its relevance to improve die designs and the development of process parameter optimisation.

Process modelling has become an effective tool in reducing the lead-time and the cost for designing forging processes. Process simulation can give comprehensive details including material flow and strain/stress/temperature distributions that assist the designer in the process design to obtain optimal results.

3.1 FEM package DEFORM™-3D

The simulations were run using the computer program DEFORM, which was specifically adapted for simulating radial forging processes. It was found to be useful in modelling the radial forging process and offers the user detailed post-processing results and information on strain, strain rate, temperature, and metal flow. SolidEdge was used to model the dies and the ingot.

The main reason for selecting the DEFORM program for the simulation was the reduction in the computation times in comparison with other FEM programs such as ABAQUS Explicit or FORGE3 as reported by other simulation and modelling centres [1]. 3D problems have taken between 1-3 days to run so far, and are dependent on the complexity of the simulation being run.

3.2. Material properties and boundary conditions

In metal forging, the flow stress (material property) and the coefficient of friction (boundary condition) are important variables for the simulation of the forging processes. The main reasons are two: Firstly, the flow stress of the workpiece directly influences the prediction of the forces and the energy for carrying out the forging operation, because it is a function of the strain (ϵ), the strain rate ($\dot{\epsilon}$), the temperature (θ) and the microstructure during plastic deformation. Secondly, friction increases forging load, changes material flow, strain/stress distribution and influences the shape of the pieces that are deformed, when the forging pressure is transmitted from the dies to the deformed workpiece.

Therefore, without the accurate flow stress and coefficient of friction, it is impossible to get an accurate simulation of a given forging process.

The deformation rates encountered in RFD process are within those typically encountered for two die press operations. These low speeds, result in low strain rates, differ from the flow stress data available at the DEFORM materials database. Values of up to

0.001 mm/s have been observed during the forging process.

In order to complete the flow stress information in the DEFORM database, a series of low strain tensile tests have been conducted on the Gleeble machine in Sidenor's R&D laboratory.

Fig.1 shows the strain-stress curves obtained for an alloyed steel grade transferred to the DEFORM material data base.

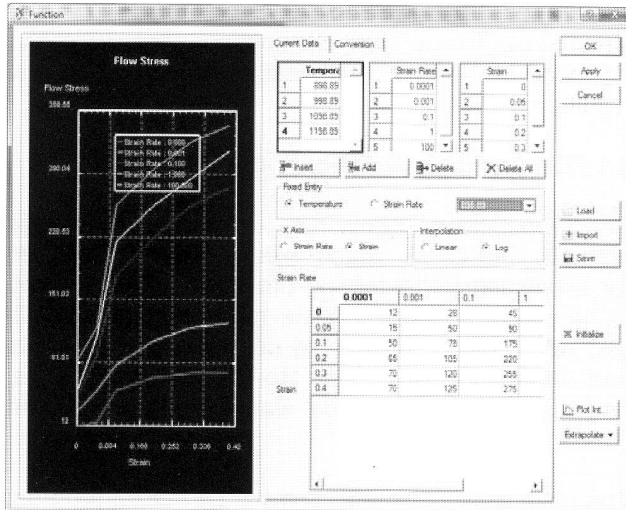


Fig. 1. Strain-Stress curves for low strain rates for an alloyed steel grade

The friction coefficient at the interface between the stock and the dies was validated according to the forging load registered during the industrial trials and the deformed geometries observed with thermographic pictures.

Tresca's friction law was used for the description of the friction conditions at the interface between the stock and the dies. The deduced value of the friction factor ranged from 0.5 to 0.7.

4 INFLUENCE OF THE RADIAL FORGING PROCESS ON THE SURFACE DEFECTS OF THE FORGED BARS AND ON THE CLOSURE OF DEFECTS OF METALLURGICAL ORIGIN

The quality of the forged bars (both internal and superficial) should be considered as the major criterion for assessment of the proper forging processes.

The most convenient way to assess the effect of forging process parameters on the local mechanical states in the deformation zone is finite element analysis.

Various simulations related to the RFD processes were carried out; the most relevant cases will be described in this paper:

- The first of the analyzed cases corresponds to the influence of the die geometry on the mechanical strain-stress state of the deformed piece.
- The second refers to the influence of the RFD process on the superficial quality of the forged product
- The third analysis focussed on the influence of the RFD process on the closure of defects of metallurgical origin.

