Fatigue Fracture of Steel Sheet when Loaded Orthogonally to the Plane of Rolling

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The mechanical properties of steel sheet show considerable differences between the three directions: direction of rolling or longitudinal direction, lateral direction, and the direction of thickness or vertical direction, pointing orthogonally on the plane of rolling given by the other two. While development of materials has lead to nearly the same static properties in the longitudinal and lateral directions, the values of ultimate tensile strength and yield strength are about 20 per cent lower in the vertical direction than in the longitudinal one, those of elongation and reduction of area even up to 70 per cent lower. This severe reduction of ductility causes problems especially in welded constructions, because these often have joints, loading a plate orthogonally to its rolled surface, whereas the calculations of the design are mostly based on the longitudinal properties of the material only.

The lower ductility and the loss of strength in the direction of thickness are mainly caused by the stratification of nonmetallic inclusions, which are flattened by the process of rolling. In consequence the metallic matrix is weakened most in the vertical direction, an additional effect of stress concentration given by the thinned disks cannot be excluded. When loaded statically in the direction of thickness the sheet cracks in several planes parallel to the plane of rolling, giving the fracture a terrace-like appearance generally known as lamellar tearing. The terrace plateaus correspond to low-ductility cleavage near the nonmetallic inclusions, the intermediate microscopic regions, especially those at the terrace slopes, represent zones of relatively high plastic deformations.

Up to now, no investigations are known about the fatigue behaviour of sheet metal loaded in the direction of thickness. The increasing use of high-yield steels in welded constructions consequently leads to minimum-weight designs, resulting in the possibility of enhanced fatigue loading, particularly of mobile units. On the other hand the additional and permanent continuing trends of space saving originate the increasing use of joints that transfer forces orthogonally to the surface of sheet metal. To generate knowledge about this point, a test program was started to compare the properties in the three coordinates, especially those of high-yield, weldable steels. For this purpose in the first part of the program similar specimens were taken from 50 mm thick plates in the longitudinal, lateral, and vertical directions. With these specimens the anisotropy of the materials shall be investigated fundamentally, i.e. without any additional influences of welding. Further tests using welded specimens will follow, and also show the properties of thinner plates loaded in the vertical direction.

The tests are running as stress-controlled, single-level Wöhler-tests with alternating tension and compression of a stress ratio $R = -1$. The resonant-type testing machine used has a load capacity of ±200 kN and a frequency of 50 cps. The tapered specimens have a minimum diameter of 12 mm.

The S-N-curves of the various steel qualities are indicating different kinds of anisotropy. Fig.1 shows a trend of curves for a CrMoZr-alloyed steel, heat-treated to a minimum yield strength of 700 N/mm^2. As it will be expected, the distributions of fatigue lives with their partly overlapping variations hardly show significant differences between longitudinal and lateral specimens. The values of the third group of specimens generally are lower 20 to 25 per cent, thus giving a good agreement to the above mentioned loss of static strength.

Preliminary results of a normalized MnNiV-alloyed steel with a minimum yield strength of 470 N/mm^2 are hinting to a different grouping of the S-N-curves. In fig.2 the relations between the longitudinal specimens and those in the direction of thickness are still comparable to those of

the other steel, showing about 25 per cent lower values for the latter specimens. The strength of the lateral specimens nearly equals that of the longitudinal ones at about $3 \cdot 10^5$ cycles, but at 10^6 cycles it is only of the magnitude of the vertical specimens. That would mean, concerning high cycle fatigue loading, a stressing orthogonal to the plane of rolling is for this steel at least no more dangerous than the usual stressing in the lateral direction.

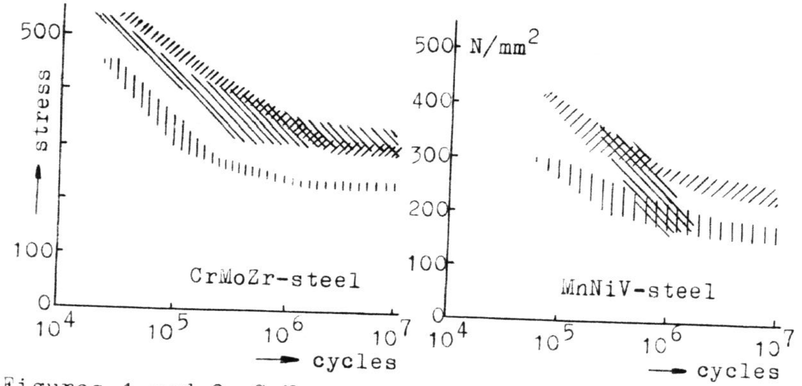
Up to now, only stress-controlled fatigue tests are made. As in static loading the vertical ductility is essentially lower, one may expect more severe differences between the three coordinates in the still intended strain-controlled tests, especially in the low-cycle region.

Fatigue fractures predominantly have the appearance of low ductility and therefore the fracture surfaces generally do not show any features of plastic deformation on a macroscopic scale. In the same way lamellar tearing produced by static loading in the direction of thickness is connected with little deformation. Nevertheless both kinds of fracture can clearly be distinguished on a macroscopic scale; fatigue fracture surfaces mostly have only one single, almost smooth plane, covering a larger area, while lamellar tearings show numerous small parallel terraces. On a microscopic scale fatigue fractures mostly have fine striations, characterizing the amount and direction of crack propagation, the microscopic structure of a lamellar tearing clearly exhibits the parabolic pits of a ductile fracture.