4.1 Die geometry

Originally the geometry of the anvils was flat as shown in figure 2 (top). When big reduction ratios were applied with those anvils, laps were likely to form during subsequent passes in the deformed areas close to the corners of the anvils.

Moreover, if the strain and stress state was too high, these areas were prone to produce superficial cracks, especially when working with low forgeability steel grades.

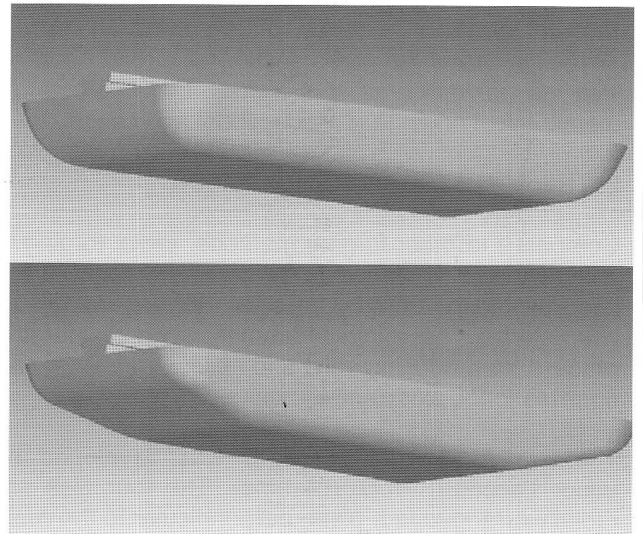


Fig. 2. Geometry of the plain anvil (top) vs taper anvil (bottom).

In order to prevent the appearance of these superficial defects, a study of the optimum anvil shape was performed using FEM simulation. To decide the optimum shape of the corner angle different taper angles (10-15-20°) were simulated and the results compared with the results obtained for the flat anvil.

In figures 3 and 4 the effect of the corner anvil shape on the distribution of the effective strain and mean stress in the deformed surface is shown in comparison with the flat anvil.

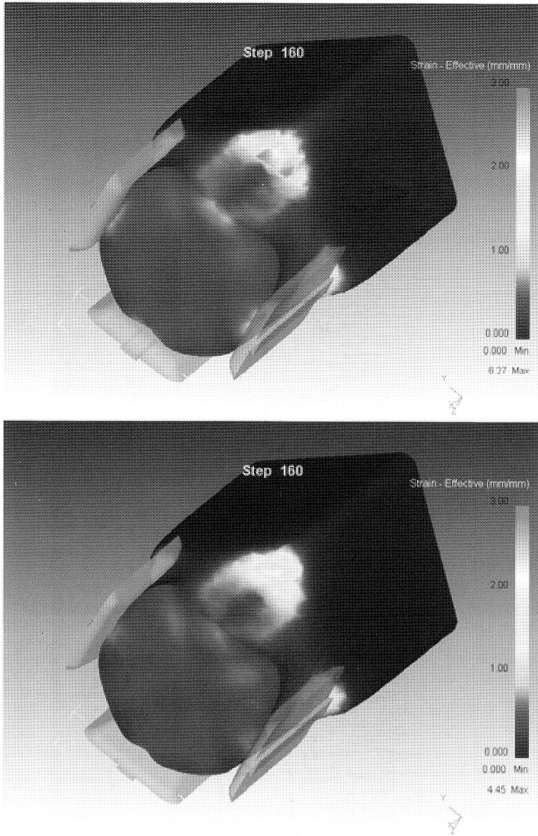


Fig. 3. Effective Strain distribution for plain anvil (top) vs taper anvil (bottom)

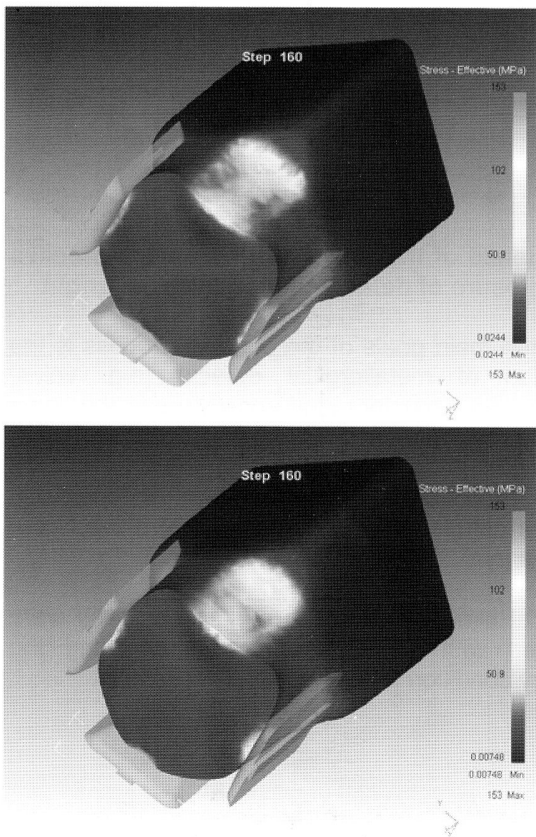


Fig 4. Main Stress distribution for plain anvil (top) vs taper anvil (bottom)

The largest absolute values of effective strain are observed in forging with the old shape flat anvils in the area under the corner of the anvil (Fig. 3a and 3b). Maximum effective strain observed is 3.0 (mm/mm) for the old die shape and 2.2 (mm/mm) for the new tool design. Something similar could be observed for the effective stress (Fig. 4b). A height reduction of 20% was selected; this value of reduction was selected as a representative value for a typical cogging process.

The simulation results confirm that the shape of the anvil has a great influence on the mechanical strain-stress state of the deformed piece and laps are less likely to be generated with the tapered anvil than with the flat anvil.

Taking the above results into consideration the shape of the anvils was modified as shown in Fig 2 (bottom).

4.2 Influence of the radial forging device process on the superficial quality of the forged products

There are a number of problems inherent in the open die process. Due to the die configuration, edge surface cracks are likely to develop in the areas of free expansion of the workpiece where tensile stresses build up, especially when working with low forgeability steel grades.

Figure 5 shows the distribution of tensile stress in the open-die forging process (top) compared to the process with the radial forging device (bottom). Important differences could be observed in the centre and the lateral areas of free expansion. Longitudinal and transverse tensile stresses occur in a large part of the deformation zone when forging with two dies

Forging with four dies limits the amount of tensile stress developed in these areas as the workpiece is confined by the lateral dies.

On the other hand, open die forging causes inevitable inhomogeneities of strains. Figure 6 shows the distribution of equivalent strain in the open-die forging process (top) compared to the process with the radial forging device (bottom).

Differences in strains of particular sections are the source of significant variations in final material properties, resulting from a different history of deformation.

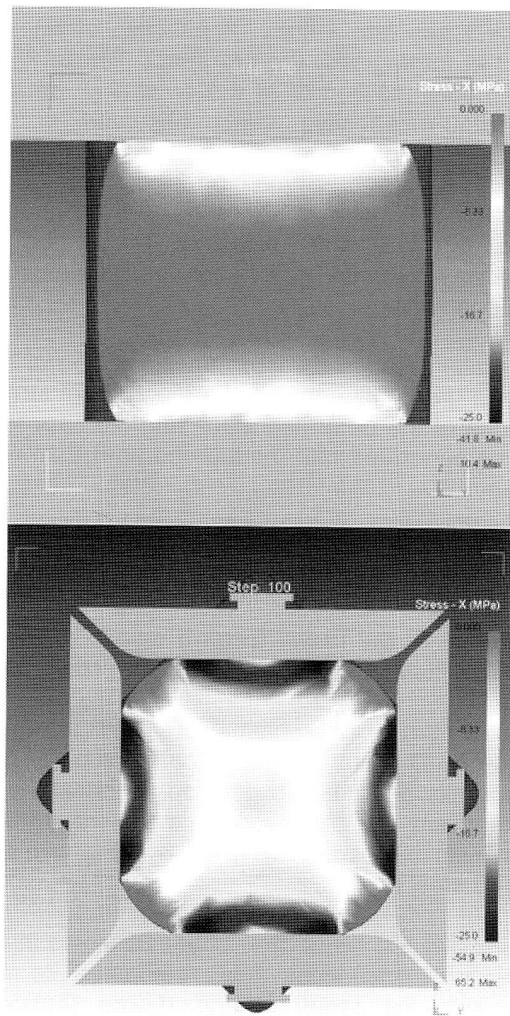


Fig 5. Distribution of Longitudinal Stress in open-die vs RFD process

Simulation results also show that deformation is generally uniform with the radial forging device process and the penetration to the workpiece centre through the sliding cones tends to be higher.