A fatigue fracture produced by stressing in the direction of thickness combines both macroscopic features. The fracture surfaces have the terraced structure again, as shown in fig.3, but in general they are smoother than a static fracture, the more the smaller the difference between the applied stress and the endurance limit is. By some exercise it is possible to distinguish the areas of fatigue crack propagation and of final rupture even on these very similar surfaces by naked eye. But it is incomparably more difficult to locate the point of crack initiation without any doubt.

The formation of terraces shows, that the weakening of the metallic matrix by nonmetallic inclusions is more severe than the stress concentration of an already existing fatigue crack. By means of a stereoscan microscope it was found, that the crack simultaneously propagates on several terrace plateaus already in the direct neighbourhood of its probable starting point. The striations of crack propagation are crossing adjacent terrace planes inclusing the intermediate slopes. Fig.4 shows such a region, the striations on the terrace slopes being concentrated to bright lines by perspective distortion. Part of this region, given in fig.5 at a higher magnification, reveals frequent interruptions of striations on the terrace plateaus by opening of the cavities of the nonmetallic inclusions. The surfaces of the slopes between the parallel terraces very often show "tire tracks", typical features for mode B of stage II of fatigue crack propagation, as can be seen on figures 3 and 6.

The surface of final rupture, which of course is a lamellar tearing, again exhibits on its terrace planes the microscopic cellular structure of a ductile fracture with its parabolic pits. An example is finally given in fig.7, showing, too, nonmetallic inclusions exposed by the fracture.



Figures 1 and 2: S-N-curves of 50 mm steel sheet, when stressed longitudinal///, lateral\\\, and vertical||||.

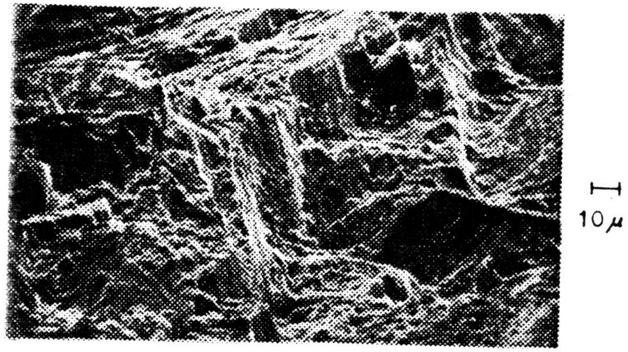
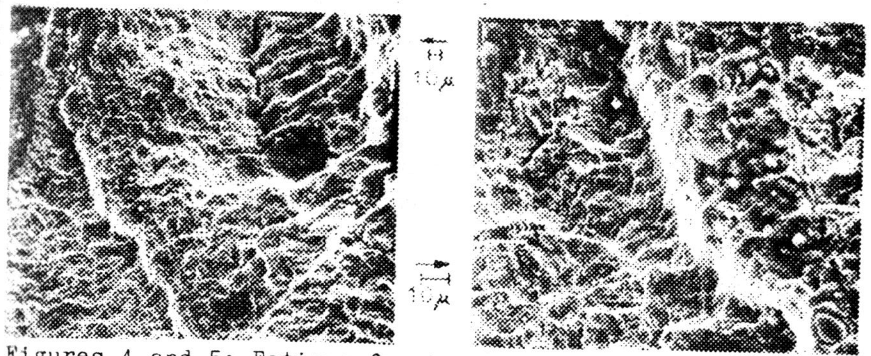


Fig.3: Terraces and "tire tracks" on the surface of a fatigue fracture, CrMoZr-steel, alternating stress in vertical direction ±240 N/mm^2, $3.72\cdot10^6$ cycles.



Figures 4 and 5: Fatigue fracture with terraced structure, MnNiV-steel, stress in vertical direction ±220 N/mm^2, 282,000 cycles (fig.5: detail of fig.4)

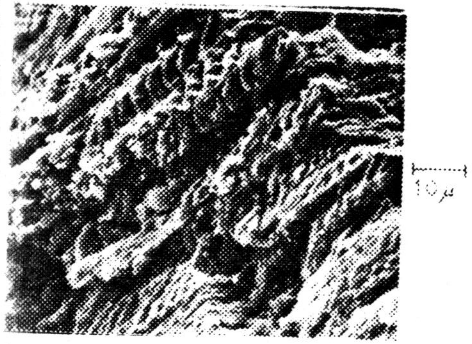


Fig.6: "Tire tracks" on the terrace slopes of a vertical fatigue fracture

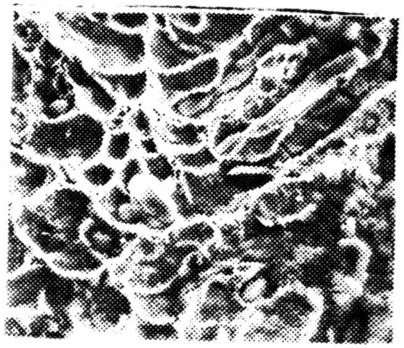


Fig.7: Final rupture surface of a specimen fatigued in vertical direction with ductile fracture in micro-regions