When forging with the radial forging device, thermographic and simulations analysis of the temperature distribution shows that smaller differences are developed between the workpiece surface and the interior of the forged piece and the workpiece temperature is maintained higher during the forging process.

Comparison of the finite element predictions and the experimental thermographic measurements for temperatures showed good correlation.

Process simulation results in terms of strain/stress/temperature distributions demonstrated that surface cracking problems may be minimized by using the radial forging device process with shaped dies.

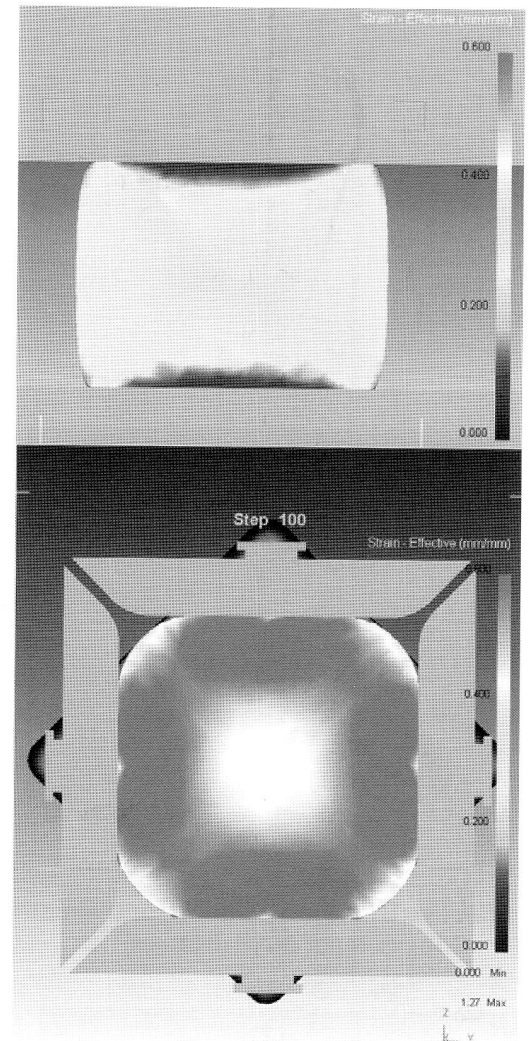


Fig 6. Distribution of strain in open-die forging process vs RFD process

4.3 Influence of the radial forging device process on the closure of defects of metallurgical origin

One of the main goals of the cogging process is the elimination of metallurgical defects (e.g. voids, shrinkage cavities) localized mostly near the ingot centreline.

In order to consolidate internal voids and porosity, extensive compressive deformation in the ingot core is necessary.

Numerical simulations of the cogging process were conducted with DEFORM program adjusting the boundary condition for this specific application.

4.3.1 Helicoidally trajectory followed by the metallurgical ingot centre

Figure 7 shows the metal flow pattern produced during forging with the radial forging device. The asymmetric ram speed configuration (cinematic) of the device produces the effect of material twisting, resulting in a better macrostructure of forged pieces as will be shown further on in this paper.

The radial forging device differs from conventional radial forging machines in that it produces a complex redistribution of material in the different directions that favourably influences the process of closing up the central metallurgical defects such as central porosity.

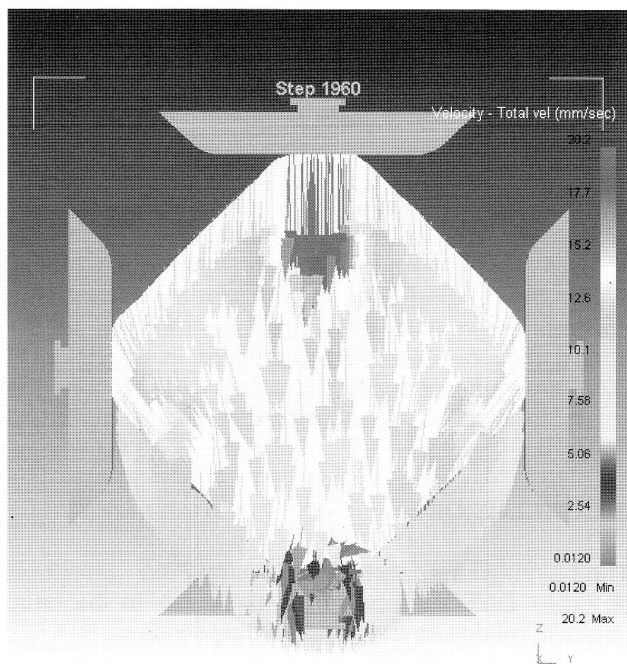


Fig 7. Metal flow pattern produced during forging with the radial forging device

The different speeds of the dies generate nonsymmetrical sliding cones and therefore the metallurgical centre of the piece is displaced.

Figure 8 shows the trajectory followed by the metallurgical centre of the ingot during a stroke for different die speeds. As can be seen the centre is progressively displaced from its originally position at the centre of the piece.

The alternative that have been analysed correspond to a ram velocity of 5 mm/s. Process parameters typical of forging in standard conditions (ram velocity 1-0.01 mm/s and tool temperature 1200°C) were assumed. To emphasize the effect of variables of the process conditions, the effect of temperature on the deformation can be neglected.

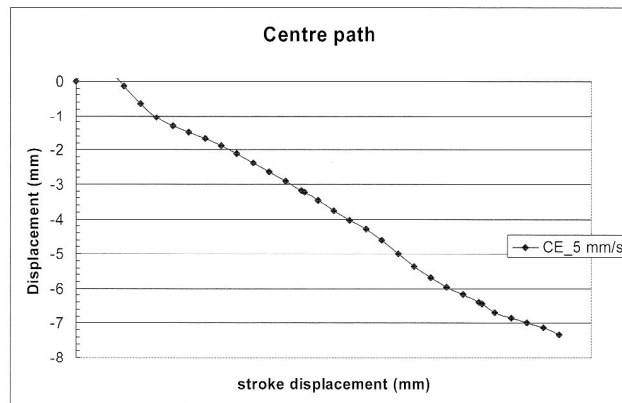


Fig 8. Centre path followed during a stroke

The displacement of the metallurgical centre during the first stroke in coordination with the rotation of the workpiece and subsequent feeding, results in the metallurgical ingot centre following a helicoidal trajectory.

The penetration of the upper sliding cone towards the workpiece centre tends to be higher in comparison to other radial forging processes.

This effect of the metal twisting, results in a more homogeneous structure and some improvement of the mechanical properties of the forged piece.

4.3.2. State of stress developed at the centre of the forged piece

The state of stress in the deformation zone is strongly dependent on the process parameters (such as the bite ratio, the reduction in height and the aspect ratio of the workpiece).

Avoidance of the tensile stresses is particularly important in the initial phase of cogging, due to poor forgeability of the as-cast ingot structure.

The effect of the bite ratio on changes of the stress state has been studied by various authors. [5-9]. The higher the bite ratio, the quicker the transition to the triaxial compressive state of stress. However, research results recently published on this topic indicate that the increase of the bite ratio over 0.7 does not influence the efficiency of void closing, so it only causes the unnecessary increase of spread and forging force.

The effect of the aspect ratio (here defined as the ratio between the height and the width of the transversal section before each pass) on changes of the stress triaxiality state at the centre of a deformation zone has been studied. The open die process has been compared with the RFD process.

During forging with the RFD the aspect ratio is maintained constant and equal to 1. However the

open die process includes different workpiece aspect ratios:

When the cross-section is completely square the aspect ratio is 1, which happens in the even passes. However in the odd passes, the aspect ratio is higher than 1 due to the lateral expansion of the workpiece in the previous passes.

Fig 9 shows the simulation results of the changes of the stress triaxiality at the centre of the forged piece for different aspect ratios and forging processes with a bite ratio of 0.5.

It can be observed that when forging with the RFD, (aspect ratio 1), triaxial compression can be obtained starting from a height reduction ratio of 18%.

When forging with the open die and with an aspect ratio equal to 1, elimination of the tensile stresses at the ingot centre is much more difficult, although possible, and requires height reductions exceeding 28%.

However, for aspect ratios bigger than 1, the longitudinal normal stress remains tensile even for great reductions in height, (35%) when the aspect ratio is (1.4) (see Fig. 9).

The curves in figure 9 show that the lower the aspect ratio, the quicker the transition to the triaxial compressive state of stress. The higher the initial aspect ratio, the more dangerous is the initial phase of deformation.

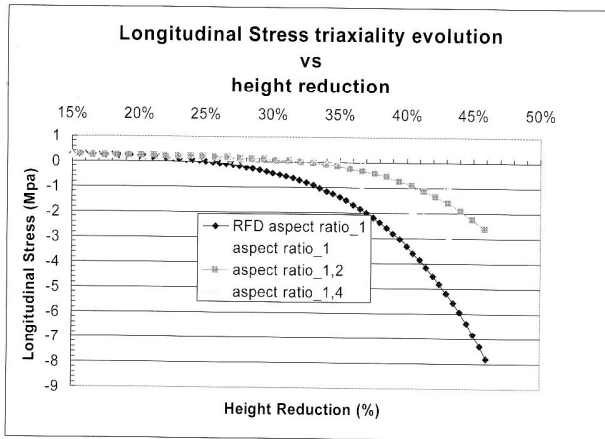


Fig 9. Effect of aspect ratio on changes of the stress triaxiality at the centre of the forged piece

The triaxial state of compression can be related to the longitudinal state of stress as the vertical and transverse stresses reach the compression state before the longitudinal stress (see Fig 10).

Another advantage of the radial forging devices over the open die process is manifested by a much quicker transition to the compression state of stress at the centre of the piece as the aspect ratio is constant and equal to 1 during the whole process.

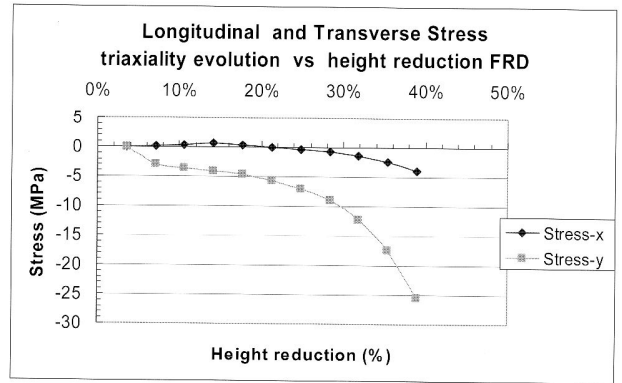


Fig 10. Longitudinal and transverse Stress as a function of Height Reduction for FRD process

For materials with poor forgeability, cogging with the radial forging device is the best solution in order to achieve a favourable state of stress in the centre of the piece.

Considering variants with the radial forging device processes, the most favourable state of stress occurred for higher bite ratios with smaller reductions. When the forging load is not the constraint, the maximum permitted individual bite ratio up to 0.7 should then be used and reductions in height up to 20% are sufficient, always taking into account the strain to fracture characteristics of the deformed material.

5. CONCLUSIONS

The simulations were run using the computer program DEFORM, which was found to be very useful in modelling the radial forging process.

On the basis of the simulations and the experimental trials carried out, it can be stated that the use of the radial forging device has a favourable effect in terms of improving the strain distribution over the cross section of the forging as well as in terms of the removal of defects of metallurgical origin.

The uniform character of the deformation which is achieved in the initial stages of forging ingots in radial forging has a favourable effect on the surface quality of the forged bars.

Furthermore, the configuration of the radial forging device produces an asymmetry in the anvil speeds which favourably influences the process of closing up the central metallurgical defects such as central porosity.

Taking into account the results of the numerical research that has been carried out, the industrial experience and the review of literature, recommendations have been formulated for the selection of parameters for the radial forging process.

6. Bibliography

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